BIM-BASED FORMWORK AND CLADDING QUANTITY TAKE-OFF USING VISUAL PROGRAMING

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

YAŞAR ÇEPNİ

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
CIVIL ENGINEERING

SEPTEMBER 2021

Approval of the thesis:

BIM-BASED FORMWORK AND CLADDING QUANTITY TAKE-OFF USING VISUAL PROGRAMING

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ABSTRACT

BIM-BASED FORMWORK AND CLADDING QUANTITY TAKE-OFF USING VISUAL PROGRAMING

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September 2021, 111 pages

Material quantity take-off (QTO) is an indispensable work item in construction projects since it is essentially utilized for scheduling and cost calculation. Traditionally, quantities are calculated based on 2D drawings, which require significant time. It is also an error-prone process because of human inclusion. Moreover, during the project execution, the take-off process gets tedious due to design revisions, missing information, accumulated errors, and inevitable mistakes while performing QTO. Hence, the architecture, engineering, and construction (AEC) industry have been paving the way for implementing Building Information Modeling (BIM) for material QTO and other crucial tasks in the building industry, such as visualization, design analysis, and clash detection. However, the reliability of BIM-based QTO is being questioned among construction practitioners. It is because, and according to the literature, the accurate and automated calculation of area-based materials like formwork and architectural claddings using BIM remains problematic. The reason is mainly due to lack of modeling conventions, agreed workflows among project participants, erroneous modeling process, and limitations of BIM software. Previous studies proposed various modeling approaches, methods for querying BIM models for quantities, creating bridges between BIM-based QTO and take-off standards, and especially recent studies suggested using visual programing for more accurate and reliable BIM-based QTO. Therefore, two different methodologies are developed in this thesis to obtain accurate formwork and architectural cladding QTO within the context of visual programing. Then, a case study is implemented using Autodesk Revit and Dynamo to test the proposed methodologies. Meanwhile, the current software capability for BIM-based QTO is investigated while verifying case study results. Accordingly, results indicate that the algorithms developed in Dynamo successfully obtain material quantities more accurately, and it is also capable of automatically creating 3D models with essential information for formwork and architectural elements. The main contributions of this study are the proposed frameworks, visual codes, and showing the limitations and capabilities of one of the most commonly used BIM tools and problems during the execution of the case study. This research can also be further improved for 4D scheduling, clash detection, and most importantly, new studies in IFC (Industry Foundation Classes) format can be performed for enabling QTO with neutral and open format approaches.

Keywords: Building Information Modeling (BIM), Quantity Take-Off (QTO), Visual Programing, Formwork QTO, Architectural Cladding QTO

ÖZ

YAPI BİLGİ MODELLEMESİ TABANLI KALIP VE KAPLAMA METRAJLARININ GÖRSEL PROGRAMLAMA KULLANILARAK HESAPLANMASI

Çepni, Yaşar
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Eylül 2021, 111 sayfa

Malzeme metrajı çıkarma işlemi, inşaat projelerinin planlama ve bütçeleme süreçlerinde vazgeçilmez bir iş kalemidir. Geleneksel olarak metrajlar 2B çizimlere göre hazırlanır ve çok zaman gerektirir. Ayrıca insandan kaynaklı hata yapma ihtimali yüksektir. Üstelik metraj çıkarma süreci proje yapım aşamasındaki revizyonlar, eksik bilgiler ve gittikçe biriken ve kaçınılmaz olan hatalar yüzünden zahmetli olmaya başlar. Bu sebeple Yapı Bilgi Modellemesi (YBM) sisteminin, görselleştirme, tasarım ve çakışma analizlerinde olduğu gibi, metraj çıkarma işlemlerinde kullanılmasının da önü inşaat sektörü tarafından açılmaktadır. Ancak YBM tabanlı metraj çıkarma işlemlerinin güvenilirliği proje paydaşları tarafından sorgulanmaktadır. Literatürdeki çalışmalara göre, kalıp ve mimari kaplamalar gibi alana bağlı malzeme metrajlarının doğru ve otomatik olarak hesaplanması hala problemli bir süreçtir. Bunun başlıca nedenleri modelleme kurallarının ve proje paydaşları arasında önceden belirlenmiş iş akışlarının eksikliği, modelleme sürecindeki hatalar ve yazılımsal kısıtlamalardır. Önceki çalışmalar, çeşitli modelleme yöntemleri ve 3B modellerin daha doğru metraj sonuçları vermesi için sorgulamalar ve aynı zamanda metraj standartları ve YBM tabanlı metrajların birbirine bağlanması konusunda önerilerde bulunmuştur. Yakın zamandaki çalışmalar ise görsel programlamanın daha doğru ve otomatik metrajlar için kullanılabileceğini öne sürmüştür. Dolayısıyla, bu tez çalışmasında kalıp ve mimari kaplamaların metrajlarını daha doğru alabilmek amacıyla, görsel programlama çerçevesinde iki farklı metot geliştirilmiştir. Daha sonrasında, önerilen yöntemleri test etmek için Autodesk Revit ve Dynamo ile örnek bir çalışma yapılmıştır. Test çalışması sırasında bir YBM yazılımında halihazırda bulunan metraj çıkarma özellikleri de incelenmiş ve geliştirilen yöntemin sonuçları ile karşılaştırılmıştır. Sonuçlar kapsamında, görsel programlama aracı Dynamo kullanılarak malzeme metrajları doğru ve otomatik bir şekilde çıkartılmış ve aynı zamanda otomatik olarak 3B kalıp ve mimari kaplama modelleri oluşturulmuştur. Bu çalışmanın başlıca katkıları önerdiği metraj çıkarma yöntemi, görsel programlama kodları, yaygın olarak kullanılan bir YBM yazılımının metraj çıkarma kapasitesinin ve kısıtlamalarının gösterilmesi ve aynı zamanda örnek çalışma yapılırken ortaya çıkan metraj çıkarma problemlerinin incelenmesidir. Bu çalışma ilerleyen aşamalarda 4B planlama ve çakışma analizi için geliştirilebilir. Aynı zamanda yeni çalışmalar IFC (Industry Foundation Classes) formatı kullanılarak yapılabilir. Böylelikle YBM tabanlı metraj çıkarmak için yazılımdan bağımsız ve açık kaynaklı yöntemler oluşturulabilir.

Anahtar Kelimeler: Yapı Bilgi Modellemesi (YBM), Metraj, Görsel Programlama, Kalıp Metrajı, Mimari Kaplama Metrajı

Dedicated to my beloved family

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to my supervisor Assist. Prof. Dr. Aslı Akçamete Güngör for her guidance, advice, criticism, and insight throughout the research. While building up this study, she encouraged me to attend international academic conferences, and I gained tremendously valuable experiences. She also willingly supported me to go abroad for an exchange program during my master's study and let me meet a new culture and have a study experience in another well-known educational institute. Besides, she gave reference to me for my first job four years ago and enabled me to gain invaluable work experience in an international project.

I also would like to thank Assist. Prof. Dr. Ralf Klein for his suggestions and comments on my research during my Erasmus at KU Leuven. I will never forget his support, friendly approach, and welcomeness. He always encouraged me to keep my motivation at the utmost level during the Covid 19 pandemic.

I am grateful to my mother Nezihe Çepni, and my father Sait Çepni for their immense support and energetic approach. I am here today thanks to their motivational words, "You will do my son!!!". I am truly blessed to have the privilege of being their son and being the brother of my lovely sister Sema Sağgün. She always believed what I am doing and why I am doing it and continuously supported me.

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ABBREVIATIONS	
AEC	Architecture, Engineering and Construction
BIM	Building Information Modeling
CAD	Computer Aided Design
GBA	Gross Building Area
LOD	Level of Development
NBIMS	National BIM Standard
RGB	Red-Green-Blue
QTO	Quantity Take-Off

CHAPTER 1

INTRODUCTION

1.1 The Motivation of the Study

Staub-French et al. (2003) stated that cost estimation is a knowledge-intensive engineering task, and it requires an educated and experienced team of professionals to perform this task. Otherwise, clients and contractors end up with considerable fluctuations in construction cost calculations of different estimators for the same project, and this inconsistency brings about overestimation or underestimation, which further results in loss of opportunities and abrupt expenses. Similarly, Aram et al. (2014) emphasized that cost calculation is the point of departure for successful project management such that budgeting, bidding, production planning, and cost control activities rely on effectiveness in cost estimation.

Jrade & Alkass (2007) stated that cost estimation during the initial phase of a project traditionally relies on the experience of estimators and assumptions based on previous data of projects having a similar scope of works while design drawings and specifications are being utilized later for the detailed estimation. It is because detailed cost calculation requires understanding the design details and differences between consecutive design revisions and their unexpected ramifications on the project budget in later stages (Lawrence et al., 2014).

Cost estimation is a critical process, and it is generally comprised of material, labor, equipment, and overhead costs. Material costs inevitably rely on quantity take-off (QTO) based on construction documents, including design drawings and specifications. Hence, Olsen & Taylor (2017) stated that design documents should be meticulously investigated for material QTO so that there is not double-counted or disregarded information on the construction documents. These documents should also be closely followed up during the project execution because they are most subject to change, and those changes might need to be reflected in material take-offs.

Quantity take-off (QTO) is a detailed measurement of building materials, and it is the backbone of construction activities (Firat et al., 2010). It is stated that QTO provides the base for preliminary cost estimation in the early project stage; meanwhile, it helps estimate project cost and duration of work items in the tendering phase while it is utilized for scheduling and budgeting construction activities in the construction stage for the economic control of the project (Monteiro & Martins, 2013). In general, the QTO process includes identifying construction items and their relations using design drawings by obtaining dimensions and calculating units of measurements such as areas, volumes, and linear meters (Shen & Issa, 2010). However, this process eventually gets tedious and time-consuming since designs are always changing, and details continuously increase in the project life cycle. Cheung et al. (2012) stated that traditional QTO gets iterative and ineffective since design development between successive activities creates time-lags during design development and design reviews, and consequently, cost calculation and QTO becomes slower. Despite its importance, traditional QTO is a manual process, and it requires a significant amount of time to interpret conventional printed and CAD drawings (Sabol, 2008).

For this reason, the AEC industry has already been using BIM for material QTO. Ashcraft (2008) stated that 3D information models include data or links to associated data required to extract material quantities such as length, area, cost information. He also added that BIM prevents processing the take-offs manually, decreasing errors and misconceptions while building up cost data with the design developments and updates. Azhar et al. (2008) worded that BIM tools have cost estimating features that automatically calculate and update material quantities; this way, whole-life costs of construction projects are better captured. Hence, a well-structured BIM model includes all necessary geometric and non-geometric building data for building components (Figure 1.1). As the model develops, a list of materials can be extracted from 3D models, and they can be used for various purposes.

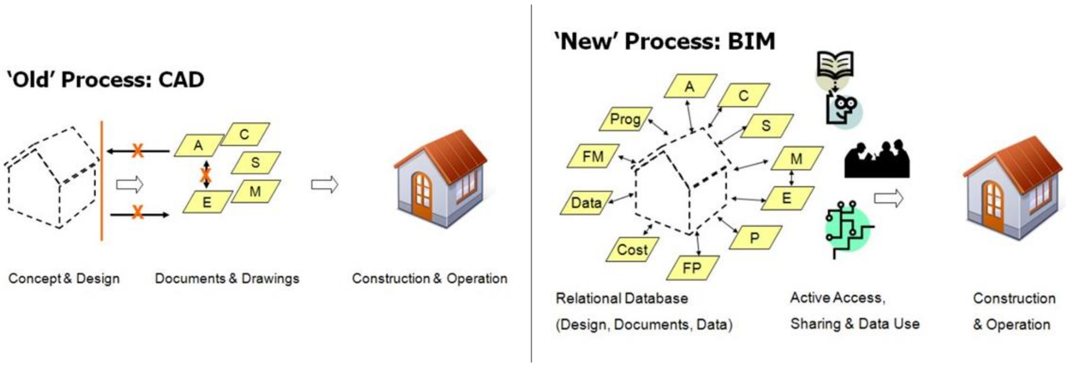


Figure 1.1. A comparison between conventional CAD and new BIM approach (Azhar et al., 2008)

However, there are some problems with obtaining accurate QTO results from 3D models. Khosakitchalert et al. (2019a) expressed that 3D models provided by designers may not have detailed building elements enough for material take-offs, or the quantities may be excessive or insufficient due to the modeling process. Lawrence et al. (2014) stressed that the estimating process is more than just counting and measuring but understating and evaluating construction conditions such as unique wall conditions and compelling situations affecting project costs.

Therefore, it reduces the reliability of BIM-based QTO even though 3D models can still be utilized for visualization, clash detection, and shop drawing production. Olsen & Taylor (2017) stated that construction practitioners find BIM-based QTO unreliable due to the limited and misleading information in 3D models and the amount of time for checking model correctness. Furthermore, Franco et al. (2015) pointed out that the cost and time for creating the detailed 3D model, implementing an automated estimation structure, and training of the BIM staff hinder the BIM implementation for material QTO. Hence, the automated modeling of building components can save time and money for the construction industry. Monteiro et al. (2014) stated that data manipulation is required in some cases for the quantity take-off data to make the quantities compatible with the required format, but BIM features for implementing necessary mathematical relations are not user-friendly. Wijayakumar & Jayasena (2013) stated that counting objects is straightforward in BIM-based QTO, but area-based take-offs are challenging and hard to extract using BIM tools. Distinguishing overlapping building components and deducting opening areas like windows and doors is not always easy due to software limitations.

According to studies in the literature, BIM-based QTO has some drawbacks due to the following reasons;

- ✓ lack of manipulation of BIM take-off data
- ✓ unexpected design conditions and unique building components
- ✓ limited and deceptive information in 3D models
- ✓ cost and time for developing detailed models for QTO
- ✓ excessive and insufficient material quantities due to the modeling process
- ✓ software limitations for area-based material take-offs

It is evident that additional effort should be made to increase BIM-based QTO accuracy for the benefit of construction practitioners, especially contractors. Moreover, the automated creation of building components should be investigated to increase the efficiency of the 3D modeling process. Therefore, this study is intended to demonstrate the application of visual programing tools for QTO calculations in the BIM environment by eliminating modeling mistakes and software limitations. Building materials targeted in the study are area-based materials like formwork for structural framing systems and floor and wall claddings for architectural finishes. In the end, this thesis reveals the fact that visual programing tools facilitate material QTO for models having modeling mistakes or limitations, and it also paves the way for automatic 3D modeling of building components like temporary formwork and architectural claddings. The proposed methods and applications of visual programing are especially beneficial for contractors who needs detailed and accurate quantification of each building component in the construction stage.

1.2 Research Questions

This thesis aims at finding solutions for the following questions:

- ✓ How can concrete formwork and architectural finish QTOs be *accurately extracted* from 3D models using visual programing tools?
- ✓ How can visual programing tools be used to *create* 3D models for formwork and architectural elements *automatically*?

1.3 Research Objectives

The main objective of this thesis is to develop visual codes in Autodesk Dynamo to obtain accurate material QTOs for structural formwork and architectural floor, wall, and ceiling elements using 3D information models. This objective aims to eliminate errors due to modeling mistakes and deficiencies in the model and overcome some software limitations for extracting accurate area information, which is highly valuable for detailed cost estimation, to enhance the BIM-based material QTO process.

The second objective is to improve visual codes to generate surfaces for formwork and architectural finishes so that these surfaces can be automatically converted into intelligent 3D model elements such as walls, floors, and generic models. This objective aims to add missing geometric information into BIM models to prevent manual updates and reduce the time spent on the modeling process. It will allow the integration of 3D models of these elements into clash detection and the 4D simulation process. For example, automatically generated formwork models, which are temporary structures in construction, can be utilized in the 4D simulation process to better visualize the concrete casting works.

1.4 Scope of the Study

This thesis study investigates extracting accurate area-based quantities from 3D models using the Dynamo for Revit as the visual coding platform, and it also focuses on creating 3D model components automatically in the Revit environment. Only structural and architectural building elements are considered in this study. Hence, two frameworks are developed for structural formwork and architectural cladding materials. Structural foundations, walls, columns, beams, slabs, and stairs are selected building components for formwork calculations, while the floors, walls, wall bases, and ceilings are considered for architectural cladding calculations. Besides, the development of visual codes is explained in detail, and an underground station building, which is a reinforced concrete structure, is tested with proposed strategies.

1.4.1 Investigated Building Components and Specific Challenges

In this study, the focal unit of measurement is surface area since its calculation requires eliminating overlapping regions and correct modeling strategies for accurate results. Hence, this thesis firstly focuses on the accurate formwork area quantification of structural elements, including foundations, walls, columns, slabs, beams, and stairs. Secondly, the thesis investigates architectural components, including floors and walls since surface area extraction of these elements is challenging due to their composite structure. As discussed in sections 1.2 and 1.3, the thesis also focuses on generating 3D models for formwork and cladding materials.

For example, Figure 1.2 shows the typical challenges in formwork quantification. Accordingly, intersection areas between beams, walls, and columns are problematic in BIM-based formwork calculations. Besides, overlaps between different building components result in inaccurate results. Figure 1.3, on the other hand, illustrates the sources of erroneous material QT for floor and wall claddings. The main reason is the overlaps among different elements, as Khosakitchalert et al. (2019a) emphasized.

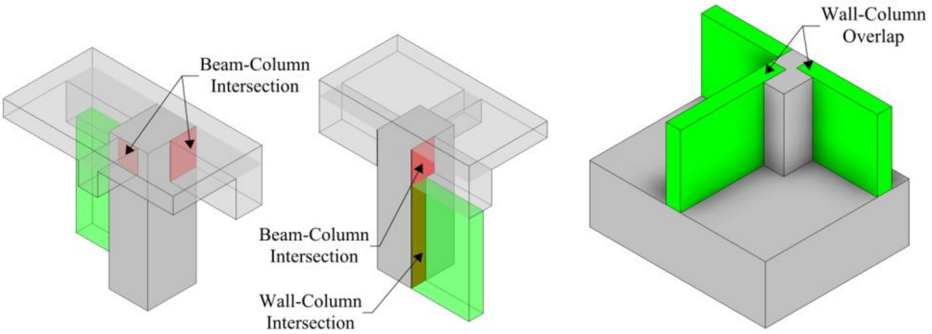


Figure 1.2. Typical formwork quantification challenges

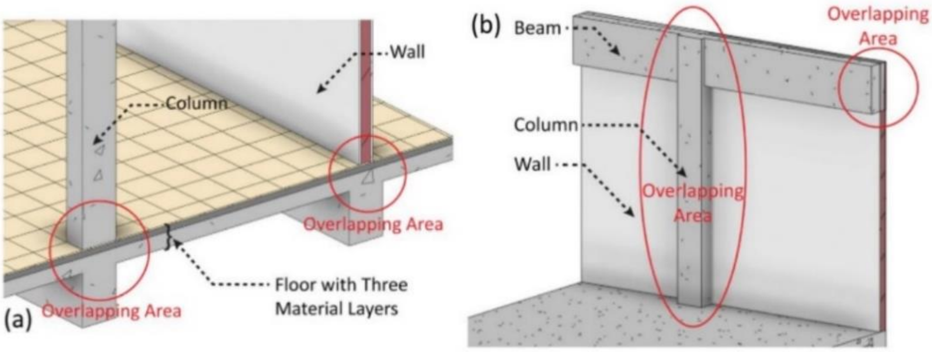


Figure 1.3. (a) Composite floor and (b) wall elements overlapping with other building components Khosakitchalert et al. (2019a)

1.4.2 Case Study Model

This study investigates an underground station structure in Turkey. Figure 1.4 represents the 3D model views of the main station building. The station is constructed as a reinforced concrete structure encapsulated with walls having 1500 mm thickness all around and supported by an 1800 mm thick mat foundation. The building is formed by two different blocks separated by a 50 mm expansion joint from the foundation top of the structure. The building has three-occupancy floors with three entry-exit structures, including both regular stairs and escalators. The entry-exit structures are also separated from the main building by a 50 mm expansion joint.

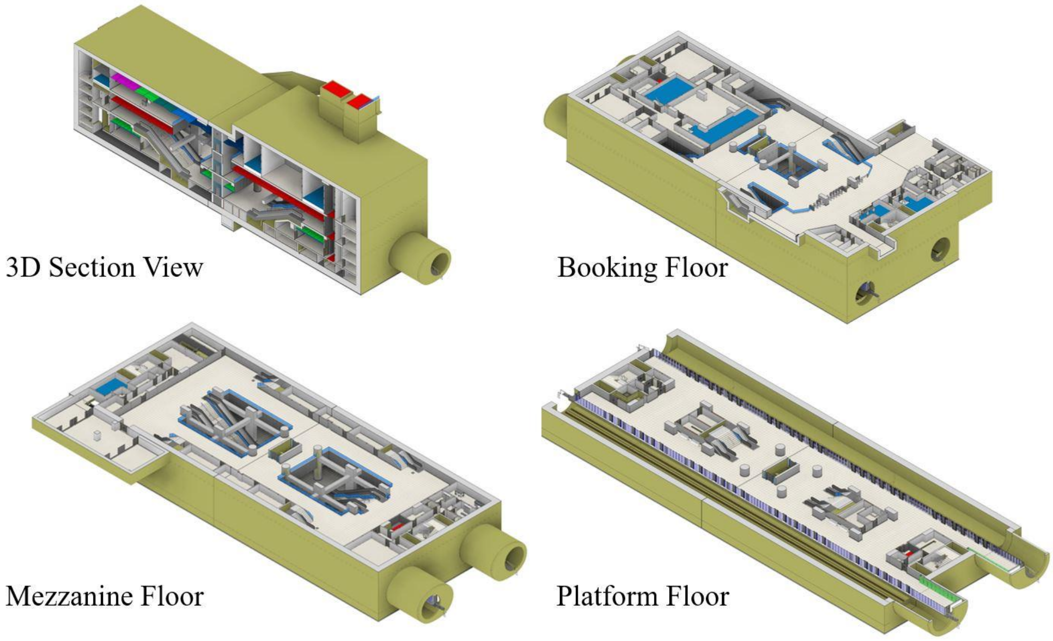


Figure 1.4. Revit model view for the case study

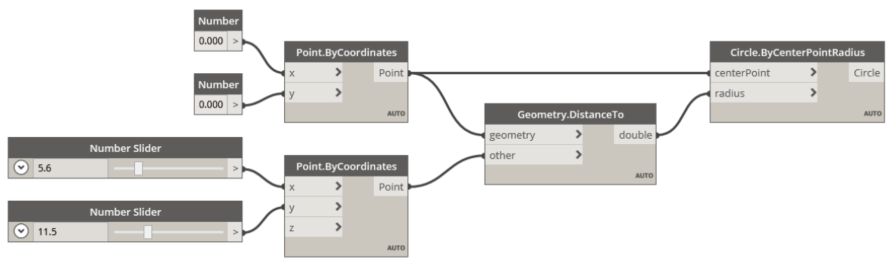
1.4.3 BIM Tools Utilized in the Study

There are many BIM tools in the construction industry. The focal BIM software utilized in this thesis is Autodesk Revit 2021, which is a suite of BIM software most commonly used in the industry by different disciplines. As a BIM software, Revit is a 3D modeling tool for engineers and architects. It mainly serves for visualization, coordination, quantity take-off, design analysis, and shop drawing production. Besides, there is a dynamic link between 3D views, plans, sections, elevations, details, drawings sheets, and schedules in the Revit environment. Hence, changes in one view, such as 3D views, also simultaneously update the other associated views. The visual programing tool used in this study is Dynamo 2.6.1, which is already ready in Revit software. Dynamo is described by Dynamo Primer as;

"A visual programing tool that aims to be accessible to both non-programers and programers alike. It gives users the ability to visually script behavior, defines custom pieces of logic, and script using various textual programing languages."

Figure 1.5 illustrates the differences between visual and textual programing for a simple code creating a circle. Accordingly, visual programing is easy to grasp by architects and engineers who do not have programing experience but also need programing from time to time. Figure 1.6 demonstrates a generic sample visual code to filter parapet walls in Autodesk Revit models using the "Top Constraint" parameter. Dynamo gets all wall elements in the model and checks their "Top Constraint" parameter, and if it is "unconnected" as marked with purple, Dynamo filters them in the "in" output of the last node as marked with red. The user also can preview the output results both in Dynamo and Revit environment simultaneously.

Visual Program:



Textual Program:

```
myPoint = Point.ByCoordinates(0.0,0.0,0.0);
x = 5.6;
y = 11.5;
attractorPoint = Point.ByCoordinates(x,y,0.0);
dist = myPoint.DistanceTo(attractorPoint);
myCircle = Circle.ByCenterPointRadius(myPoint,dist);
```

Figure 1.5. Differences between visual and textual programing (https://primer.dynamobim.org/)

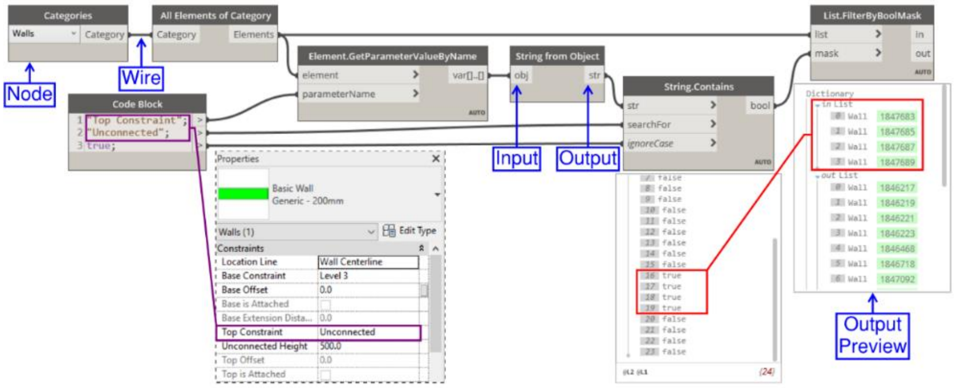


Figure 1.6. Sample Dynamo workflow and its key points

The chapters in this study are organized as below:

- ✓ **Chapter 1** introduces the problems in BIM-based QTO processes, research questions, objectives, and scope of the thesis. It also provides information regarding the evaluated building components, case study model, and BIM tools utilized throughout the study.
- ✓ **Chapter 2** presents the literature studies on BIM, advantages, and limitations of BIM-based QTO, visual programing, formwork, and architectural finish quantification, and identifies the research gap in the previous studies.
- ✓ **Chapter 3** explains the methodology using frameworks for achieving accurate BIM-based QTO and generating 3D model components.
- ✓ **Chapter 4** presents the case study application of proposed methodologies.
- ✓ **Chapter 5** discusses the results obtained from proposed strategies and real case data.
- ✓ **Chapter 6** summarizes the main research findings, discusses the limitations of the thesis study, and provides new directions for future studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Building Information Modeling (BIM)

BIM is a multidimensional, historically evolving, and complex phenomenon representing a building digitally in an object-oriented three-dimensional environment or being a repository of project data to enable information exchange and interoperability using advanced software tools (Miettinen & Paavola, 2014).

In a more concrete way, the National BIM Standard defines BIM as *"a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition." NBIMS also states that "a basic premise of BIM is a collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in the BIM to support and reflect the roles of that stakeholder."*

Azhar (2011) enounced that the construction industry can benefit from BIM since it provides detailed information for geometry characterization, spatial relationship, geographic data, quantity take-off, cost estimation, material inventory, and project scheduling. He also added that BIM is beneficial for faster and more effective processes, better designs, controlled whole-life costs and environmental and life-cycle data, better production quality, automated assemblies, and better client service.

Concerning Succar's (2009) work in Figure 2.1, BIM enables the fragmented AEC industry to collaborate effectively using the information models to rehearse the construction projects before executing the actual work. Besides, the BIM environment increases work efficiency during construction and helps manage the facility after completion.

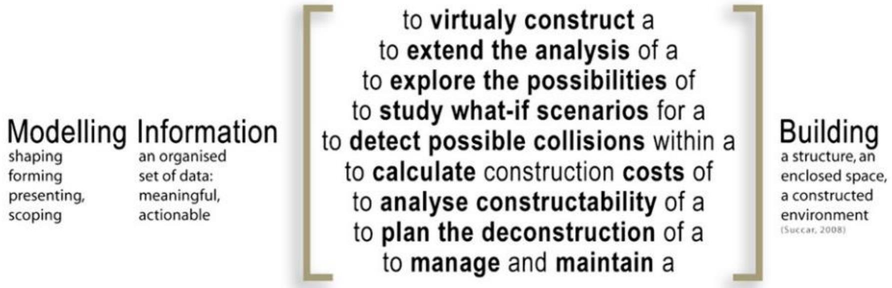


Figure 2.1. Some common connotations of multiple BIM terms (Succar, 2009)

Moreover, Yun & Kim (2013) gathered BIM definitions from various organizations, as shown in Figure 2.2. Accordingly, BIM is described as collecting, storing, and managing of building data, including geometric and non-geometric information.

Organization	Definition
AIA	A model-based technology related to the project information DB (linked to regional, national and international standards such as specifications)
ArchiCAD	A storage medium that contains graphic and non-graphic documents (specifications, schedules, and extra documents)
Autodesk	Creates consistent and concurrent information on building projects The created information is used in operations management, design decision-making, high-quality construction document production, performance prediction, cost prediction, and construction planning.
Bentley	Life cycle graphic and non-graphic modeling for effective outcomes
GSA	Computer software data model that was developed to document building designs and manage new social capital
NIBS	Expresses life cycle information such as physical and functional characteristics to show better values

Figure 2.2. Definition of BIM by different organizations (Yun & Kim, 2013)

Furthermore, Penttilä (2006) stated that BIM is a way to operate the building design, construction, and maintenance in a computer environment during the whole life cycle of buildings. He also added that computer-aided design (CAD) methods are primary tools to prepare geometric and non-geometric data, and there are various approaches to improve a software-independent format to facilitate information flow among AEC parties, and it is IFC (Industry Foundation Classes) within the context of this study. IFC developed by buildingSMART is a neutral and open format to share and exchange construction information in the building industry (Bonduel et al., 2018). Pauwels & Terkaj (2016) stated that the IFC standard is a conceptual schema and a data exchange format for the AEC industry since it facilitates BIM data sharing among various BIM tools to elevate the functionality of computer-aided design (CAD) for structural analysis, 4D planning, and 5D cost calculation.

Even though there are many aspects to conduct detailed research about BIM, this research aims to enhance the quantity take-off (QTO) and automated 3D modeling features in BIM using visual programing tools.

2.2 BIM-Based Quantity Take-Off

Ahn et al. (2016) stated that as a rapidly emerging and innovative environment, BIM enhances the design and management of construction projects by lowering the costs and schedule variations while contributing to the overall process and quality of the project. BIM-based project management provides a strong constitution between scope, time, and cost and enables the automated update of project plans when changing main or subparts (Peterson et al., 2011). Hence, managing accurate estimation and actual project planning costs using the BIM approach plays a prominent role in the successful construction business because cost estimation can be created easily when construction costs are determined and linked to the construction elements and scheduling activities (Pučko, 2014).

Ghaffarianhoseini et al. (2017) mentioned that economic benefits are one of the apparent current benefits of BIM. Accordingly, reducing documentation errors, increasing marketing advantages, and less staff turnover are the short-term benefits of BIM contributing to the construction economy. Meanwhile, reduced construction costs and fewer contractual claims are the long-term benefits. They also added that cost calculations could be obtained from the building model and keep construction practitioners updated about the cost variations as design changes because BIM helps to evaluate whether a building with a given size, quality level and desired requirements are feasible to construct within a given cost and time.

Harrison & Thurnell (2015) conducted a qualitative study in New Zealand, and the benefits of BIM-based estimation were revealed. Accordingly, enhanced visualization because of the 3D function of BIM facilitates the decision-making process because it reduces quantity take-off assumptions and inaccurate drawing interpretation. Efficient data extraction for early-stage design estimation is also crucial for the take-off process because it is generally used as a bulk-checking tool for manual measurements. Furthermore, efficient data extraction for detailed estimation and producing schedules of quantities are other benefits of BIM, but here it is also noted that these benefits are valid for certain building items and require some manual adjustments. Participants are generally agreed that the usage of BIM and trust for BIM-based QTO is expected to be soaring up in the future owing to increasing experience and awareness.

Khosakitchalert et al. (2019a) conducted a detailed literature study and grouped research into four groups for BIM-based QTO. Accordingly, the first group concentrates on BIM modeling approaches for accurate quantities. For example, Zima (2017) investigated composite walls and compared single walls and walls with different material layers. He summed up that a single wall approach is helpful for quick and rough estimations, but walls modeled with different layers serve better for detailed material QTO, and accuracy is higher than the former approach. The second group investigates the cost and QTO calculations in early design stages where 3D models are not sufficiently detailed yet for material take-off. Rajabi et al. (2015)

developed a scenario for quantifying MEP systems for the early design stage based on the idea that BIM is not just a detailed 3D model. Accordingly, he advocated that the quantities would be more accurate as the relations and logic became more precise. Moreover, Lim et al. (2016) examined problems with existing rebar quantification tools and framed the logical steps for potential algorithms and later rebar classification for a systematic estimation is developed to prevent omissions and duplications for integrated project delivery systems. The third group aims to link BIM-based QTO with standard databases. Zhiliang et al. (2011) proposed an information model requirement for cost estimation for tendering process in China. They first categorized the information required for cost calculation into seven parts: the building products information, the division-items project information, the cost-items information, the schedule information, the quantity information, the resource information, and the price information. Later, the IFC standard is utilized to describe previously defined requirements, and the IFC standard was unable to support desired information requirements such that they modified the IFC schema to enable direct integration with the cost estimation standards of China. The fourth group that Khosakitchalert et al. (2019a) is considered investigates querying information and material quantities from 3D models. Lin et al. (2013) suggested a novel framework using IFC schema, Natural Language Processing (NLP), and International Framework for Dictionaries (IFD) to retrieve data from BIM models and represent the data in the format of tables, charts, animations. They concluded that this approach could be implemented for cost management with detailed study to enrich the IFC content and advanced IFC mapping strategies. Hence, BIM-based QTO is investigated in terms of querying BIM models, integrating BIM with various standards, proposing new modeling techniques, and obtaining quantities from insufficiently detailed 3D models. Recently, visual programing approaches were also implemented for BIM-based QTO, and they will be discussed in detail in sections 2.5 and 2.6 as the main focus of this thesis is also visual programing for BIM-based quantification.

2.3 Limitations of BIM-Based Quantity Take-Off

Even though BIM has many benefits for the construction industry, some limitations and problems are emerging due to improper implementation. For example, Sattineni & Bradford (2011) emphasized that there are different departments for cost estimation and BIM in construction companies, and consequently, time reduction and quality increase for cost estimation cannot be achieved. It is because estimation and BIM departments can work in an uncoordinated process, which in reality should share the same data and feed each other to benefit from BIM-based QTO and cost estimation in every step of the projects. Smith (2014) stated that the AEC industry generally confronts problems in BIM-based QTO because the quality of BIM models is not trustworthy owing to a lack of understanding of automated QTO among estimators and limitation of solid knowledge of the QTO process that may give rise to not realizing CAD and BIM problems when it comes to BIM-based QTO.

Olatunji et al. (2010) stated that specific data, vitally crucial for estimators, may not be available in 3D information models since models provide material quantities superficially; hence wastes, joining and lapping allowances, in-line fittings and accessories, material contexts, treatments, and other indirect inputs may not be extracted from BIM models. Monteiro & Martins (2012) revealed that composite building components such as walls and floors are difficult to manage in BIM models. Although section details represent the original configuration, the 3D model is still one single element for walls and floors, bringing about the same dimensions for every layer of the component. Modeling mistakes, limitations in BIM tools, and not setting up ground modeling rules result in questioning the reliability of BIM-based material quantification (Bečvarovská & Matějka, 2014).

BIM implementation requires significant time and cost investments by the AEC industry, such as staff training, software, and hardware updates (Ghaffarianhoseini et al., 2017). However, companies generally suffer from interoperability issues, non-user-friendly delivery formats, and lack of skills and experience towards BIM, thereby low return on investment and not adopting BIM-based QTO.

Abanda et al. (2017) stated that there are four main limitations of the current BIM-based QTO. The first one is the lack of measurement standard, meaning that there might be inconsistency and quantities may not be compared easily, as a second reason, and in the case of existence of a measurement standard, the standard might be based on specific countries where software is developed. Hence, the quantities might not be helpful for other countries and might require additional workflows. Another reason is that software having standard measurement catalogs includes those standards in their installation folders, and it cannot be shared with other tools when required to acquire information. The last reason is that there is a manual and time-consuming process to arrange quantities extracted from BIM tools to put the quantity data into the desired format. Accordingly, managing and manipulating BIM data for material quantity might be challenging even we have the quantities in 3D models. According to a study conducted by Harrison & Thurnell (2015) in New Zealand, the following reasons are the main barriers to achieving BIM-based material QTO.

- ✓ Software interoperability issues
- ✓ Incompatibility with quantity surveying formats and lack of industry standards and protocols
- ✓ The necessity of manually reviewing and checking extracted quantities
- ✓ Lack of government intervention
- ✓ Lack of context for construction means and methods and training issues
- ✓ Cultural resistance
- ✓ Increased client costs

As the previous research reveals, there are many aspects of BIM-based QTO and cost estimation requiring detailed studies and improvements. However, this study mainly focuses on problems emerging from modeling approaches, software limitations, and the organization of BIM data.

2.3.1 Importance of Level of Development (LOD) for BIM-based QTO

BIM is a process such that information embedded into models develops during the life cycle of projects, and the development of the information over time brings about a new concept named level of development (LOD). BIM Forum (2019) defines the level of development as "the degree to which the element's geometry and attached information have been thought through – the degree to which project team members may rely on the information when using the model." The input to an element should be considered as the level of detail, and the reliable output of an element is to be understood as the level of development (BIM Forum, 2019). It is essential to understand both concepts since they are closely related and used interchangeably in some sources.

There are six different LOD stages in practice and literature: LOD 100, 200, 300, 350, 400, 500, and these stages need to be achieved at different phases of the project. Figure 2.3 illustrates the development of a wall element from LOD 300 to LOD 350. LOD 350 model includes the wall studs, actual opening dimensions, which affect the quantification and coordination processes.

LOD is crucial for BIM applications since models with more details are more applicable and reliable for quantification, coordination, and scheduling. Song & Fischer (2020) states that site supervisors cannot take advantage of unimproved models that are insufficient for daily planning since specific products like brackets and drywall frames are not present in the model. It is because they cannot quantify the material needed for a specific job, even they cannot see a complicated assembly for visualization owing to lack of LOD.

It is evident that preparing a model in high LOD is taking some time, but Leite et al. (2011) concluded that additional modeling effort increases precision and enables better decision making in the project life-cycle. For example, modeling architectural claddings and structural core walls separately may cause small time loss during the design stage, but it is beneficial for the construction stage since take-offs can be quickly and correctly extracted from models.

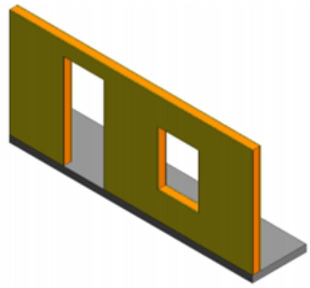
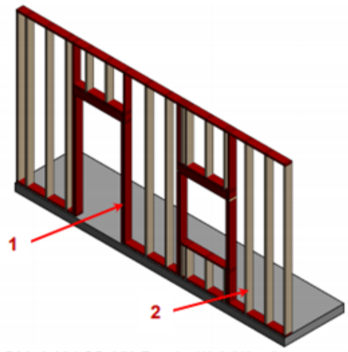
300	Specific wall modeled to actual dimensions. Penetrations are modeled to nominal dimensions for major wall openings such as windows, doors, and large mechanical elements. Shear panels	 *69 B2010.06-LOD-300 Exterior Wall (Wood)*
350	Wood framing is developed with sufficient elements to support detailed interface coordination with other systems such as MEP. All penetrations are modeled at actual rough-opening dimensions. Openings modeled with support framing around openings *Image notes:* *1) Elements in red are critical wall support elements that cannot be easily cut for coordination of MEP opening through the walls.* *2) Infill wood framing modeling may be omitted at this LOD if stated in the BXP.* *3) Cladding and sheathing are not shown for clarity in this image.*	 *70 B2010.06-LOD-350 Exterior Wall (Wood)*

Figure 2.3. Differences between LOD 300 and LOD 350 (BIM Forum, 2019)

All project participants should determine LOD in the project life-cycle and create models to make the quantification process feasible and comfortable (Firat et al., 2010). LOD needs to be changing to reflect preliminary and detailed cost estimations during the execution of projects (Sabol, 2008). Hence, models should have enough LOD for better visualization, job follow-up, and quantification purposes. Furthermore, model elements should be modeled following the construction sequence with actual dimensions so that models serve for budgeting and scheduling activities.

2.4 Visual Programing Tools

Visual programing tools have already been adopted in the AEC industry since they are user-friendly and provide automated processes for construction professionals. Kensek (2014) performed a case study to enquire the feasibility of integrating environmental lighting, humidity sensors, and carbon dioxide receptors to BIM using Dynamo for Revit and Rhino Grasshopper for the benefits of intelligent building façade systems. Later, Kensek (2015) carried out new case studies to build an energy simulation package with Dynamo and checked the reaction of the 3D model with light sensors and simultaneously updated shadings of the building façade according to solar angles. According to these studies, Dynamo can create a workflow for 3D models, automatic updates can be achieved using parametric relations, and it enhances the sustainable design alternatives for building façades.

Collins (2016) utilized Dynamo to create architectural precast concrete fabrication with five types of parametric properties, including top caps, turn backs, reveals, notches, and embed locations. With this approach, Collins (2016) coordinated precast concrete panels with other exterior wall assemblies, generated automatically updateable shop drawings and tickets, and calculated material quantities like the volume of concrete and type and number of embeds. Ignatova et al. (2018) stated that the option "family name" is a built-in parameter in Revit, and there is no standard Dynamo node to get the embedded parameters, but with the help of Python, a new custom node is developed to get the required family parameters. It means that Dynamo provides an open environment to improve BIM's capacity and useability further.

Pocobelli et al. (2018) performed a study to analyze humidity in the BIM environment so that weathering and degradation of heritage building façades can be introduced to BIM. For this purpose, they created the case study model and placed moisture measurements in the form of families to specific model points. Later, they used Dynamo, and imported the required Revit elements, obtained RGB colors, and merged them with previously created RGB color range to distinguish moisture changes. Bueno et al. (2018) obtained environmental performances of a social housing model by integrating manufacturer based LCA data in Revit using Dynamo and MS Excel in the early design stages for the reliable decision-making process and complex data management for building components.

Likhitruangsilp et al. (2018) developed a system calculating the impacts of change orders by evaluating the changed conditions of the building, time, and schedule using Dynamo for Revit and addressed the data acquisition, change detection, schedule impact analysis, cost impact analysis, and reporting methods. Sadeghi et al. (2019) presented a study enabling BIM-based workflow to capture and retrieved facility management information to generate operation and maintenance data according to the end-user requested format using Dynamo as an add-in for extending parametric functionality of Autodesk Revit.

Shahsavari et al. (2019) performed a case study for the design uncertainties affecting building energy performance, and Dynamo for Revit is utilized to extract model variables for an energy analysis tool that analyzes sensitivity and uncertainty for decision-making. Yang et al. (2019) utilized Dynamo to handle the complex geometry and knowledge composing heritage building and performed a mesh-to-HBIM (Historic-BIM) and HBIM-ontology integration to extend the capacity of BIM. Yang et al. (2020) later stated that the adoption of Dynamo minimizes human inclusion in the BIM modeling processes.

Previous studies show that Dynamo is already used for various applications to automate processes, manipulate BIM data, perform uncertainty analysis, and create 3D geometry to reduce errors. Therefore, Dynamo can be further utilized for cost estimation and material QTO purposes. Here, it is essential to note that studies implementing visual programing in BIM-based QTO are to be discussed in sections 2.5 and 2.6.

2.5 Formwork Quantification

Formwork, a temporary structure for molding materials, is an indispensable part of the construction industry since it is inevitably integrated with the design and construction of concrete structures due to industrialization in the modern era (Shapira, 1999). However, the construction industry conventionally pays attention to the design and construction of permanent structures, and temporary structures such as formwork and scaffolds assisting in building the actual structure are generally ignored in terms of detailed design, estimation, and construction process (Shapira, 1999).

This trend also continues in the CAD environment because formwork and scaffolding, as temporary structures, are generally missing from 3D models resulting in manual involvement for formwork quantification (Liu et al., 2014). This is because BIM tools, including IFC schemas, do not have a specific tool for formwork modeling and investigation and generally do not calculate formwork areas correctly where building elements intersect (Monteiro & Martins, 2013). On the other hand, formwork models need to be developed on the existing 3D models to increase cost estimation accuracy for temporary formwork structures; otherwise, the estimation remains statistical (Cho & Chun, 2015). Thus, various research focused on improving the BIM-assisted formwork QTO using specific BIM tools and approaches.

Meadati et al. (2011) proposed a BIM-based repository for teaching purposes by associating additional information to 3D models to represent design loads through 3D models, alternative design analysis, and constructability analysis automation of shop drawing productions and material quantity take-off using Autodesk Revit and Navisworks environment. Kannan & Santhi (2013) created formwork components in Autodesk Revit, which are simplified families and developed manually, for a high-rise building to compare the selection and operation of conventional formwork systems, climbing formwork systems, and automatic and semi-automatic climbing formwork systems. Jiang & Leicht (2016) proposed an ontology-based strategy to capture and determine the mutual interdependencies between design and construction process for formwork construction. They systematically structured the constructability knowledge to enhance and create reusable information and continuous collaboration among project participants, thereby saving time and effort in the constructability process of RC structures.

Mansuri et al. (2017) proposed a framework for the management of formwork systems in terms of reusability, minimizing formwork planning, reducing temporary storages, lowering the formwork damages, and cutting down the crane lifts and operation on construction sites by using organized and effective handling of BIM data developed in Tekla Structures environment. Their study concluded that there is a time-consuming process of developing formwork models that also affect the efficiency of their formwork management strategy. Eventually, they suggest the development of automatic formwork modeling tools.

Lee et al. (2017) developed an object-oriented approach to integrate schedule and cost estimation using ArchiCAD models to represent productivity with visual progress in 3D models and generate a productivity best-fit line, which can be utilized as a baseline for similar projects. Kannan & Santhi (2018) later developed a Revit add-in, named CONSTaFORM, to assess various concrete systems in terms of constructability. They classified the constructability attributes for material, labor, and construction in terms of cost, time, quality, safety, and sustainability.

Eroglu (2019) evaluated formwork quantification features of Autodesk Revit based on the BIM model, which is previously prepared in Nemetschek Allplan. In this study, a 3D model of an actual hospital building is also created in Revit, and formwork quantities are extracted from the model using a free add-in called "Sofistik BIMtools" since there is no available feature to calculate formwork area directly from 3D Revit models. Later, the formwork area results from Revit, Allplan and manual calculations are compared. Accordingly, he concluded that the formwork area for foundation elements, structural columns, and parapet walls is correctly calculated from the Revit model, while the wall formwork area cannot be calculated due to the limitations of formwork area tool in Sofistik BIMtools. Similarly, the formwork area of beams cannot be calculated accurately from the Revit model, especially when there is a drop slab on the sides of beam elements. Moreover, floor areas are also extracted inaccurately compared to actual results since the formwork tool cannot distinguish and evaluate shaft openings. Hence, there are still problems with formwork quantification due to software limitations and modeling approaches.

Khosakitchalert et al. (2019a) suggested using their visual programing approach BCEQTI (BIM-based compound element quantity take-off improvement) to estimate structural concrete volumes and formwork areas using Dynamo for Revit. After that, Khosakitchalert et al. (2019b) developed a visual algorithm based on their previous study and calculated structural formwork areas for foundations, walls, columns, beams, floors, and stairs in an RC building. Their studies calculated the surface area for columns, walls, foundations, beams, slabs, and stairs for a building having prismatic structural components.

Lee et al. (2021) developed a formwork design tool, converting meshes into a geometric form with identical square-shaped meshes to create a 3D vertex set for automatically calculating quantities and formwork types. Their software consequently created a formwork layout for walls and deck systems, but it needs to be tested further for connection and supporting members and validated with actual formwork quantity based on conventional 2D CAD drawings.

2.6 Architectural Material Quantification

Monteiro & Martins (2013) stated that the surface coatings like finishes, protections and embellishments requiring a delicate measurement process could either be modeled for the same material QTO or surfaces of 3D structural elements can be utilized with a presumed error margin. Accordingly, the first approach increases the model size significantly, while the second results in a considerable amount of measurement errors requiring in-depth analysis. Hence, material QTO for architectural components is a significantly crucial process for accuracy and time management.

Cheung et al. (2012) introduced a knowledge-based tool for early design cost estimation to assess the changes in building mass and types in Google SketchUp and simultaneously update the quantities for walls, floors, doors, and windows. Liu et al. (2016) suggested a construction-oriented QTO framework specifically focusing on light-frame building construction with an ontology-based semantic approach to obtain the material quantities not explicitly modeled in Autodesk Revit. Kim et al. (2019) revealed the quantity discrepancies in interior materials, including masonry, wood, thermal and moisture protection, insulation, and finishes due to model representation and unnecessary modeling and provided suggestions for the BIM modeling process to reduce inconsistencies in material take-offs.

Eroglu (2019) also investigated quantification features of Autodesk Revit for architectural elements in his study. Accordingly, without human errors, the quantity results for exterior architectural walls, façade insulation, exterior plastering and painting, number of windows, doors, and curtain wall areas are calculated accurately from Revit models. This study shows the importance of modeling quality and approaches because the quantity results can be obtained accurately when building elements are correctly modeled, and materials are assigned cautiously.

Khosakitchalert et al. (2019a) developed a visual programing algorithm to extract surface area information by eliminating modeling mistakes for architectural wall and floor elements from erroneous models using the Dynamo tool for Revit. Khosakitchalert et al. (2020a) also suggested a wall framing quantification method for general and sub-contractors by enhancing the power of the visual programing tool Dynamo. Khosakitchalert et al. (2020b) later proposed a visual programing algorithm to automatically separate wall and floor elements into their layers and convert each layer to an individual model component so that material quantities for each wall and floor layer can be accurately obtained.

2.7 Literature Gap

Even though BIM provides more accurate and faster quantity take-off results, construction practitioners usually consider BIM unreliable for the QTO process unless models are developed meticulously. Creating accurate 3D models for material QTO is time-consuming and requires more work hours and cost investment. Hence, BIM implementation is generally limited to visualization, coordination, and project documentation in construction projects. Cost estimation and cost integration with BIM-based material QTO is left behind compared to other BIM applications in the construction sector. As referred to in previous sections, there are various research approaches to improve BIM-based QTO. Recent studies mainly focus on applying visual programing tools to benefit from 3D models having modeling mistakes and deficiencies or overcoming software limitations to some extent. Thus, this thesis aims to improve workflows for accurate QTO in the Autodesk Revit environment using Dynamo. Structural formwork and architectural claddings, including floor, wall, and ceiling materials, are investigated within this research scope.

The focus for the formwork elements is to obtain the formwork area of each structural element in 3D models. While previous studies obtain formwork quantities in category level, this study obtains the formwork area in element level, which is more valuable from cost estimation and scheduling viewpoints. Besides, the research focuses on automatic formwork model creation to facilitate the 3D modeling process. This approach will enable fast and accurate formwork quantification, and 3D formwork models can be used in 4D scheduling.

The goal for quantifying cladding elements is to extract accurate QTO for wall, floor, and ceiling elements in conjunction with creating 3D models for these elements. Quantities are calculated using the structural 3D model, and room elements are placed manually and populated automatically with spreadsheet data. The idea is based on the fact that material names for floors, walls, and ceilings for each building room are generally tabulated in spreadsheets for building projects. This data may or may not be extracted from BIM, but it can be integrated with 3D models. This way, structural model geometry can be used for accurate material QTO, and even materials can be modeled automatically. This approach will be beneficial for projects where BIM models are erroneous or not detailed enough. The proposed methods are especially useful for the construction phase requiring detailed and accurate material quantification for scheduling and budgeting activities.

CHAPTER 3

METHODOLOGY

3.1 Formwork Quantification Framework

Construction projects heavily rely on reinforced concrete (RC), and concrete is a moldable material that can be cast in any desired shape using formwork structures. While doing this, the concrete casting is generally executed systematically, requiring detailed analysis and planning such that foundations are cast first and walls and columns wait for the foundation's setting. Structural slabs and beams are placed upon completion of vertical structural elements, and stairs and parapet walls are mainly constructed after casting the adjacent building components. Hence, this hierarchy is also considered while developing the proposed method in this study. The formwork area of a structural category is calculated by intersecting its surfaces with other structural categories to eliminate surfaces that do not require formwork installation. For example, beam and slab elements are cast after the construction of structural walls and columns, and some surfaces of beams and slabs are already formed and supported by previously installed building elements, and they do not require formwork. Another example is that beams and floors are poured together for better integration and design requirements, and in this case, some surfaces of beam or part of some surfaces may not require formwork due to construction methods (Figure 3.1). Besides, concrete stairs may not be considered in the formwork calculation of other structural categories since they are cast later and consequently not acting as natural formwork for different building components considering the construction sequence.

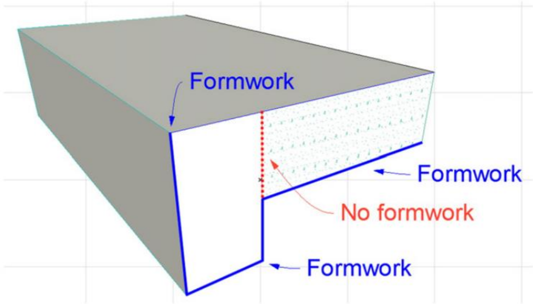


Figure 3.1. Issues in extracting formwork quantities from a BIM model

(Monteiro & Martins, 2013)

Therefore, the below assumptions are made while developing formwork calculation and modeling framework by pondering possible construction sequence and software capabilities:

- ✓ Foundations are cast first, and all sides of the foundation are open, meaning that excavations around the building are wide enough for formwork installation.
- ✓ Walls are cast after foundations, and then columns are cast. In this case, walls and columns integrated into each other are considered to be poured at different times to simplify the calculation process and classify wall and column quantities separately.
- ✓ Stairs are cast after the completion of all adjacent construction. According to Figure 3.2, some stair faces intersect with walls, columns and beams, and if stairs are considered in the calculation of walls, columns and beams, then the formwork area for those elements will be underestimated. Hence, it is assumed that stairs are cast later, and area deduction will be made from the stair formwork area, which is more realistic. It is also important to note that open side surfaces, bottom surfaces, and vertical side of stair risers need to be considered in the formwork calculations.
- ✓ While modeling formwork elements in Revit, the generic models category is utilized since there is no available category or structure for formwork modeling in the software.

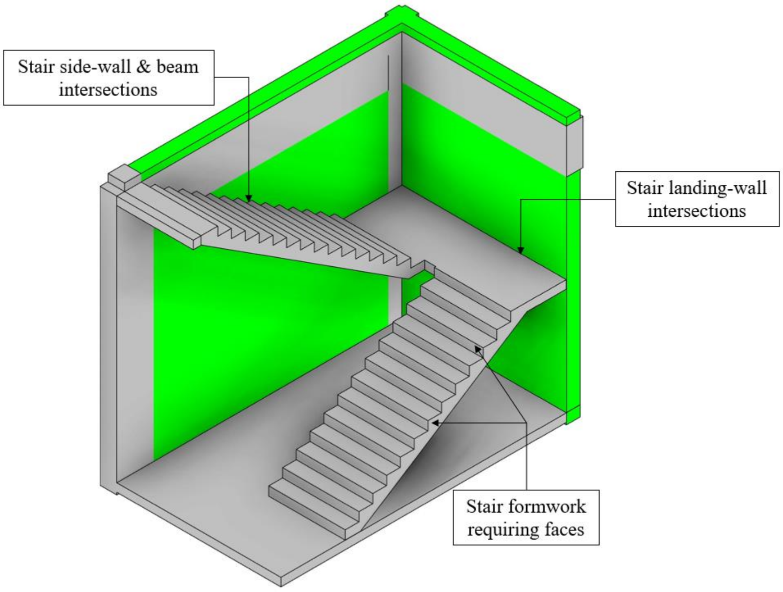


Figure 3.2. A view illustrating stair casting assumptions

The proposed framework aims to calculate formwork areas accurately and create formwork models for structural foundations, walls, columns, beams, slabs, and stairs. For this reason, the algorithm eliminates overlapping areas among different building components, extracts the formwork areas, which is usually not possible due to software limitations like beam-column intersections and wall opening surfaces. Furthermore, Dynamo for Revit helps extracting surface area information for tapered beams, inclined wall surfaces, slanted columns, circular columns with drop panels, and arched openings, so these are also considered in developing the formwork framework.

Figure 3.4 illustrates the framework of the algorithm to calculate and model formwork elements. The framework comprises both manual and automated processes shown inside dashed box in Figure 3.4. The manual part is to prepare the BIM model and manipulate the outputs of the automated process. The manual part includes creating project parameters in the first place and grouping and saving formwork models in the form of another Revit file after their creation. Moreover, linking formwork models back to the original model and creating schedules to see them in the model environment is part of the manual process. Checking formwork panels and removing unnecessary ones due to lack of algorithm capacity are also considered manual processes. The formwork area, formwork type, and formwork ID parameters are assigned to generic models categories in the project parameter creation part (Figure 3.3). The first parameter is used to store surface area information, and the second one is for storing the type of structural category to which formwork belongs. The third one is to store element IDs of structural elements to which formwork belongs.

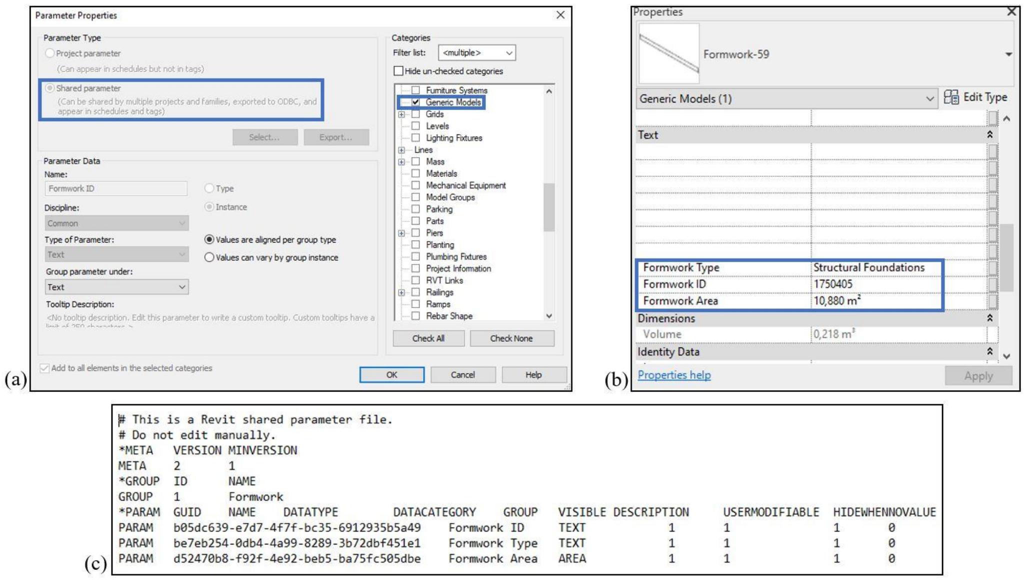


Figure 3.3. Shared parameter assignment (a), population of shared parameters (b) and shared parameter text file (c)

Figure 3.3a shows the assignment window for shared parameters. Here parameters are grouped under text group parameters meaning that they are gathered under the text part in the properties tab. Figure 3.3b illustrates how shared parameters are utilized. Accordingly, these parameters are filled automatically. Figure 3.3c demonstrates how the text file looks like for shared parameters that are continuously updated automatically once changed. These three parameters can be scheduled, which is crucial from the QTO standpoint, and tagged when required. Moreover, the shared parameter file shown in Figure 3.3c can be utilized in different projects without creating the parameters again.

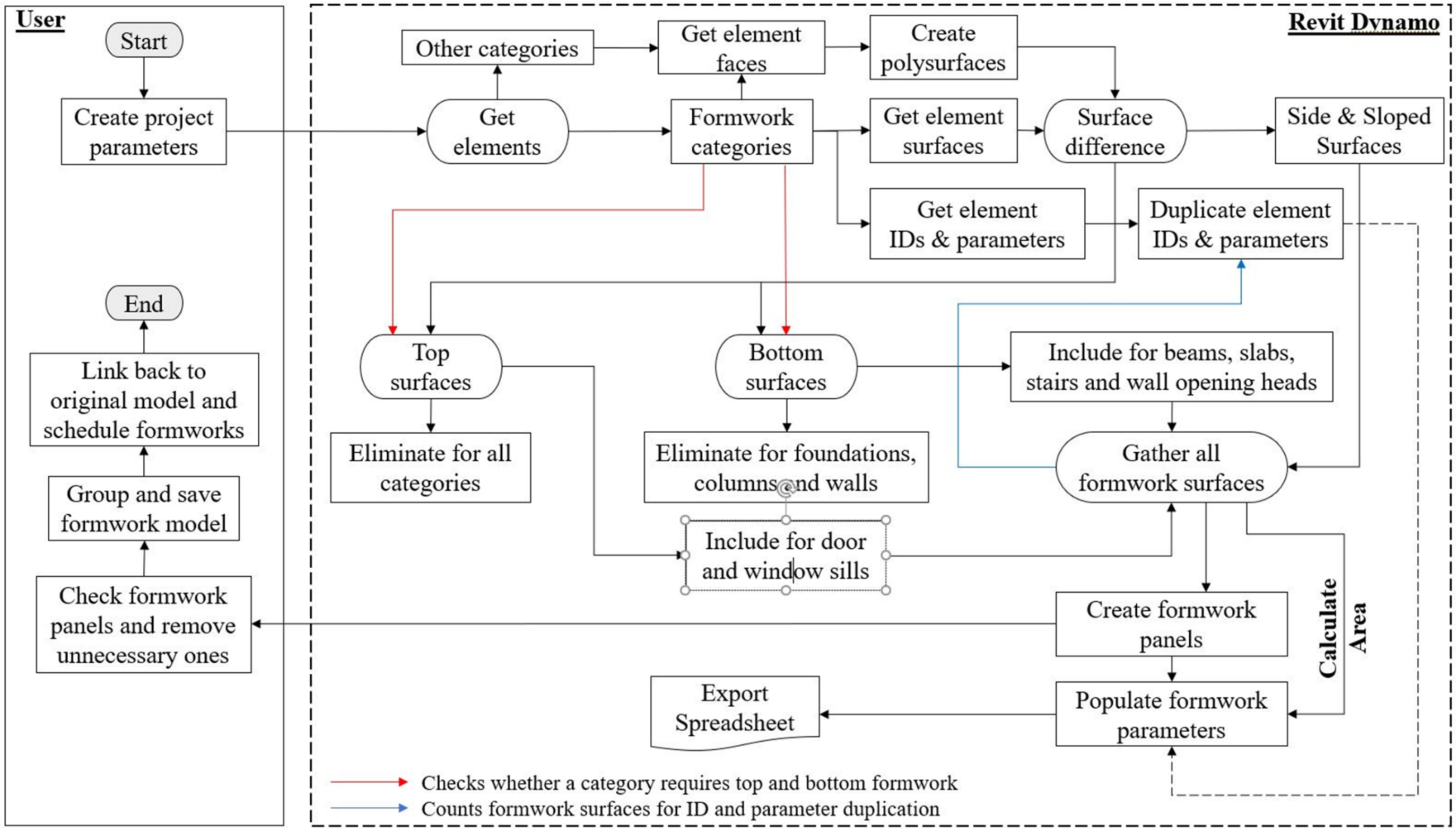


Figure 3.4. Formwork area calculation and modeling framework

According to Figure 3.4, Dynamo first gets the elements for both formwork categories, the category that formwork surfaces are to be calculated, and other categories used to distinguish formwork surfaces. After that, element faces of other categories are obtained, and simultaneously element surfaces for the formwork category are also extracted. Element faces of other categories are combined into polysurfaces, and the surface difference between created polysurfaces and element surfaces of the formwork category is obtained.

After removing all overlaps and grouping surfaces that do not connect or touch with other elements for the formwork category, subgrouping of new surfaces is started. Firstly, all sides and sloped surfaces are separated because these surfaces are definitely to be formed in the construction process. Secondly, top surfaces are filtered and checked whether they are required to form. For all surfaces except for door and window sills, top surfaces are eliminated because they will not be formed in the construction process. Similarly, bottom surfaces are also filtered, and they are eliminated for foundations, columns, and walls while reassessing for beams, slabs, stairs, and wall opening heads like door and window tops. While performing top and bottom surface classification, formwork categories are controlled in a roundabout way, and it is shown with red dashed lines in Figure 3.4. After the organization of surfaces, they are all gathered and considered as formwork requiring surfaces. Later element IDs and extracted parameters like element names, marks, material types are duplicated as the number of surfaces for a single element. It is because there are different numbers of surfaces for each building element requiring formwork installation. For example, three surfaces need to be formed for a beam while four surfaces for column and six surfaces for a wall element. Hence, the element IDs and other parameters should be duplicated three, four, and six times for beam, column, and wall, respectively. Following this process, parameters and element IDs are matched with formwork surfaces, and formwork panels are created using the generic models category in Revit. After panel generation, previously defined parameters like formwork IDs, area, and type are filled as previously demonstrated in Figure 3.3b. In the final stage of the formwork process, results are exported into a spreadsheet.

3.1.1 Preparation of Visual Code for Formwork

This section introduces the preparation of visual codes in Dynamo using the proposed framework, and only the Dynamo part shown in Figure 3.4 is to be discussed here. Figure 3.5 shows how to get formwork elements and other elements from the 3D Revit model. For other elements, a list is created, and it is later manipulated, while formwork elements are excluded from that list. The main idea is to keep the list structure of formwork elements so that element IDs are not lost along the workflow. This approach helps classifying formwork surfaces efficiently.

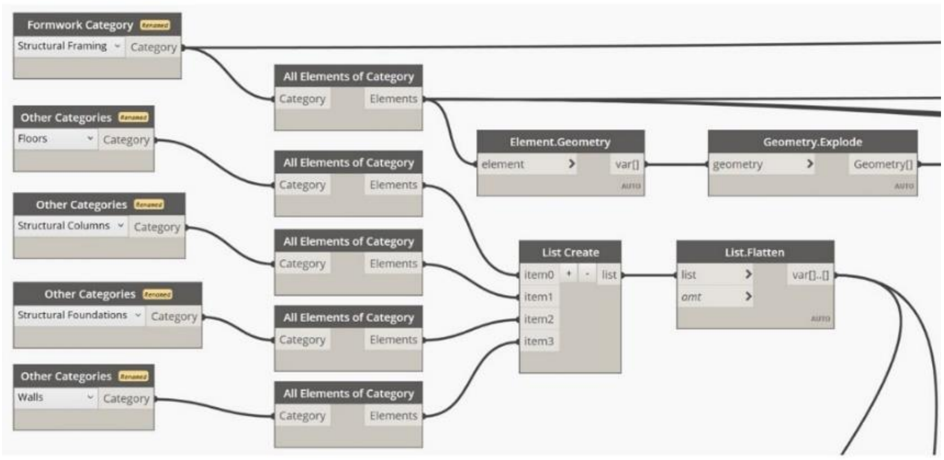


Figure 3.5. Dynamo workflow for input variables

Figure 3.6 demonstrates how surface difference operation is performed. Surfaces coming from formwork elements are connected to surface input, and all other surfaces and polysurfaces are connected to others input in the *Surface.Difference* node. A system error is obtained when running the code, and it will be investigated in detail in the discussions section. Moreover, after getting surface differences, additional operations are done like cleaning lists from null elements and exploding remaining polysurfaces into single surfaces. It is important to note that this whole operation still keeps the list structure coming from Figure 3.5 for formwork elements.

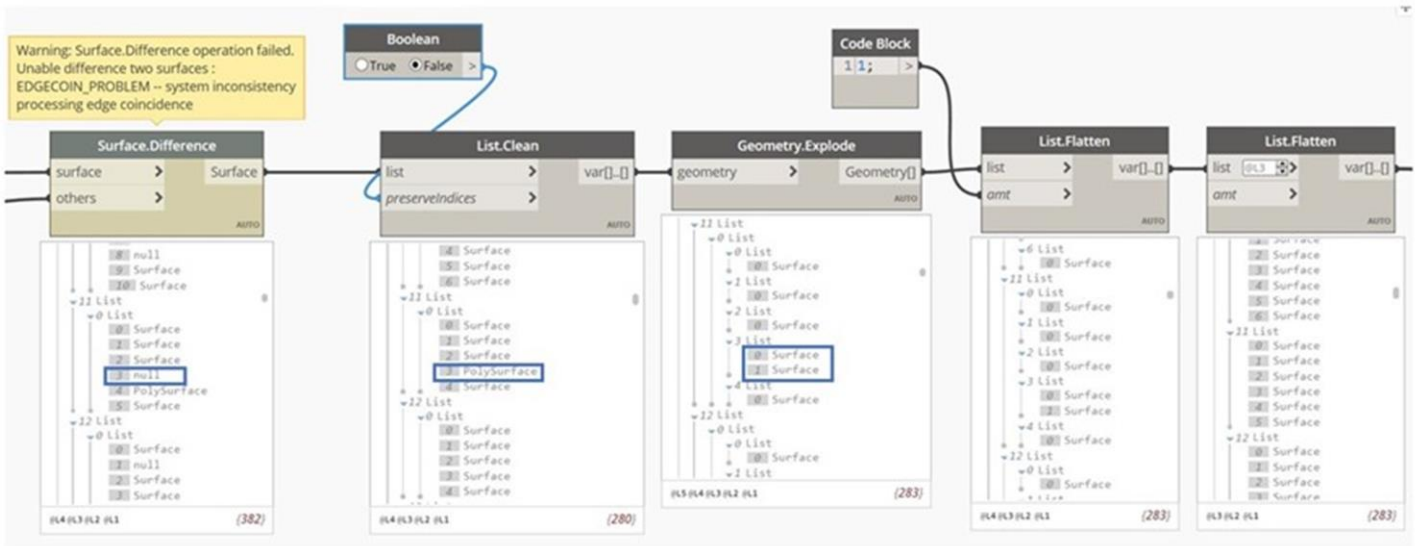


Figure 3.6. Dynamo workflow for eliminating overlapping areas among building components

Figure 3.8 shows the elimination of top and bottom surfaces using vector operation tools in Dynamo. Accordingly, a point is generated on the center of each surface using nodes 1 and 2. After that, these vectors are compared with normal vector in the z-axis using *Vector.IsAlmostEqualTo* node and true and false boolean values are obtained. Later whole surface list is checked according to boolean values, and top surfaces are eliminated, and all other surfaces are processed further to check bottom surfaces. While checking bottom surfaces, the only difference is to reverse the z-axis vector using *Vector.Reverse* node and filter side and sloped surfaces.

Figure 3.7 illustrates the workflow to create enough formwork IDs for each formwork surface for classification purposes. Therefore, ID information for each formwork element is obtained using *Element.Id* node and the number of formwork surfaces are counted using *List.Count* node. After that, element IDs are multiplied using the number of surface counts using *List.Cycle* node.

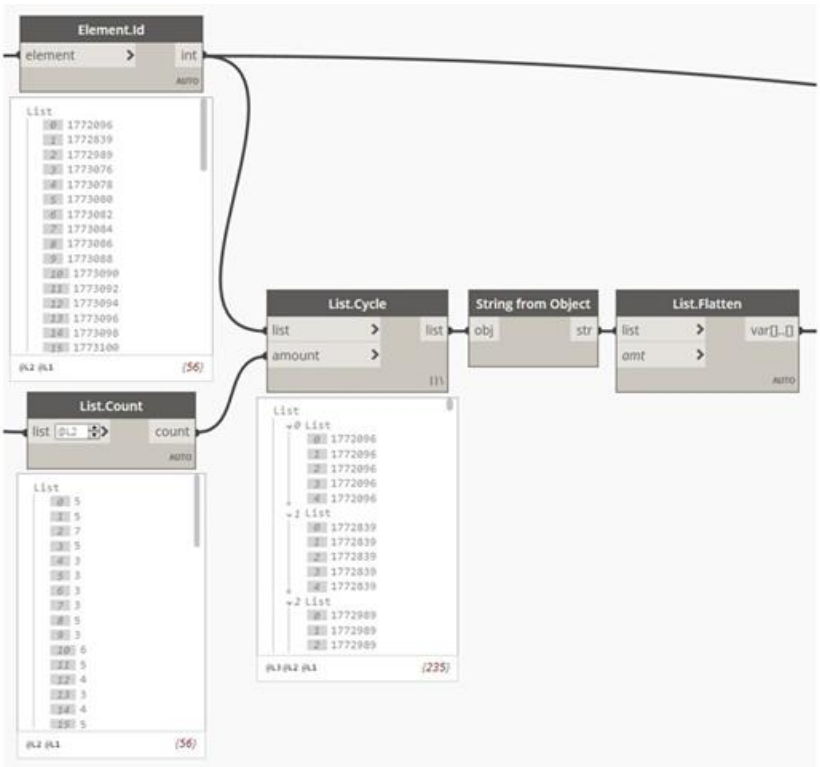


Figure 3.7. Dynamo workflow for generating formwork IDs using element IDs

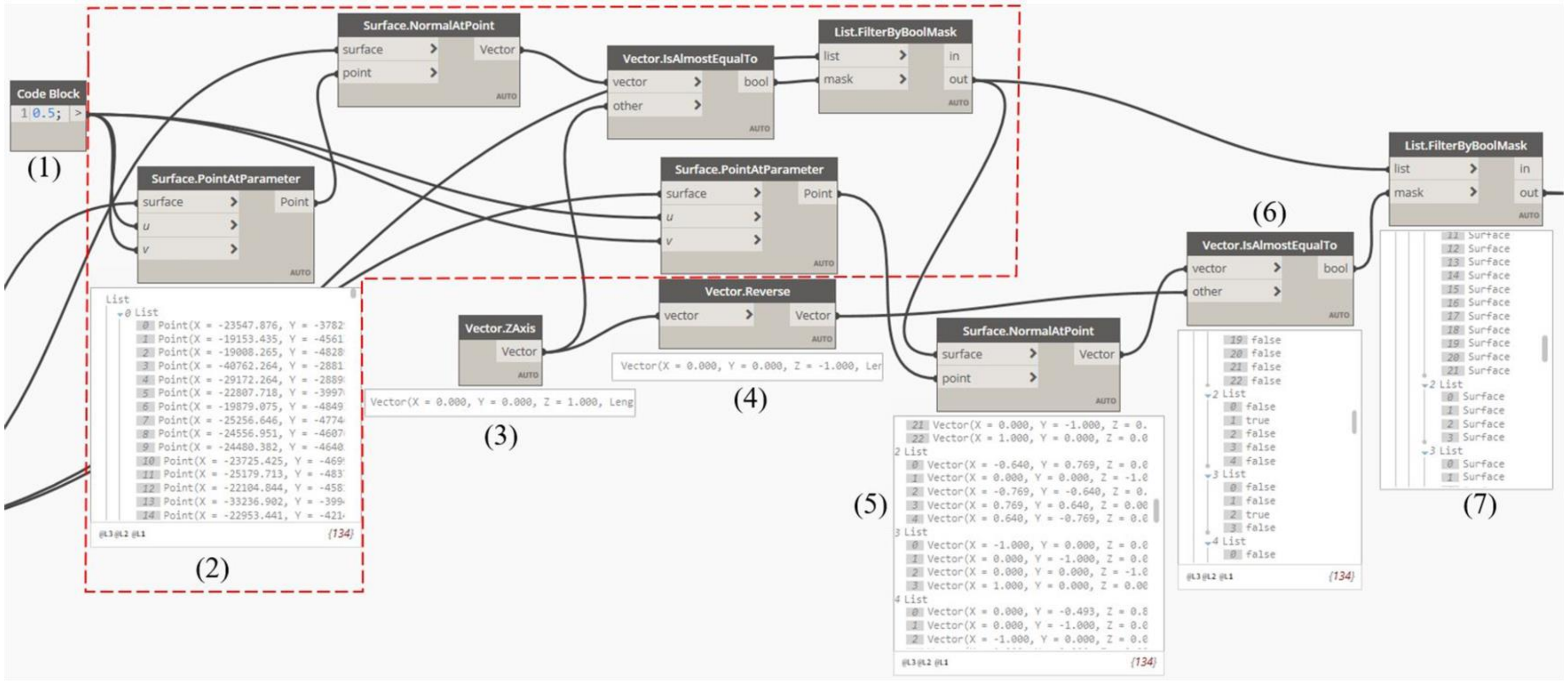


Figure 3.8. Dynamo workflow for eliminating top and bottom surfaces

Figure 3.9 shows how to create formwork panels using the generic models category. Here, it is essential to note that panel thickness is considered 20 mm based on standard plywood dimensions. In this workflow, *FamilyInstance.ByGeometry* node from springs package in Dynamo is utilized to convert formwork surfaces into generic models. With the help of this node, each surface is converted to a family instance with different names. While naming each panel, the number of surfaces are counted, and numbers are created from 1 to counter value, and then these numbers are concatenated with "Formwork" string to create family and type names.

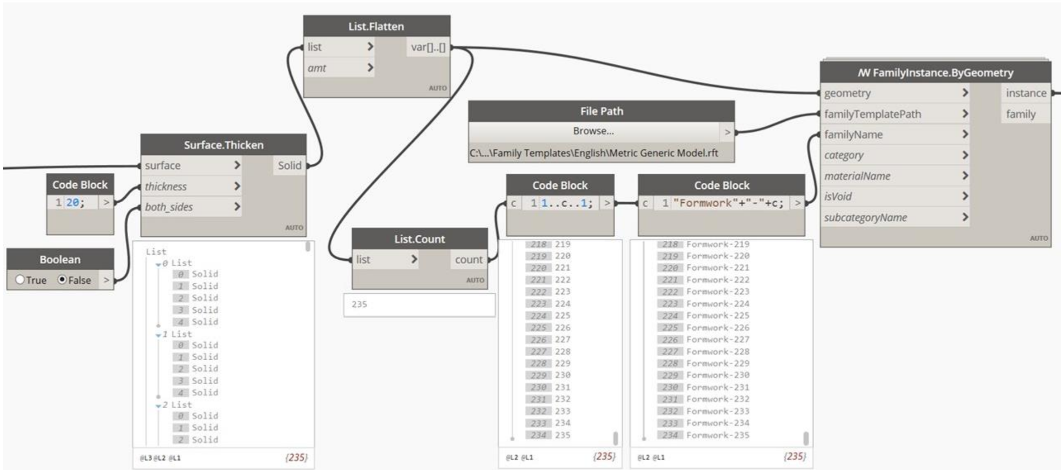


Figure 3.9. Dynamo workflow for generating formwork panels using generic models

Eventually, all area values and formwork and element parameters are extracted to a spreadsheet using the workflow shown in Figure 3.10. This process is typical in most Dynamo codes such that all the output values are first gathered in one list, and then that list is transposed, and values are written to MS Excel using *Data.ExportExcel* node.

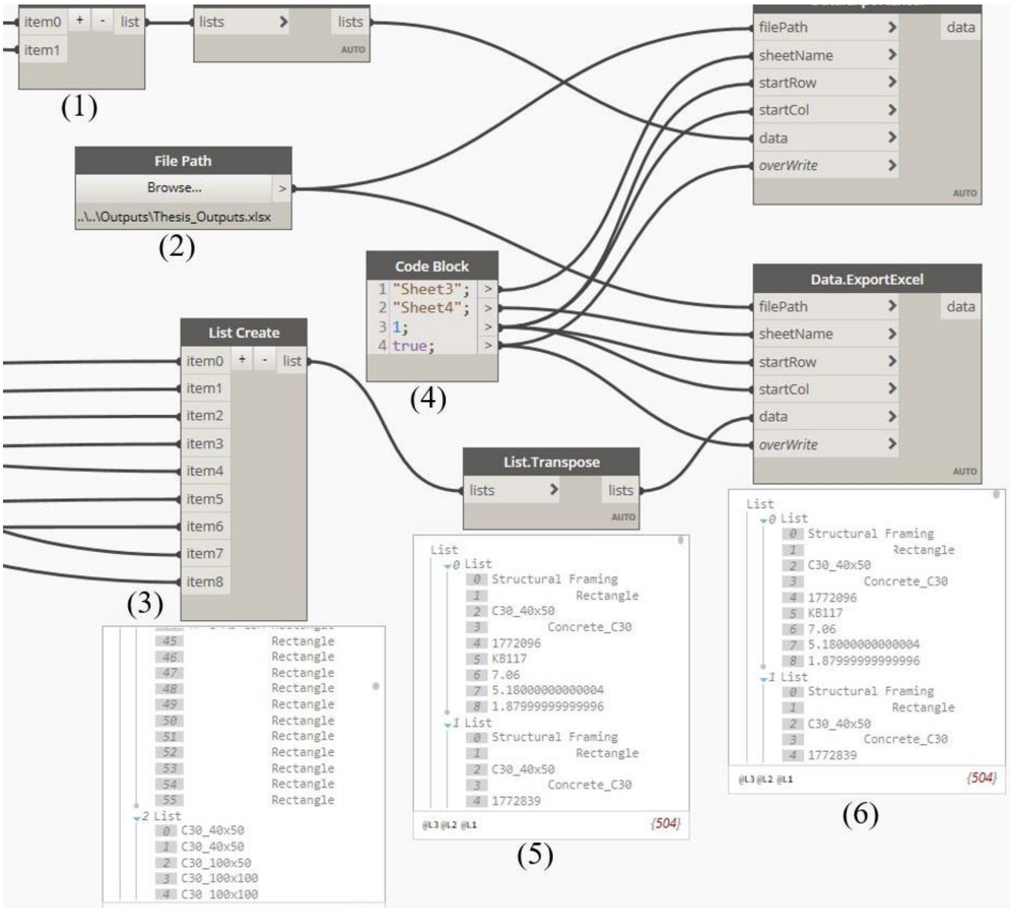


Figure 3.10. Dynamo workflow for exporting results to a spreadsheet

3.2 Cladding Quantification Framework

Contractors are prominent stakeholders in construction projects, and they need to have detailed and structured data regarding the project in which they are involved. Mainly, they need to know all materials and quantities to prepare cost calculations and forecast their future conditions. When BIM is adopted from the beginning of the project with required building data, the contractors can benefit from information-rich 3D models regarding material quantities and cost estimation. However, as discussed previously, BIM models may contain limited data, and construction drawings and schedules may be manipulated in the 2D environment resulting in deviations from the 3D model and loss of geometric information. Hence, construction practitioners face situations like building data stored on spreadsheets and models provided by the design team, but they cannot use them together or check the reliability of quantitative data. Considering these situations, this part of the study proposes a framework to use BIM model geometry and spreadsheet information to obtain the quantities of materials in a building room using the visual programing tool Dynamo.

The following assumptions are made while developing architectural cladding calculation and modeling framework by pondering possible construction sequence and software capabilities.

- ✓ Floors are completed before wall cladding installation.
- ✓ Ceilings are installed after completion of wall claddings
- ✓ Revit and Dynamo do not support ceiling model generation, so ceilings are modeled using the generic models category.

The proposed framework aims to calculate accurate surface area quantities for floor, wall, and ceiling materials and total length for wall base materials in a building room. Moreover, the framework also focuses on creating 3D model elements for these building components automatically. Figure 3.11 shows the overall framework, and tasks inside the dashed boxes are performed automatically. The manual part is about organizing and preparing building data, such as placing room elements into the BIM model, creating project parameters for data storage, and sorting and grouping room information in a spreadsheet accordingly. The automated part transfers room information between the spreadsheet and Autodesk Revit and extracts the building geometry to obtain correct surfaces and lines for the floor, wall, wall base, and ceiling components.

According to Figure 3.11, the process starts with the room placement in the 3D model, and room data is organized in the spreadsheet based on the Revit room numbers. Moreover, some project parameters like base material height, ceiling area, material extension above the ceiling, and room number for doors are also assigned for the later stages to store the room data. The room number for doors parameter determines which finish material is required at door sills while passing from one room to another. The ceiling area parameter is created to store the ceiling area information. The material extension above the ceiling and base material height parameters is created to store the wall cladding starting level and wall heights.

The automated process starts with importing room data into Revit and creating the required wall, floor, and ceiling types. After that, the automated process continues with getting the building geometry inside Dynamo and filtering room elements. Room element geometries are then exploded, and room perimeters and top of room surface are separated. At the same time, door opening widths are filtered and using them together with room perimeters, base area calculated and modeled.

Room perimeters are then used for the creation of floor elements. For this purpose, the room boundary is combined into a closed polyline curve, and this curve is converted into a floor element, and its area is automatically calculated.

Similarly, room perimeters are also utilized for wall element creation. In this case, wall elements are placed along the room perimeter, and while doing that, rooms are checked whether they have wall base material affecting the main cladding of wall surfaces. If so, these base materials are deducted from the overall surface area of walls, and then wall claddings are modeled.

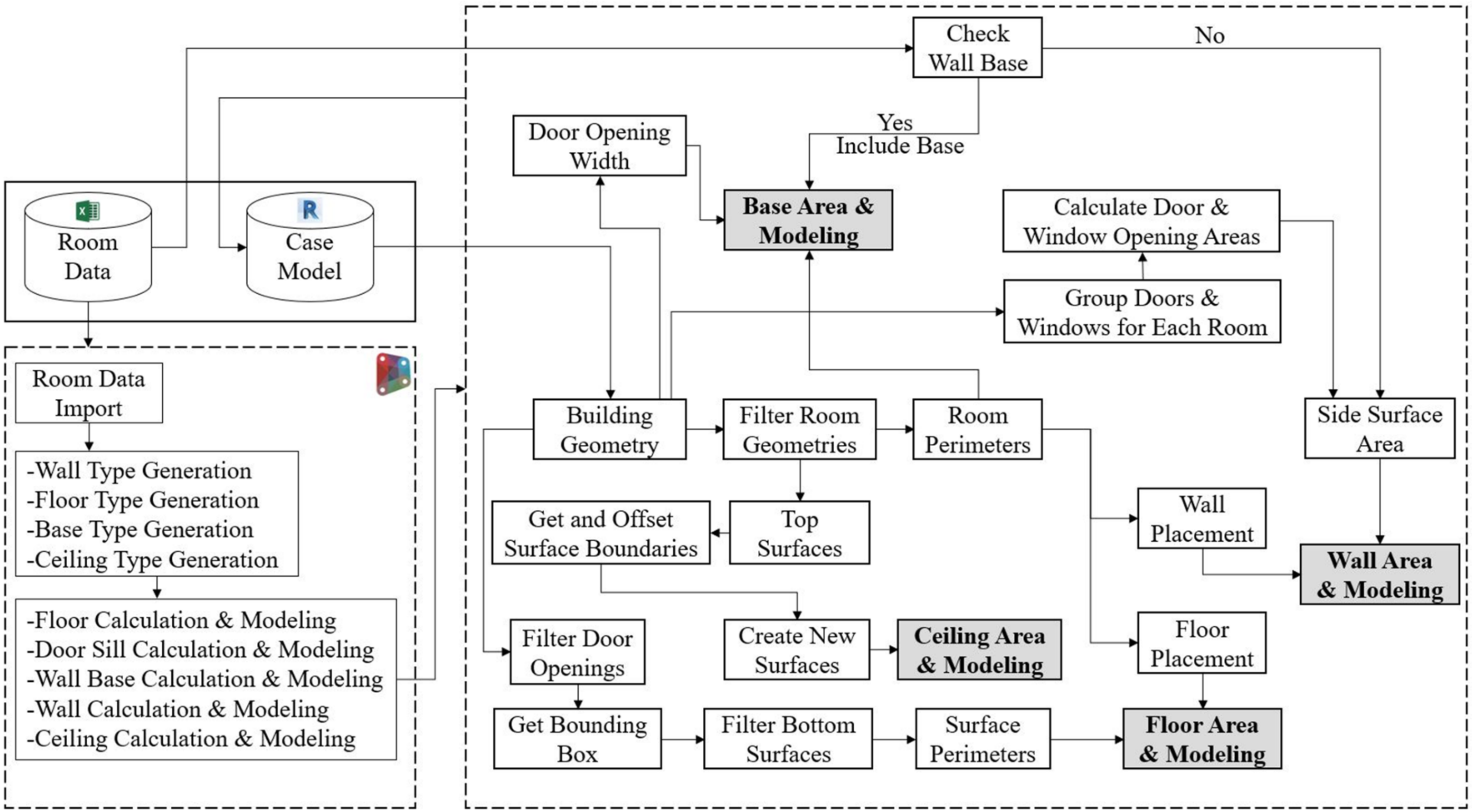


Figure 3.11. Cladding area calculation and modeling framework

While calculating and modeling wall bases, room perimeters are again utilized, but in this case, at door locations, the width of the door needs to be deducted. For this purpose, door bounding boxes are extracted, and they are scaled to larger geometries at their original coordinates so that doors and room perimeters are intersected with each other and room perimeters

For ceilings, room solid geometries are exploded into surfaces, and top surfaces are filtered. These surfaces are later exploded again to obtain the perimeter curves, and these curves are shifted towards to center of the room by the thickness of wall cladding, considering the ceiling installation is performed after wall installation. Then, new surfaces are created using the new curves, and surface area is calculated, and ceiling models are generated.

3.2.1 Preparation of visual code for claddings

This section introduces the preparation of visual codes in Dynamo using the proposed framework, and only the Dynamo part shown in Figure 3.11 is to be discussed here. Figure 3.12 shows how room data import starts. Accordingly, a code block is defined with required parameters, and these parameters are looked up in the spreadsheet, and their corresponding values are imported into Revit. For example, Dynamo gets the floor finish material of a room using the "Floor_Finish" parameter.

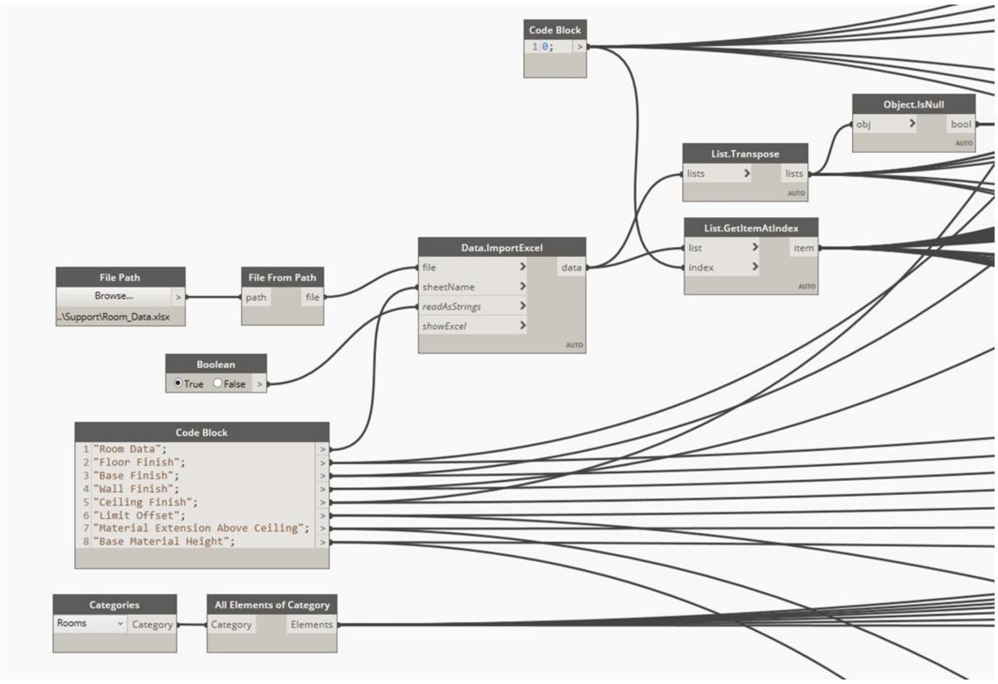


Figure 3.12. Dynamo workflow for importing room data

Figure 3.13 demonstrates how to organize room data in order to prepare for Revit import. For data manipulation, *List.IndexOf* and *List.GetItemAtIndex* and *List.RemoveItemAtIndex* nodes are frequently utilized in almost every location so that required data can be added, filtered, and removed. Moreover, *String.Contains* and *List.FilterByBoolMask* nodes are utilized to divide lists into two categories by using true and false boolean values.

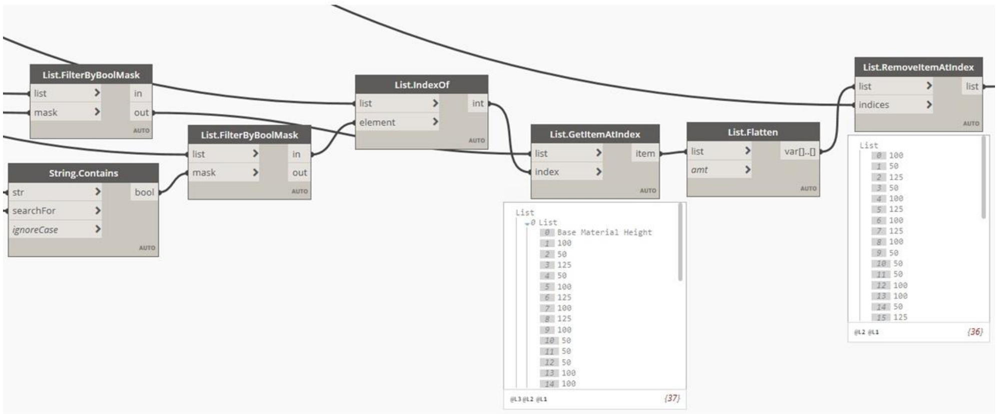


Figure 3.13. Dynamo workflow to manipulate room data before importing Revit

Figure 3.14 illustrates the last stage of the type generation code. The node *FamilyType.SetCompoundLayerWidth* is taken from the clockwork package to generate different wall and floor types based on room data imported from the spreadsheet.

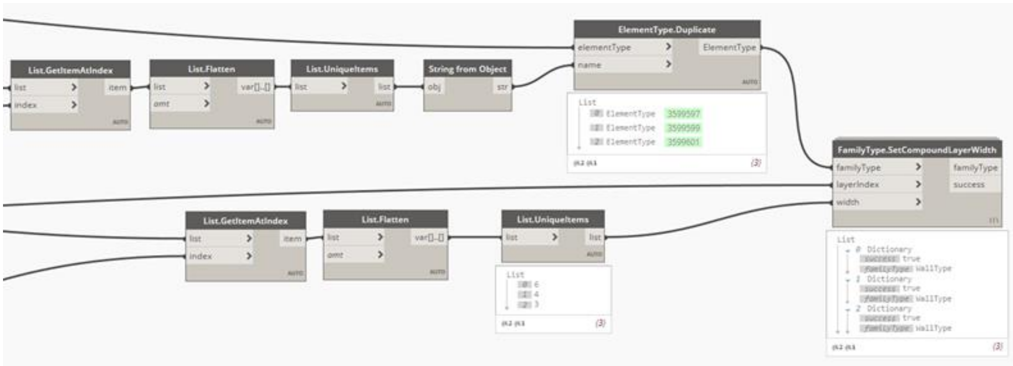


Figure 3.14. Dynamo workflow to create different family types for floors and walls

Figure 3.15 shows the process of creating floor claddings using *Floor.ByOutlineTypeAndLevel* node. Here room perimeters are obtained, and their finish boundaries are converted into curves using *PolyCurve.ByJoinedCurves* node and these curves are used as the outline curve for the floor element. Simultaneously, the floor cover and level on which the floor is to be placed are also used as input for the floor creation.

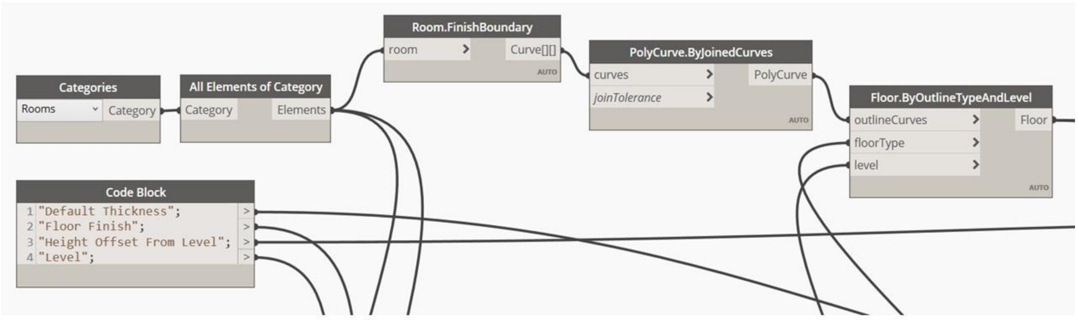


Figure 3.15. Dynamo workflow for creating floor claddings

Figure 3.16 demonstrates how wall claddings are created. Again, room finish boundaries are utilized, and they have first converted closed curves. Then these curves are offset by the thickness of cladding material (-a/2 in the code block) so that the cladding material and structural wall part align with each other. After that, these curves are again converted into new curves, and they have used a curve input in the *Wall.ByCurveAndHeight* node. Wall height, level, and type are also provided as input for this node to create wall claddings.

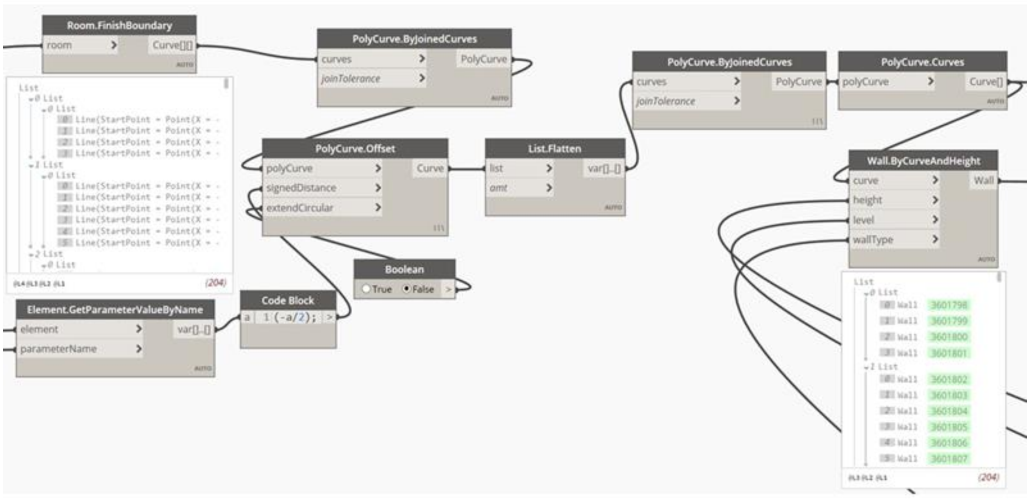


Figure 3.16. Dynamo workflow showing the key part of wall cladding creation

Figure 3.17 includes two different code workflows. The one inside the dashed rectangle is used to create floor cladding at door sills. For this purpose, the bounding box of door openings is extracted, and the bottom surface of this geometry is considered as the floor area at door sills.

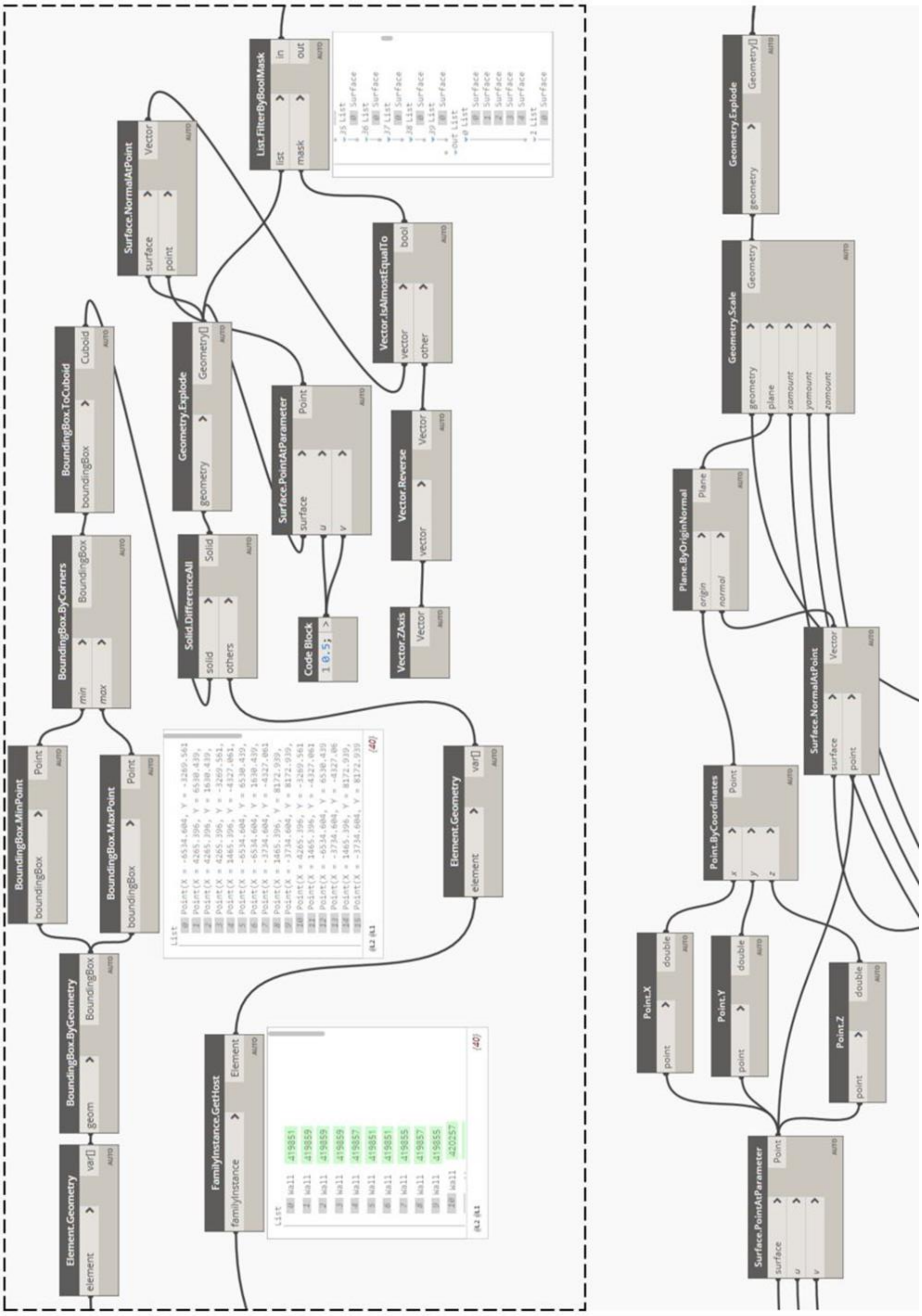


Figure 3.17. Dynamo workflow for creating floor claddings at door sills and scaling doors to eliminate room perimeters

The code outside the dashed box in Figure 3.17 is utilized to scale door geometries so that they can clash with room perimeter boundaries. This way, the width of the doors is deducted from the room perimeter lengths, and the remaining room perimeter is used for creating wall bases along the room boundary. The scaling process is done only in one direction, meaning that the width of the door is not changed after scaling.

Figure 3.18 demonstrates how to model ceiling elements. Revit and Dynamo do not support creating ceiling categories in 2021 versions. Hence, similar to formwork elements, the generic models category is used to model ceiling components and area information stored in the previously defined ceiling area parameter.

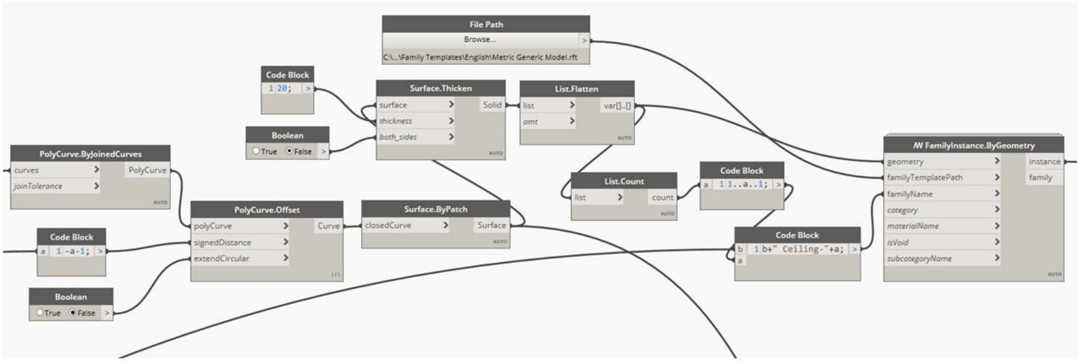


Figure 3.18. Dynamo workflow to create ceiling components as generic models

CHAPTER 4

CASE STUDY

An underground station building is studied within the scope of this study, and the design model of the structure, which is developed in Revit 2020, is used to test proposed frameworks for formwork and architectural claddings. The designer already separated structural and architectural models. According to the thesis structure, both formwork and architectural cladding tests are to be performed using the structural model. The architectural design model is used to verify architectural cladding results. Below is the general information about the structure and the materials of the building.

- ✓ **Structure type:** Underground metro station with entrance structures
- ✓ **Foundation type:** Mat foundation
- ✓ **The number of railway platforms:** Two platforms
- ✓ **The number of floors:** 11 floors (Basement, platform floor, and nine floors)
- ✓ **The number of expansion joints:** Four expansion joints
- ✓ **The number of stairs:** Eleven concrete stairs with additional escalators
- ✓ **Floor Covering Materials:** Ceramic tile, screeds, and leveling concrete
- ✓ **Interior Wall Materials:** Aerated concrete walls, paints, and ceramic tile
- ✓ **Exterior Wall Materials:** Concrete wall with waterproofing and insulation
- ✓ **Ceiling Materials:** Paint, gypsum board, suspended ceilings

Accordingly, this study aims to quantify and model formwork for structural components and floor covering materials, interior wall materials, and ceiling materials for architectural components. This study is performed using Autodesk Revit 2021, so the design model is first upgraded to the new version before testing.

4.1 Formwork Quantification and Modeling

4.1.1 Foundation Formworks

In the first step, foundation formwork calculations and modeling are performed. The foundation type in this case study is mat foundation meaning that it is a continuous concrete slab extending the gross area of the building.

The visual code is applied to the foundation elements, and it is observed that formwork calculations and modeling are not taken place at some locations. The reason is investigated and found that some foundations are modeled with floor category even though they should be created with foundation category (Figure 4.1). Since this study considers that every building component placed directly over the grade is a foundation, a new code is implemented to include floors (modeled as foundations) into foundation calculations. Therefore, a 3D model is opened, and all such floors are selected manually. Then, “Foundation” is written in their comment properties, as shown in Figure 4.1. This way, these floors are filtered in Dynamo, and they are treated as foundation elements (Figure 4.2).

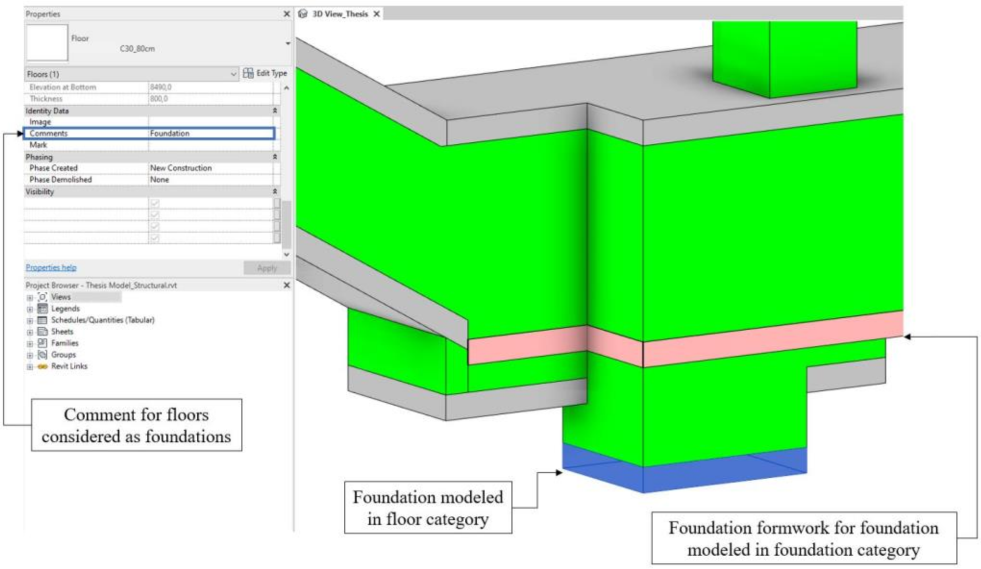


Figure 4.1. Foundation elements modeled with floor category in Revit

The floors are separated using *List.FilterByBoolMask* node based on their comment value, and they are combined with actual foundation category in a list node. After that, the normal process is applied, and the formwork area and modeling process are performed using the framework shown in Figure 3.4. Figure 4.3 shows the created formwork panels and populated formwork parameters.

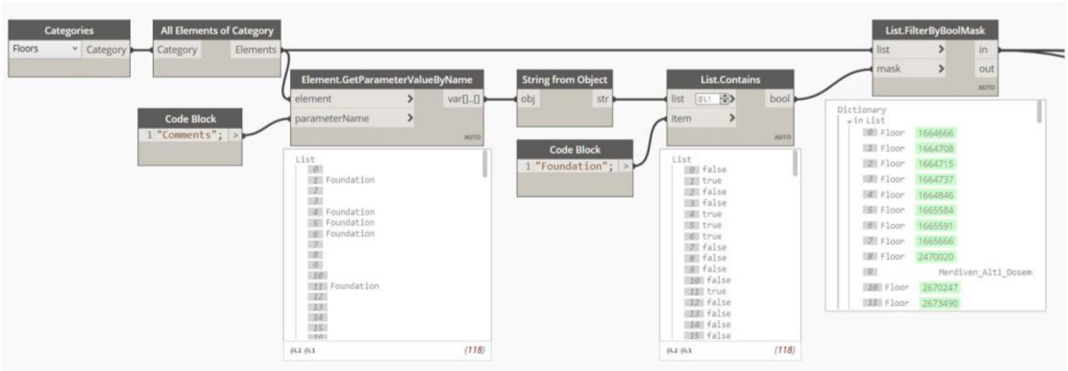


Figure 4.2. Distinguishing floor elements based on their comments property

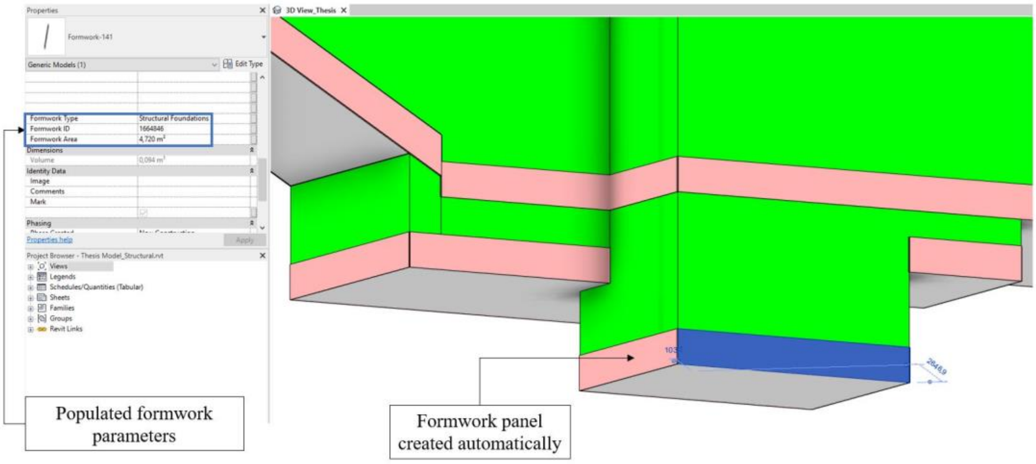


Figure 4.3. Foundation formwork panels and populated formwork parameters

Furthermore, it is realized that inclined surfaces cannot be eliminated at some locations because of the lack of code implementation. When the script eliminates top and bottom surfaces, it checks whether their z-vector is 1 or -1, respectively. However, inclined surfaces have z-vectors in between the below values.

For this reason, code in Figure 4.4 is implemented into the current code workflow, and inclined surfaces of foundation elements, which again do not require formwork for both upward and downward direction, are eliminated from the calculation. According to Figure 4.4, the script checks for the normal vector (z-vector) of each surface, and if they are different from 1 and -1, they are removed from the calculation process.

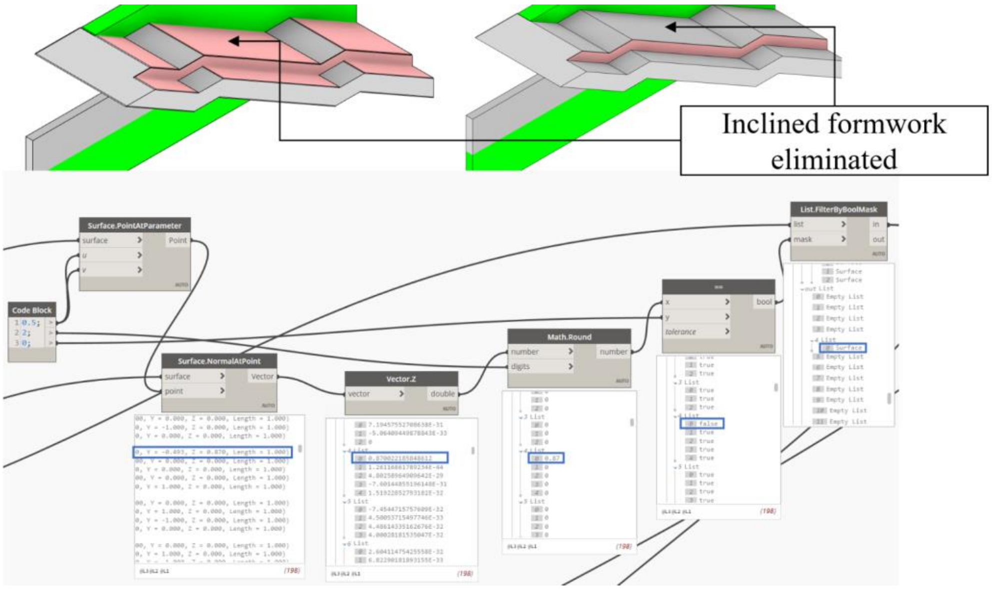


Figure 4.4. Inclined formwork surface elimination

4.1.2 Column Formworks

In the second step, formwork calculation and modeling are done for structural columns, including circular, rectangular, and square shapes. Even though the formwork calculation and modeling are correct at most locations, there are some locations where the beam area cannot be deducted from the column area. For example, beam and floor areas are correctly deducted from the surface area of the circular column shown in Figure 4.5. However, one of the beam areas cannot be reduced from the surface area of the rectangular column on one side in Figure 4.6, while formwork for the other sides is calculated and modeled accurately. The reason is investigated, and it is observed that some beam elements are not correctly joining and touching with column elements. Hence, the trim and extend option is used to extend beam elements to the face of the column. This operation is done for five beam elements after visually investigating the formwork panels. After the correction, the code is rerun, and the error is corrected.

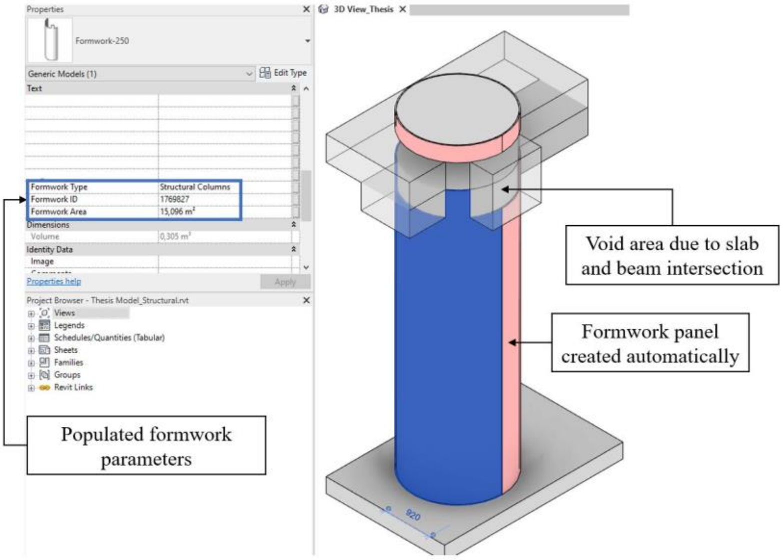


Figure 4.5. Circular column formwork panels and populated formwork parameters

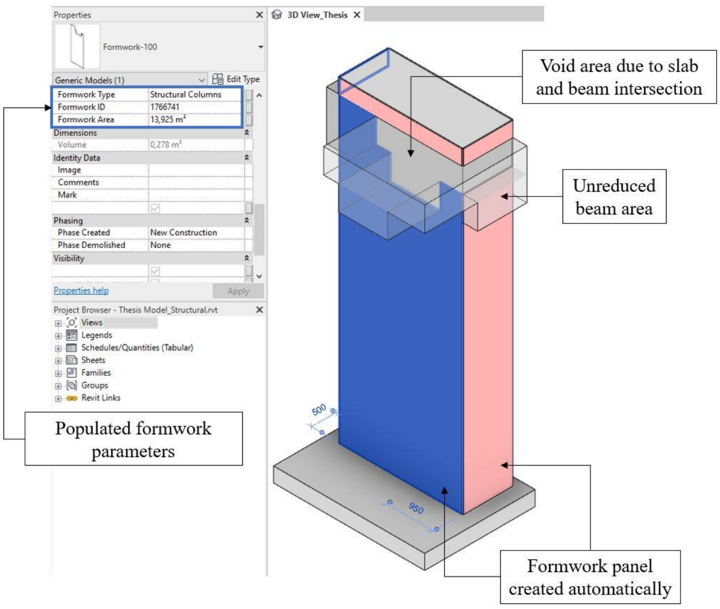


Figure 4.6. Rectangular column formwork panels and populated formwork parameters

4.1.3 Wall Formworks

In the third step, the wall formwork calculation and modeling process are performed, but due to the high number of wall elements (301 wall elements), the calculation process took around five hours. Even though the process is completed and formwork models are created, there are some problems. For example, Figure 4.7 shows the calculation result, and accordingly, most faces of the walls are calculated and modeled correctly. However, the areas at wall and wall intersections cannot be deducted while the area between the top slab and the top of the walls is eliminated correctly. Besides, all side surfaces and top surfaces of wall openings are calculated and modeled correctly, but only one bottom surface for one opening can be created. Hence it is decided to review the visual script, and it is realized that the list structure is mixed up while removing overlapping areas between two wall elements. After correcting the script by creating another list, as shown in Figure 4.8, the unreduced areas at wall and wall intersections are calculated and modeled correctly.

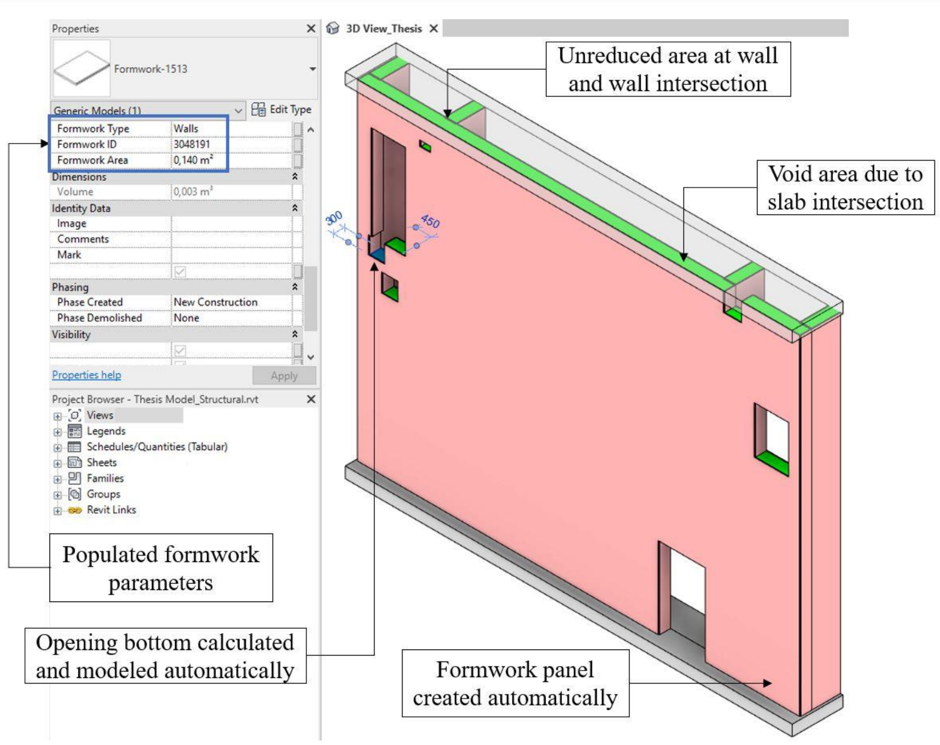


Figure 4.7. Wall formwork calculation and modeling results

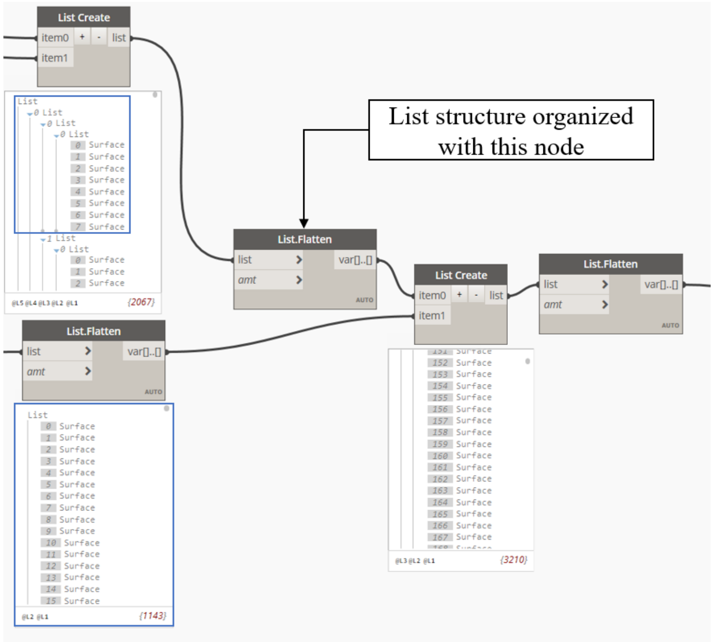


Figure 4.8. Organization of list structures using *List.Flatten* node

Figure 4.9 shows the correct calculation and modeling for wall and wall joints. Moreover, an arched surface is demonstrated to reinforce that the visual approach can manage the challenging wall surfaces.

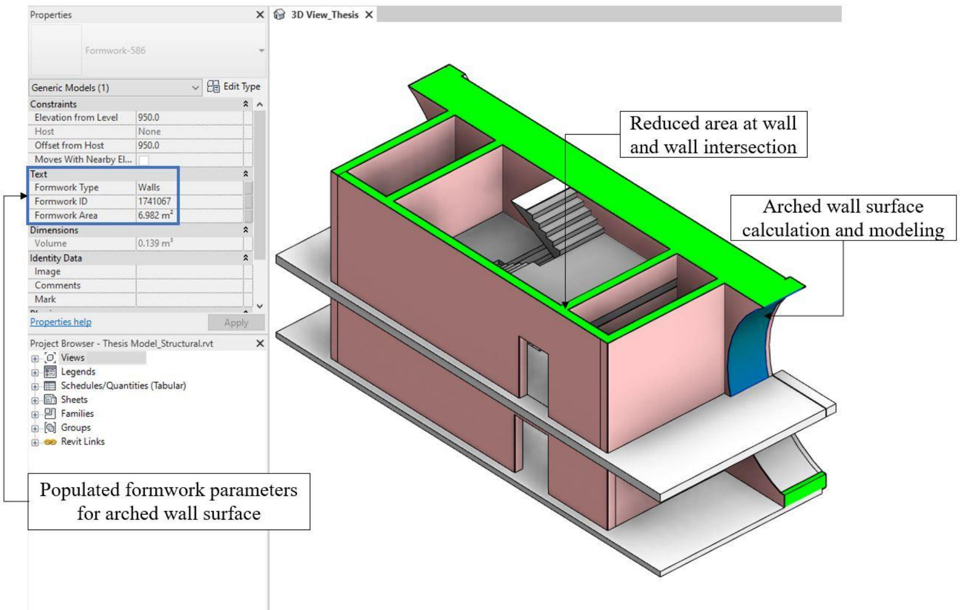


Figure 4.9. The corrected result of wall formwork modeling

4.1.4 Beam Formworks

In the fourth step, beam formwork calculation and modeling are performed, and it is realized that the problem faced for columns are also experienced in beam formwork calculation. Therefore, after the first run of the code, the trim and extend command is applied for beam and column connections to make beam surfaces touch the column surfaces. Another big problem is experienced that most beam and floor connections are not calculated and modeled accurately because of a software problem. Accordingly, Dynamo cannot generate element geometry for four big floor elements due to their complex model and various openings on the floor surfaces. Another approach, which will be discussed in section 4.1.5, is utilized to obtain the geometry of those floor elements, and visual code is rerun after correction. Eventually, beam formwork calculation and model generation is completed with accurate results, as visualized in Figure 4.10.

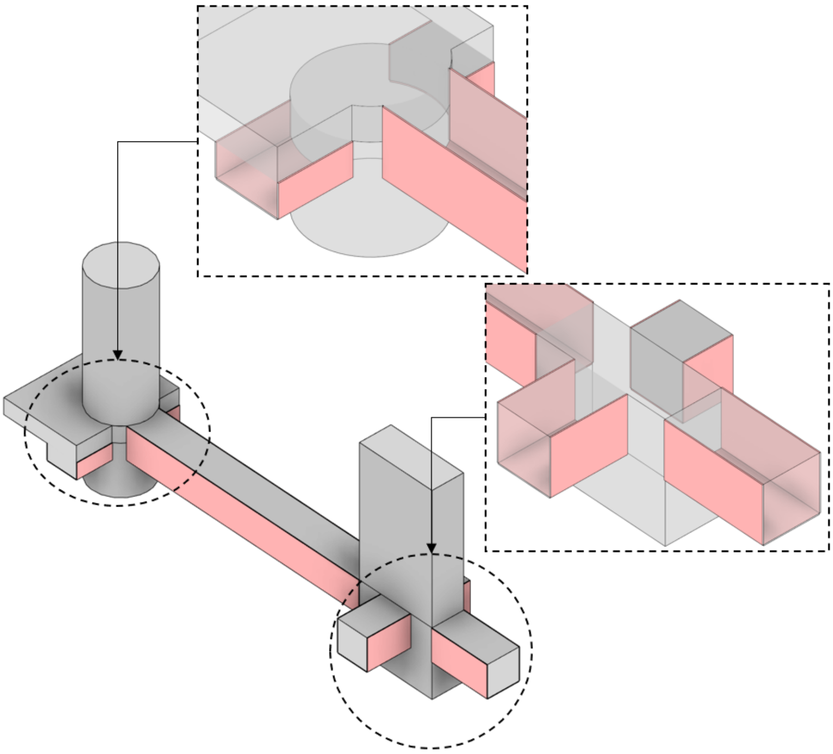


Figure 4.10. Typical beam, column, and floor connections calculated and modeled correctly

4.1.5 Slab Formworks

In the fifth step, slab formwork is calculated, and it is realized that the visual code neglects four slabs with a total projection area of approximately 4000 m2. The reasons are investigated, and it is concluded that slabs with complex boundaries and various openings cannot be imported into Dynamo. Since these four slabs intersect with many different elements, another approach is used for those floor elements.

Floor elements that cannot be converted into Dynamo geometry are first colorized in Revit using the workflow shown in Figure 4.11. The highlighted elements are then filtered in the 3D view, and the workflow shown in Figure 4.12 is applied. Accordingly, floor elements and their top surfaces are selected manually using *Select Model Element* and *Select Face* nodes. After that, Dynamo automatically gets the thickness of floor elements and creates a solid extrusion using the selected top face and floor thickness. In order to locate the created solid geometry precisely at the exact location with the actual floor element, *Geometry.Translate* node is used. Here, the thickness of the floor is divided by two and multiplied by -1. The calculated value shows how much vertical translation should be done in the z-axis to place the solid geometry. The solid geometry is exploded into surfaces, and these surfaces are included formwork calculation process.

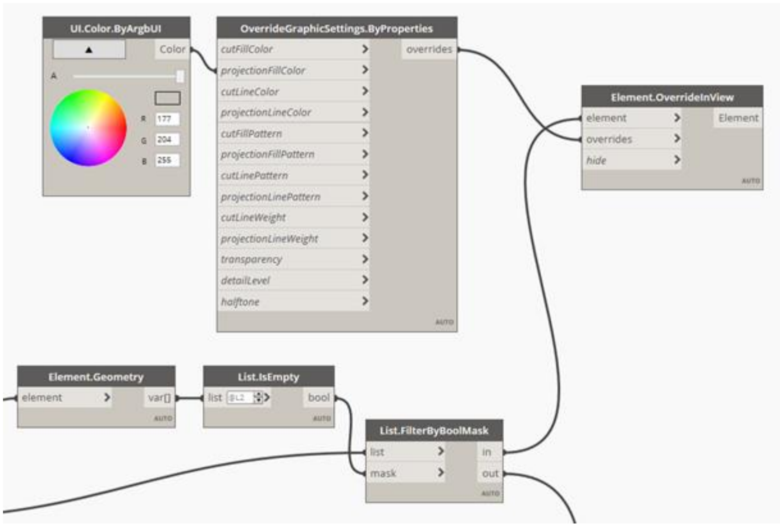


Figure 4.11. Visual script part for overriding problematic floor elements

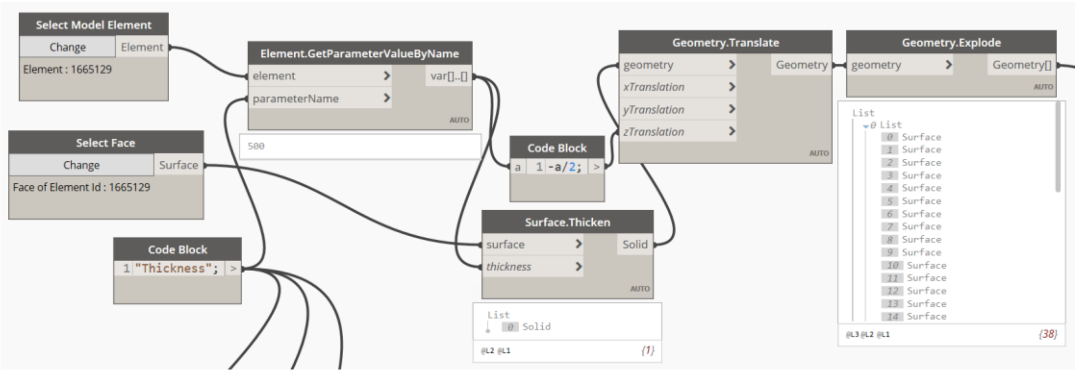


Figure 4.12. Visual script part for creating the geometry of problematic floor elements

Eventually, slab calculations and modeling process are completed, and results are obtained in Figure 4.13. Slab sides are calculated, the bottom of the slab is formed according to the boundary of columns and beam, and small floor pieces are even calculated using the proposed approach.

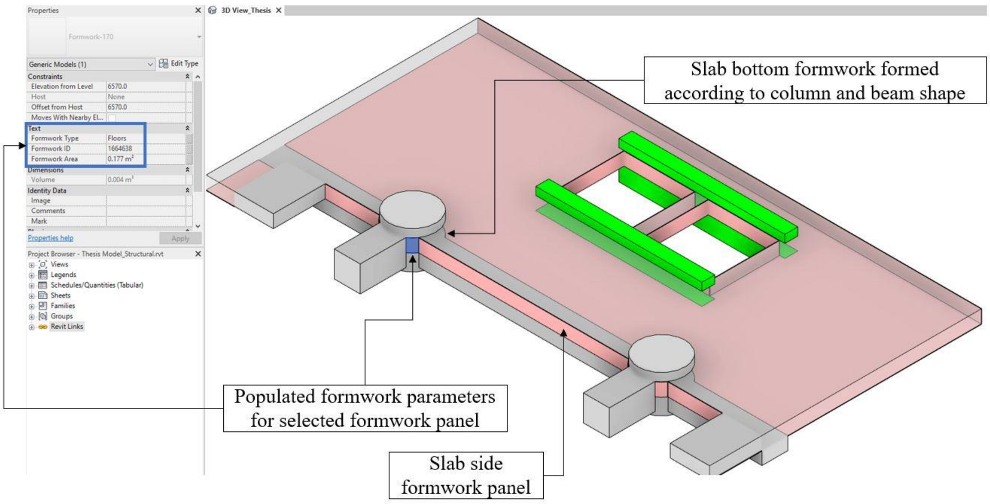


Figure 4.13. Slab formwork calculation and modeling results

4.1.6 Stair Formworks

In the sixth step, stair formwork is calculated and modeled, as shown in Figure 4.14. The calculation process was straightforward. All top surfaces and surfaces clashing with other elements are automatically eliminated, and formwork panels are generated. Detailed investigation of stair formwork results is made in section 5.1.

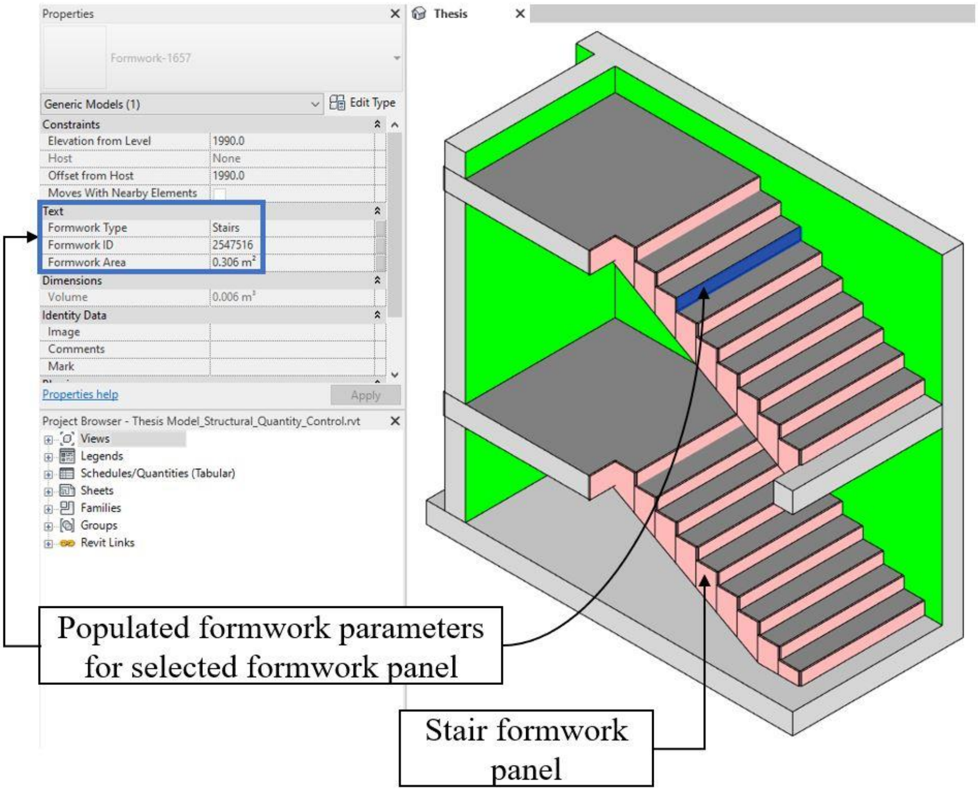


Figure 4.14. Stair formwork calculation and modeling results

4.2 Cladding Quantification and Modeling

According to the case study model, there are 131 rooms in this building, but this study only investigates seven rooms for calculation convenience. The investigated room levels, names, and numbers are shown in Table 4.1. These values are extracted from the original architectural model, and they are all actual design data.

Table 4.1. Investigated building rooms information

Level	Name	Number
UNDER PLATFORM LEVEL	WATER TANK	R1
UNDER PLATFORM LEVEL	WATER TANK	R2
UNDER PLATFORM LEVEL	ELECTRICAL ROOM	R3
UNDER PLATFORM LEVEL	FIRE PUMP ROOM	R4
UNDER PLATFORM LEVEL	WASTE WATER PUMP ROOM	R5
UNDER PLATFORM LEVEL	ELECTRICAL ROOM	R6
ABOVE PLATFORM LEVEL	TECHNICAL ROOM	R7

The architectural model for the case study is well-detailed, and quantities extracted from the model are assumed to be correct. However, creating a detailed architectural model with LOD to provide accurate QTO is very time consuming and hence such models are not generated in all projects. Therefore, this study provides a solution for models with less information and details such that a reinforced concrete model is considered, and spreadsheet data is utilized to obtain quantities in conjunction with 3D models and generate the 3D models of architectural claddings. Hence, some room elements are selected, and they are placed into the structural model. Some of the rooms shown in Table 4.1 have complete architectural walls, which are not available in the structural model, and structural walls bound some rooms. There should be some room bounding elements to define room elements in Revit, and due to the requirement of workflow and framework, room separation lines are drawn manually for some rooms to define room elements (Figure 4.15). After drawing these lines, room elements are placed as shown in Figure 4.15. Later, room numbers are manually written for each room property, and it terminates the manual process.

To sum up, the manual process for the architectural quantification and modeling can be listed as the followings;

- ✓ Draw room separation lines if necessary
- ✓ Locate room elements
- ✓ Provide room number information

The model is now ready for the automated process, and the first thing is to fill room parameters and then create the required floor, wall, and ceiling types.

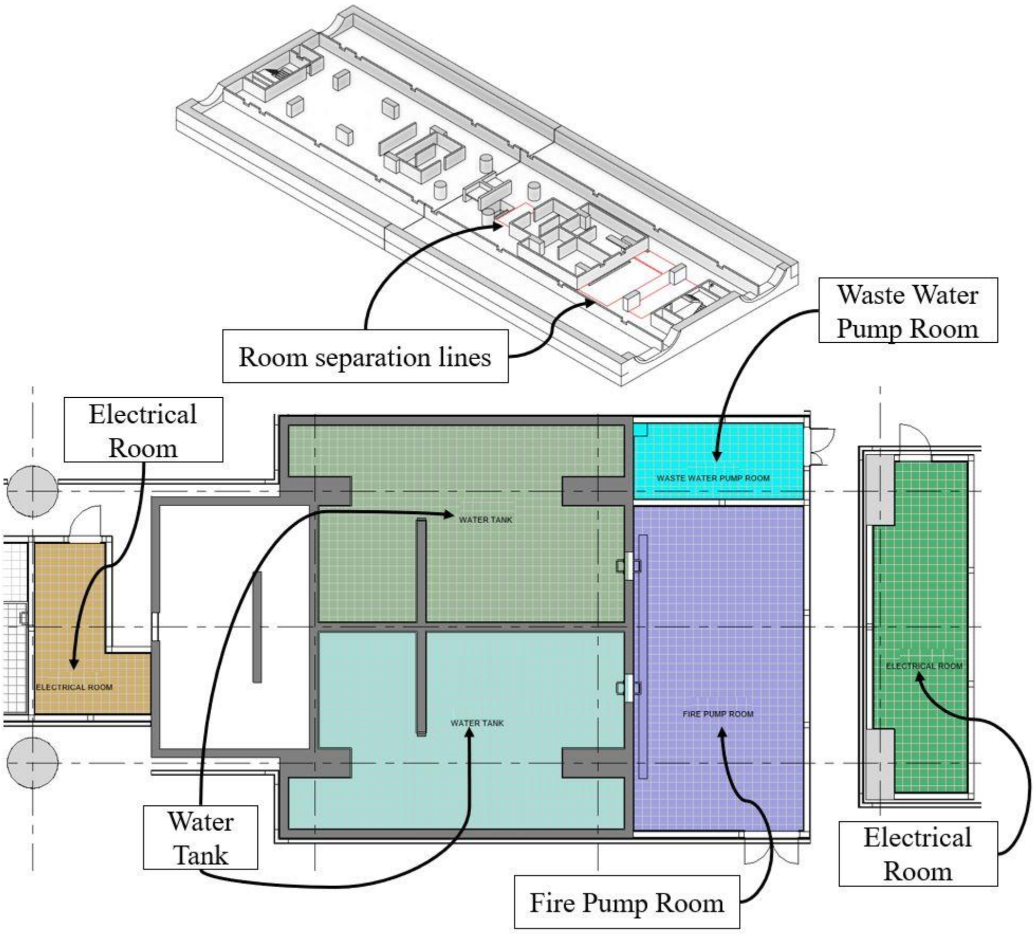


Figure 4.15. Room separation lines and some room elements

Room data is also obtained from the original architectural model using the Dynamo code shown in Figure 4.16. Extracted values are then grouped according to room numbers in MS Excel, and they are imported to newly created room elements in the structural model (Figure 4.17). Using these parameters, new floor and wall elements are generated with the required material thickness, and those elements are used for the 3D modeling process. Figure 4.18a shows all floor types available in the structural model before running Dynamo code, and Figure 4.18b shows the newly generated floor types based on room data presented in Figure 4.17.

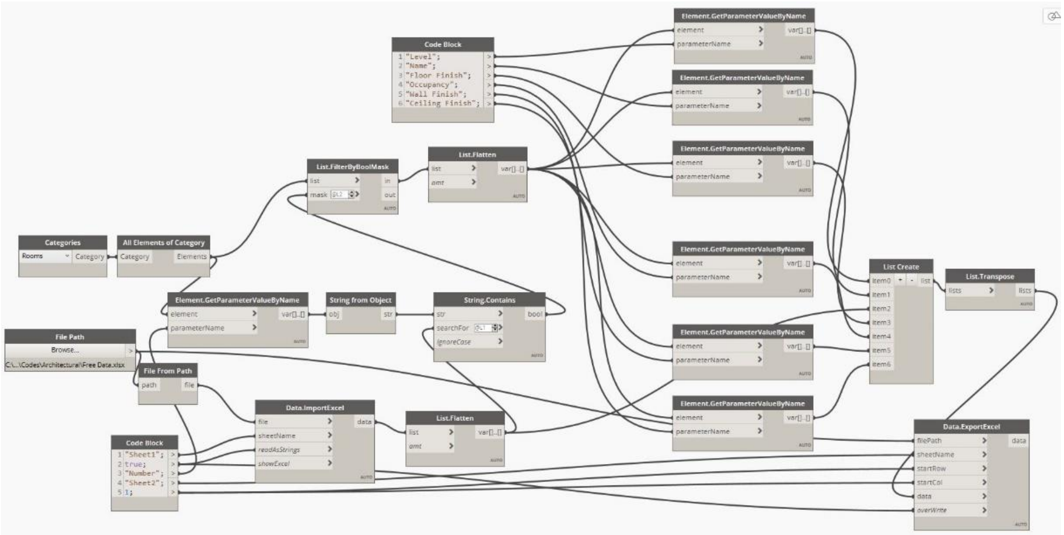


Figure 4.16. Dynamo code for extracting room data from the design model

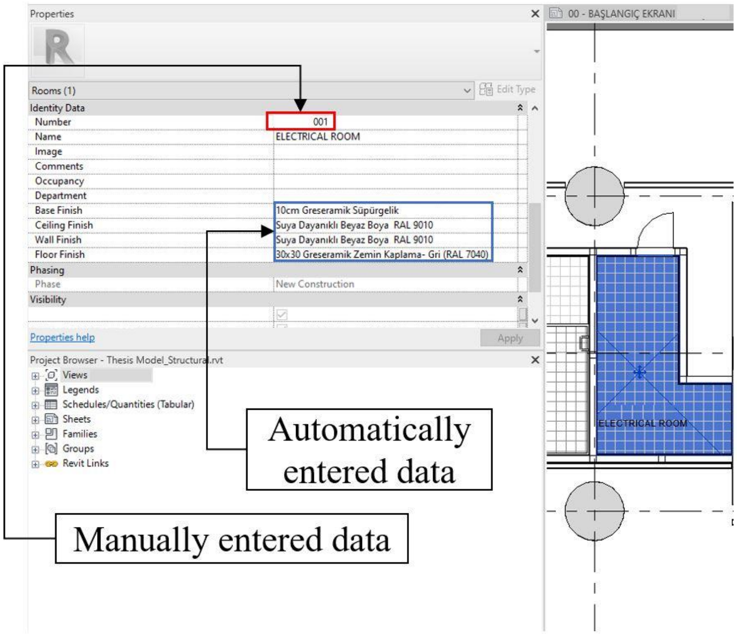
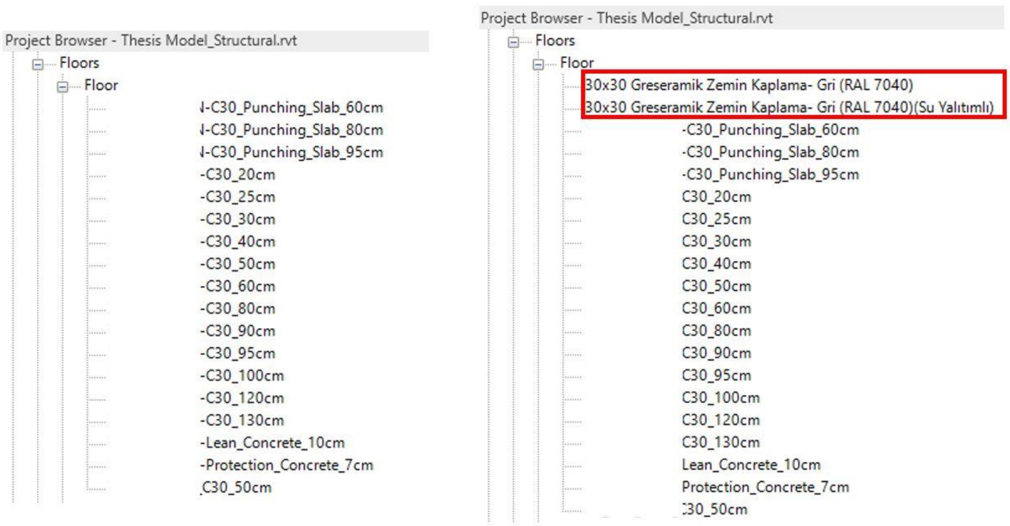


Figure 4.17. Manual entered and automatically created room data



(a) (b)

Figure 4.18. Automatic floor generation results in Revit project browser
(a) previous floor list (b) floor list after Dynamo run

4.2.1 Floor Claddings

Floor claddings are calculated and modeled according to the visual code given in Figure 4.19. All room elements are extracted, and their surface perimeters are utilized to place floor claddings in the room. Moreover, the code shown in Figure 4.20 is used to calculate and model floors at door sills. For this purpose, the Model-in-Place command is used to put the mass shape of door elements, and these masses are utilized for placing floor elements. Eventually, floor claddings are obtained both inside the room and at door sills (Figure 4.21).

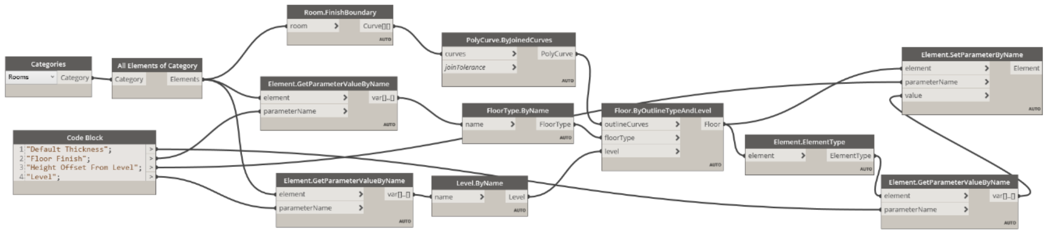


Figure 4.19. Floor cladding calculation and modeling code

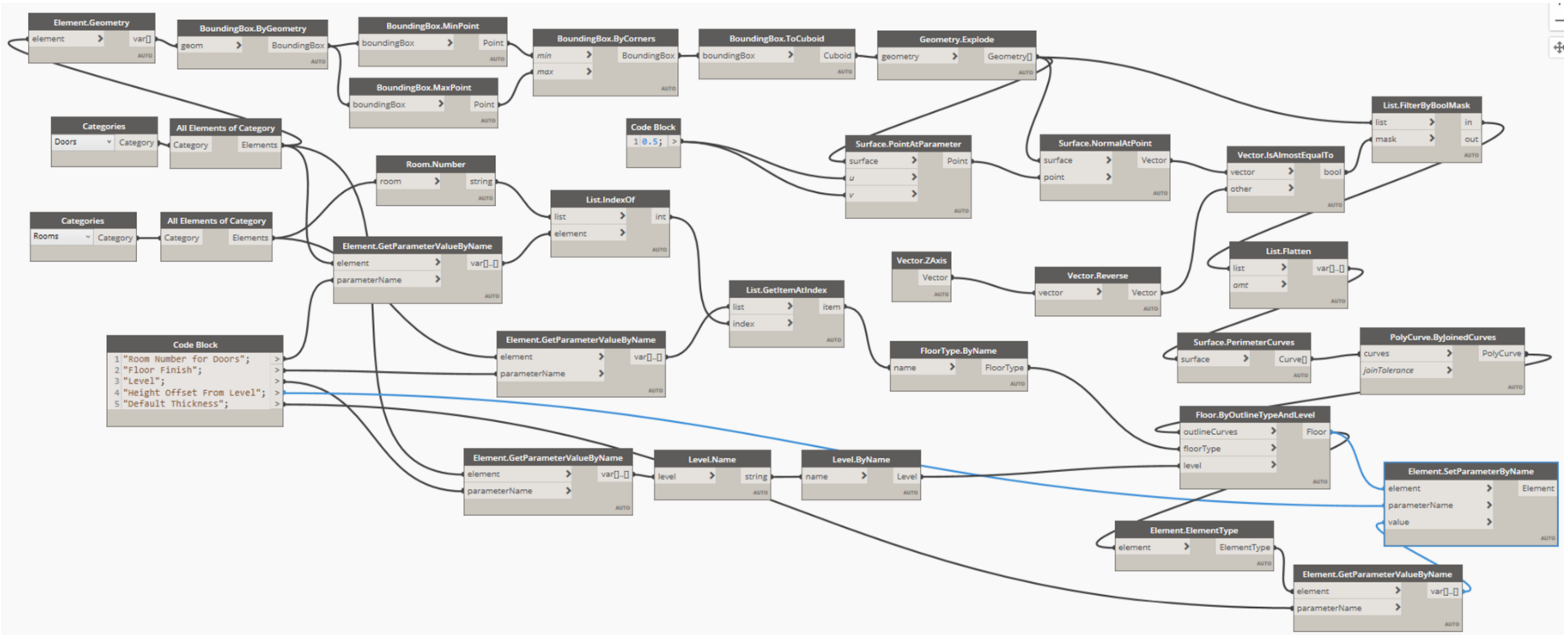


Figure 4.20. Dynamo workflow for creating floor claddings at door sills

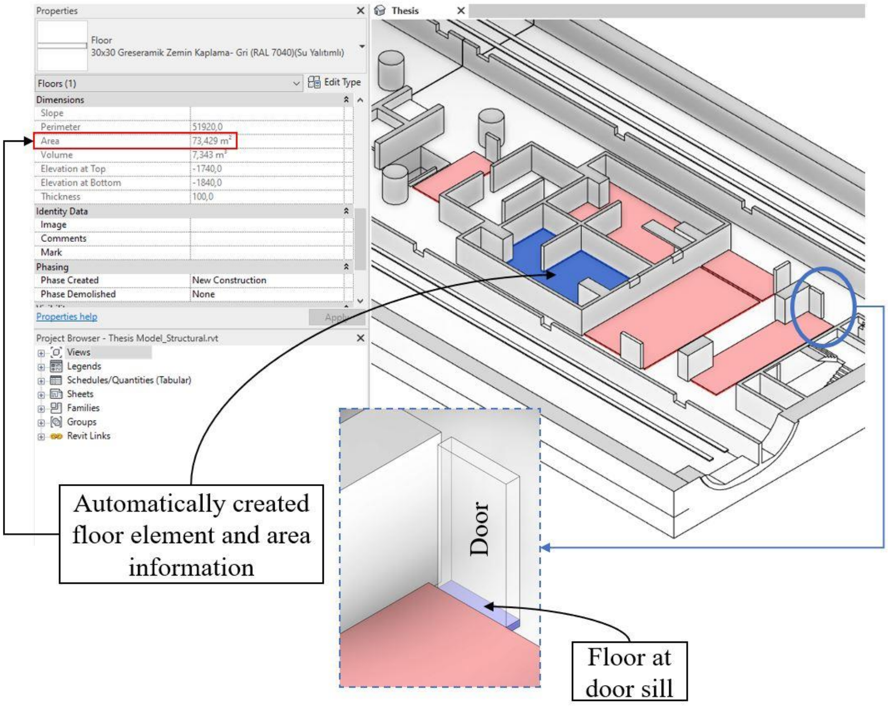


Figure 4.21. Floor cladding calculation and modeling result

4.2.2 Wall Claddings

Wall claddings are calculated and modeled according to the framework provided in Figure 3.11. The geometry of previously placed room elements is obtained, and their perimeters are used to located wall claddings. After generating the wall element, its surface area is automatically calculated by Revit since it is a regular wall element. Wall claddings are also modeled around the column elements, which is usually a manually overwhelming task, as shown in Figure 4.22. However, it is observed that created wall elements cannot be cut with the door and window elements, and the reason is that these doors and window elements are created using the Model-in-Place option, so they are not acting as regular Revit families. Hence, wall profiles should be modified manually to prevent overestimation due to door and window openings. The framework shown in Figure 3.11 is designed for rooms having suspended ceilings. Hence, a parameter material extension above the ceiling is added for each room element. However, some room elements do not have a suspended ceiling, and they have only paint over concrete. In this case, Dynamo gives an error and cannot calculate wall heights, so *"if"* node is implemented and if the value of material extension is 0, then a 0 value is inserted in the calculation. Otherwise, the actual value of the parameter is utilized (Figure 4.23).

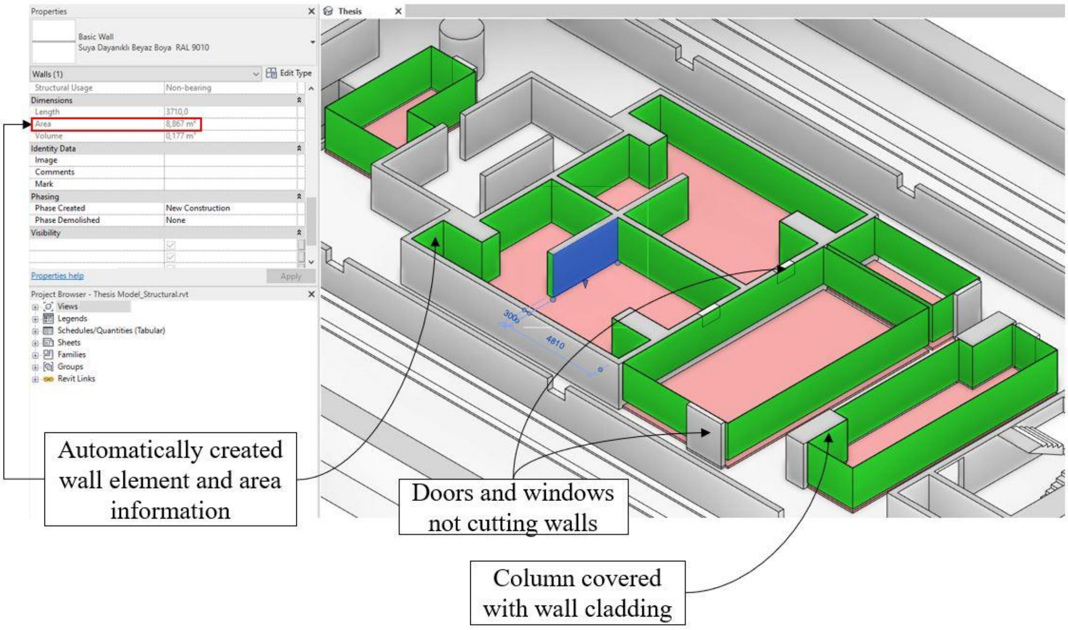


Figure 4.22. Wall cladding calculation and modeling result

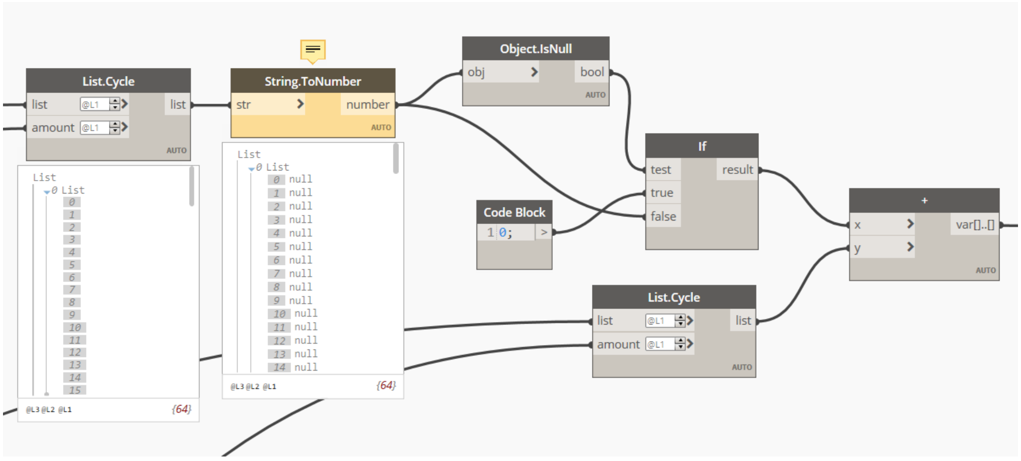


Figure 4.23. Overcoming material extension above ceiling parameters with 0 value

4.2.3 Wall Base Claddings

Wall base calculation and modeling are done using the room perimeter curves, but door opening widths are deducted from the total length of the room perimeter. For this reason, the workflow shown in Figure 3.17 is utilized to manipulate door geometry. Besides, top and bottom offsets of wall bases are arranged using the floor cladding thickness since wall bases are located over the floor cover. This way, the overlap between the base material and floor cladding is prevented. Figure 4.24 presents the wall base results for the fire pump room.

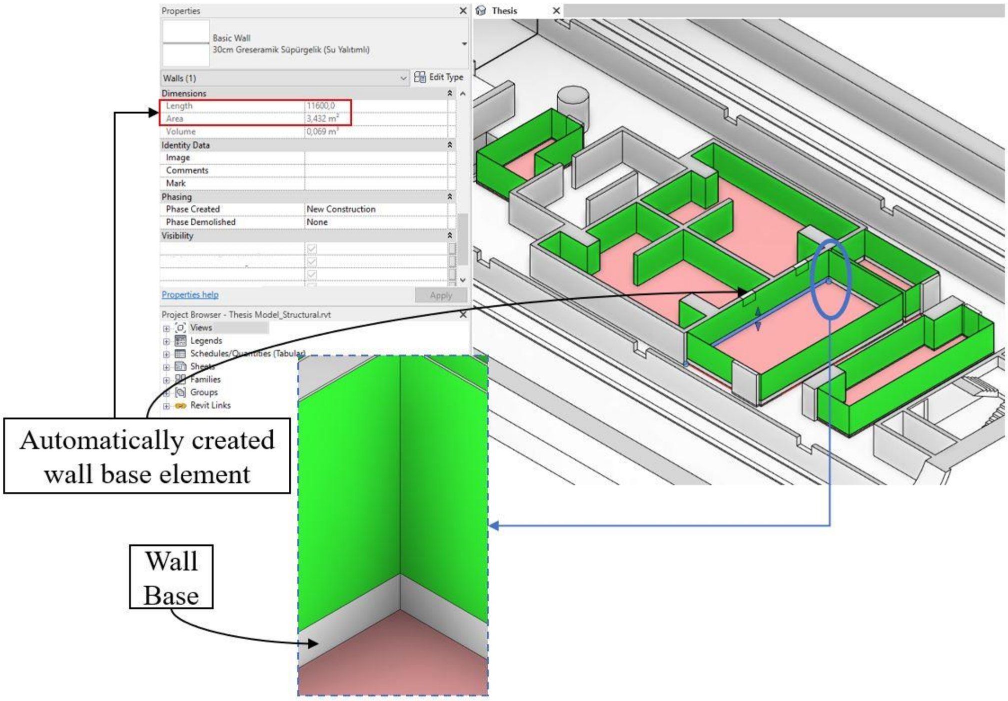


Figure 4.24. Wall base cladding calculation and modeling result

4.2.4 Ceiling Claddings

Ceiling calculation is done using the top surfaces of room elements. They are first exploded into curves, and obtained curves are shifted towards to center of rooms by the thickness of wall cladding. It is because ceilings are assumed to be constructed after wall cladding is done. After that, the curves are converted back to surfaces, and they are converted to generic models. The surface area information is stored under the ceiling area parameter. Figure 4.25 demonstrates the ceiling calculation and modeling results. It is shown how ceiling elements are placed after wall cladding to prevent overlap.

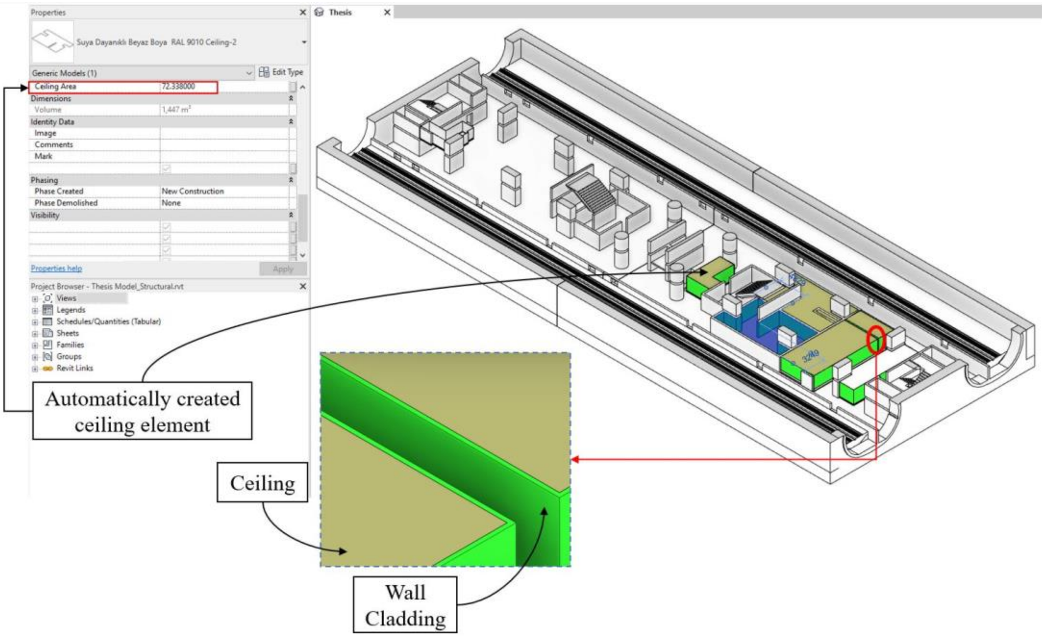


Figure 4.25. Ceiling calculation and modeling result

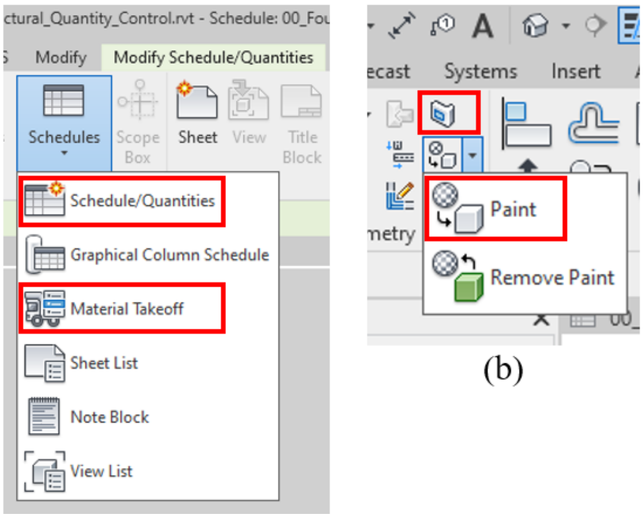
CHAPTER 5

DISCUSSION OF RESULTS

In this part of the thesis, the quantities obtained using Dynamo are compared with Revit Schedule/Quantities and Material Takeoff options. The reasons for deviations are discussed in detail, and the accuracy of BIM-based QTO obtained by following the developed frameworks using Dynamo for Revit is revealed.

5.1 Results for Formwork Calculations and Modeling

Material QTO is performed for formwork and formwork models are generated for the case study structure in section 4.1 using the visual programing tool Dynamo for Revit. Quantity results are compared with Revit Schedule/Quantities and Material Takeoff options (Figure 5.1a) since actual construction data is not available yet. Material Take-off option is utilized together with Paint and Split Face options in Revit (Figure 5.1b). Both options require significant amount of time for arranging data for take-off process. Revit Schedule/Quantities option requires additional parameters that can appear in schedules and assigning and formulating these parameters require time and detailed software knowledge. Material Take-off option requires spliting correct faces for formwork installation and painting each surface one by one, which again requires time and attention. Accordingly, formwork requiring surfaces are carefully separated using Split Face and Paint option is applied, then material paint is scheduled using Material Takeoff option. Even though the Revit Schedule/Quantities option is weak in area extraction, various formulations are applied to get the most accurate results. The results obtained from both options are compared with Dynamo results in Table 5.1 for foundations, walls, columns, beams, slabs, and stairs categories, and deviations are calculated. Furthermore, a few individual building components are selected, manual take-off is performed, and results are compared in Table 5.2.



(a) (b)

Figure 5.1. (a) Revit Schedule/Quantities and Material Takeoff options, and (b) Paint and Split Face options

Table 5.1. Formwork quantification result comparison for individual elements

Formwork Category	Revit Schedule Quantity (m2)	Revit Paint Material Quantity (m2)	Proposed Method Result (m2)	Deviations Revit Schedule & Proposed Method (m2)	Deviations Revit Paint & Proposed Method (m2)	Deviations Revit Schedule & Proposed Method (%)	Deviations Revit Paint & Proposed Method (%)
Foundation	1302.79	1341.36	1332.95	30.16	-8.41	2.26	0.63
Walls	23703.47	24038.25	23993.25	289.78	-45	1.21	0.19
Columns	2416.16	2416.16	2290.63	-125.53	-125.53	5.48	5.48
Beams	1267.24	954.35	952.22	-773.81	-2.13	33.08	0.22
Slabs	15757.09	12274.74	12211.74	-3545.35	-63	29.03	0.52
Stairs	-	957.57	1004.43	-	46.86	-	4.67

According to Table 5.1,

i. Deviations between the proposed method and Revit Schedule/Quantities option is 30.16 m2 while it is 8.41 m2 between the proposed method and Material Takeoff using paint option for foundation category. Besides, the mean absolute percentages between the proposed method and Revit Schedule/Quantities and Material Takeoff options are 2.26 and 0.63, respectively. As explained in section 4.1.1, some foundation elements are modeled using the category of the floor, and those floor elements are calculated considering that they are foundation elements. Similarly, those floor elements are scheduled differently, and their results obtained from Revit Schedule/Quantities, and Material Takeoff options are added to foundation results. However, it is also realized that one floor element is modeled using the Mass-in-Place option, and area information cannot be extracted using Revit Schedule/Quantities, which is the main reason for the 30.16 m2 area difference. 8.42 m2 deviation results from the fact that Dynamo cannot deduct the surface area of two floor elements intersecting with foundation elements, as shown in Figure 5.2a. It is also important to note that side formworks for foundation elements are calculated by implementing a calculated schedule parameter using default perimeter and foundation thickness parameters (Figure 5.2b). This implementation has significantly increased the accuracy of Revit quantities because Revit usually provides the projection area of the foundation category, which is not vital from the formwork quantification standpoint.

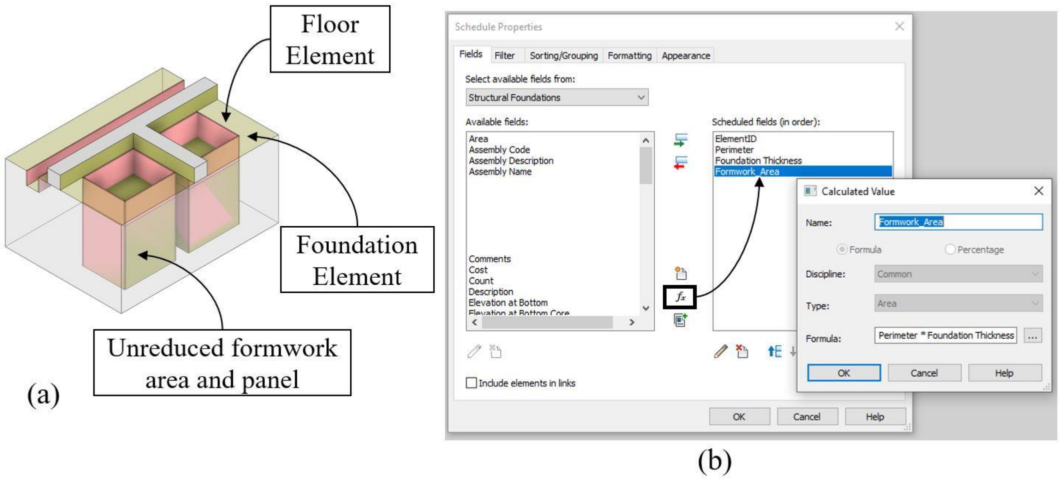


Figure 5.2. (a) Unreduced formwork area between foundations and floors, and (b) calculated schedule parameter addition in Revit

ii. All formwork surfaces are carefully painted for wall elements and assumed that the Revit Material Takeoff option results are more accurate and correct than other options. Revit Schedule/Quantities option provides only vertical projection area of wall elements. Hence, similar to foundation elements, a calculated schedule parameter is added by multiplying the default wall area by two since both sides of the walls are formed. Even though the accuracy is significantly increased, it is still less than Revit Material Takeoff and Dynamo results because this approach does not account for wall openings. On the other hand, Dynamo results are very close to Revit Material Takeoff options, but there is still an underestimation because Dynamo could not calculate the base surface of openings, as shown in Figure 5.3. The reason is that the normal vector for those surfaces is on the positive z-axis, and while eliminating top surfaces, those surfaces are lost in the calculation process. Hence, Dynamo code needs to be improved to get more accurate results. In addition, it is observed that Dynamo can create formwork panels and calculate formwork areas for irregular shapes. In this case, the most irregular shape is the connections between the main building and tunnels, creating an arched wall surface. These surfaces are also calculated, but some could not be created due to the same reason explained previously. The direction of the normal vectors with z-positive directions cannot be obtained and needs further study, as shown in Figure 5.4. It verifies that Dynamo can handle irregular formwork surfaces.

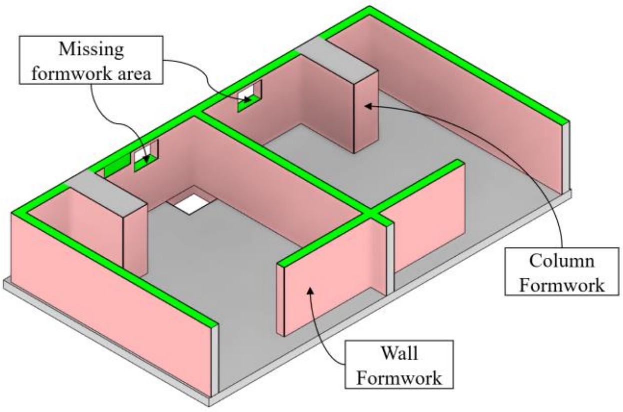


Figure 5.3. Wall opening formwork problem

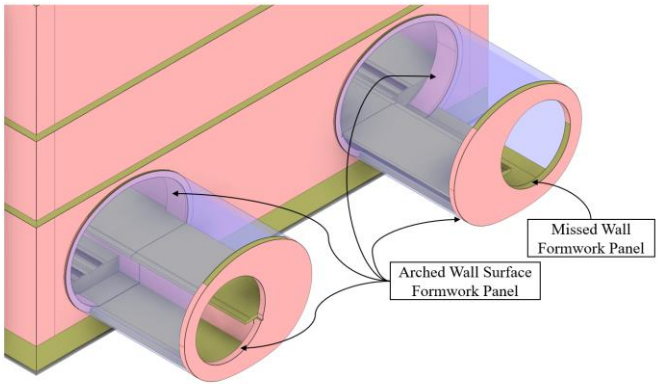
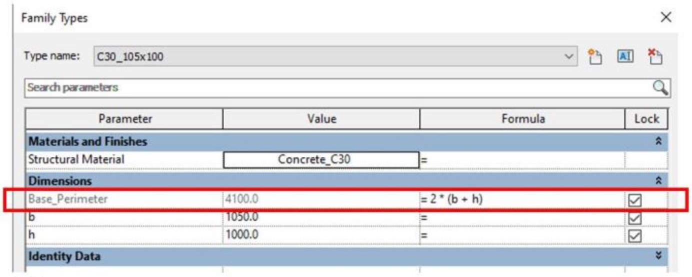
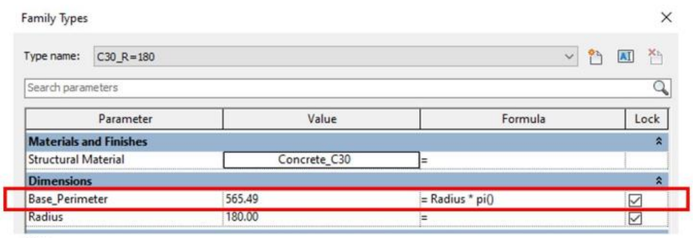


Figure 5.4. Arched wall surface formwork panels

iii. For column category, results obtained from Dynamo are more accurate compared to other options. Revit Schedule/Quantities option does not provide column surface area, and for this reason, some manipulations are done to at least obtain some results. Firstly, the column family editor is opened, and the base perimeter parameter is added, and it is connected to column default dimensions. Since rectangular and circular columns exist in the case study, different formulations are implemented for circular and rectangular columns (Figure 5.5). After that, the base perimeter parameter is scheduled, and it is used together with the column default length parameter to get the side surfaces of structural columns, which is vital for formwork calculations (Figure 5.6). This approach provides the gross vertical surface area of columns, but it does not account for beam-column, wall-column, and floor-column intersections. Moreover, formwork requiring surfaces of columns are painted, and they are also scheduled using the Material Takeoff option. It is observed that Material Takeoff and Revit Schedule/Quantities options provide the same results, and they are not deducting the column intersections with other elements. On the other hand, Dynamo extracts column surfaces and eliminates intersection areas, bringing more accuracy.



(a)



(b)

Figure 5.5. Parameter addition for column base perimeter, (a) for rectangular and (b) for circular columns

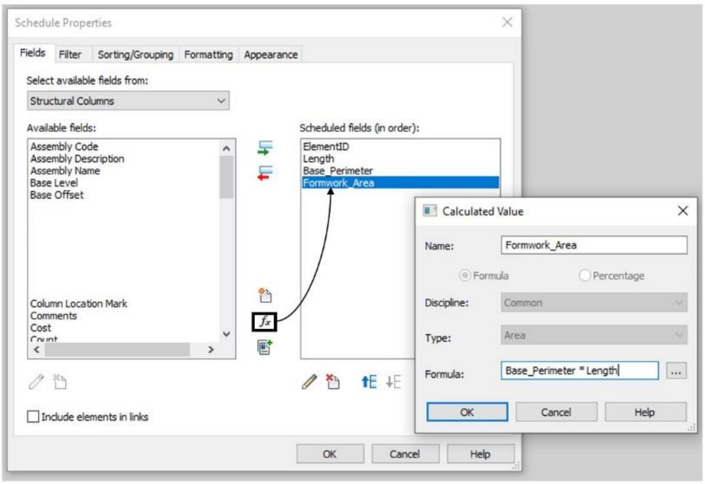


Figure 5.6. Calculated schedule parameter addition in Revit for columns using predefined base perimeter parameter

iv. Revit does not provide formwork area information for the structural framing (beam) category similar to the column category. Hence, a section perimeter, beam width, and height parameters are assigned, and these parameters are used to get the formwork area together with the default cut length parameter (Figure 5.7). For this purpose, section perimeter is first multiplied with the cut length of the beam to find the total surface area of beams, then cut length is multiplied with beam width and deducted from the total surface area not to include top surfaces of beam elements. Even though this approach provides good results, beam and floor intersections cannot be reduced, and it causes overestimation. Hence, the Revit Schedule/Quantities option provides 33.08 percent higher quantities than other methods according to Table 5.1. There is a 2.13 m2 difference between the Material Takeoff option and the proposed method. The main reason why Material Takeoff is more accurate is the cut relationship between structural framing and floor categories. It means that when painting formwork requiring surfaces of beam elements, intersection areas between floors and beams are not painted, ensuring accurate results. Dynamo provided accurate results for beams, such that beam-column, beam-floor, and beam-wall joints are correctly eliminated, as demonstrated in Figure 4.10.

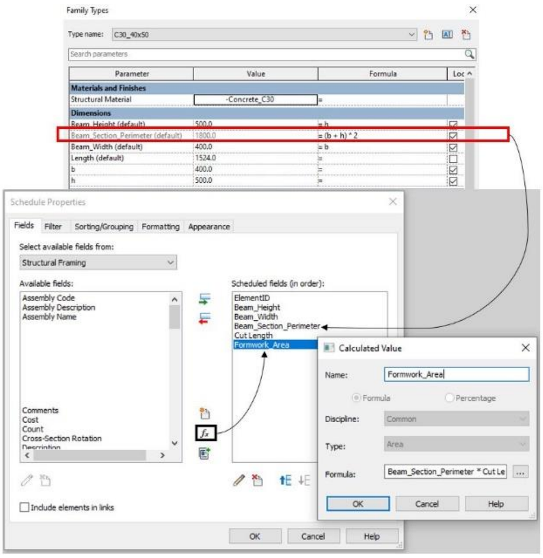


Figure 5.7. Beam section parameter creation and its use in calculated schedule parameter

v. There is a considerable difference, which is 29.03 percent, for the Revit Schedule/Quantities option for floor elements. Hence, reasons for the deviations are investigated. A calculated schedule parameter for Revit Schedule/Quantities is added to obtain the side formwork area, similar to foundation elements. However, it does not account for the intersection of floor elements with other building components, ending with overestimation. It is because all perimeter of slabs are multiplied by the thickness of the slab, so no reduction is made when elements intersect. The results from the proposed method are accurate and compatible with the Material Takeoff option, but the generic formwork model cannot be created for the bottom of two large floors, and the reason cannot be comprehended in detail. It is observed that these surfaces belong to the floor elements, which created problems while obtaining their geometry, as explained in section 4.1.5. We assume that this is a software bug in Dynamo such that Dynamo sometimes cannot handle complex floor boundaries and too many floor openings. However, obtaining area information is not affected, and the area of problematic surfaces is extracted, so that is the reason quantities are accurate.

vi. Revit Schedule/Quantities option does not provide formwork area of stairs and does not enable adding and manipulating parameters. Hence, this part is empty in Table 5.1. For stair elements, formwork is needed on the bottom, sides, and vertical faces of risers, so these faces are carefully painted, and the Material Takeoff option is utilized to extract quantities. In general, the formwork model created by Dynamo is investigated, and the results are promising with only 4.67 percent deviations. At some locations, it is observed that stair landings are modeled using floor elements as shown in Figure 5.8; therefore, that places are included in slab formwork quantities and are not reflected in stair formwork QTO.

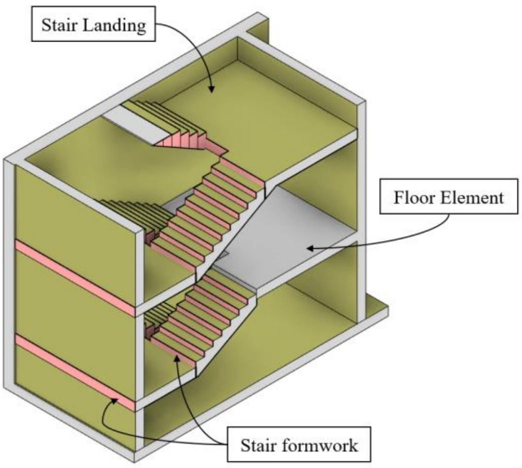


Figure 5.8. Stair landing modeled with floor element and stair formwork view

5.1.1 Manual Formwork QTO Check for Individual Elements

Formwork areas are grouped according to the structural category in the previous section. This section compares the results obtained from Dynamo, Revit Schedule/Quantities, Revit Material Takeoff, and manual calculations for specific elements to show the verification process at the element level. The below calculation belongs to column SB106 with element ID of 1766739, also shown in Table 5.2. Accordingly, all elements connecting to the SB106 column are determined, and all the intersecting areas are deducted from the total column side area. The deducted building components and automatically generated formwork panels and their interaction with column SB106 are shown in Figure 5.9.

$$A_{SB106} = A_{SB106} - A_{KB105} - A_{KB109} - A_{KB104} - A_{Slab}$$

$$A_{SB106} = 6.12x(2.50 + 1.00) * 2 - 1.00x1.00 - 0.5x(1.75 + 1.00) - 0.50x1.00 - 0.50x1.00 - 0.50x1.00 - 0.5x(2.50 + 0.75) = 37.84\ m^2$$

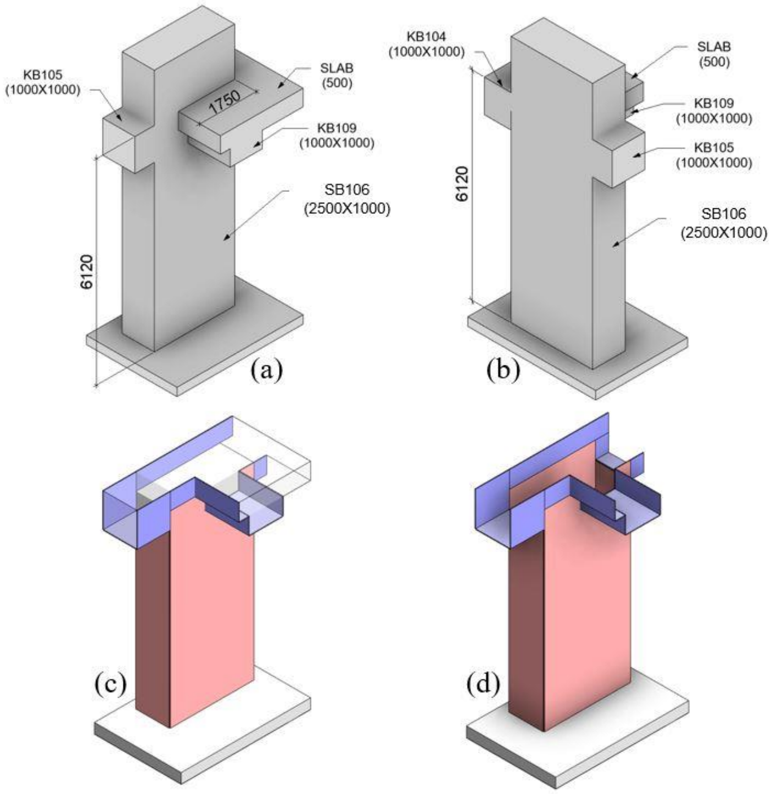


Figure 5.9. Manual QTO example for SB106 column

A similar calculation process is done for sample elements from other categories, and results are shown in Table 5.2 and Table 5.3. The higher error occurs in the floor and stair categories since the problematic floor element is selected for the example and the Dynamo code is not giving accurate results for the selected stair element, and errors in other categories are acceptably more negligible. For stairs, the error comes from where stairs and landings meet, and for foundations, the error occurred because of the floor and foundation joining case shown in Figure 5.2.

Table 5.2. Formwork quantification result comparison for individual elements using actual values

Formwork Category	Element ID	Revit Schedule Quantity (m2)	Revit Paint Material Quantity (m2)	Proposed Method Result (m2)	Manual Results (m2)	Deviations Revit Schedule & Manual (m2)	Deviations Revit Paint & Manual (m2)	Deviations Proposed Method & Manual (m2)
Foundation	1752394	289.80	289.80	289.80	289.80	0.00	0.00	0.00
Foundation	1752403	355.86	347.16	356.42	347.16	-8.70	0.00	-9.26
Walls	1805543	49.03	51.40	50.73	51.40	2.37	0.00	0.67
Columns	1766739	39.34	39.34	37.84	37.84	-1.50	-1.50	0.00
Columns	1766743	39.34	39.34	38.34	37.84	-1.50	-1.50	-0.50
Beams	1773134	35.10	23.40	21.35	21.35	-13.76	-2.06	0.00
Beams	1773128	35.10	23.40	22.00	21.35	-13.76	-2.06	-0.66
Slabs	1665201	1802.73	1599.37	1652.92	1599.37	-203.36	0.00	-53.55
Stairs	1762239	-	26.52	31.63	26.52	-	0.00	-5.11

Table 5.3. Formwork quantification result comparison for individual elements using mean absolute percent values

Formwork Category	Element ID	Revit Schedule Quantity (m2)	Revit Paint Material Quantity (m2)	Proposed Method Result (m2)	Manual Results (m2)	Deviations Revit Schedule & Manual (%)	Deviations Revit Paint & Manual (%)	Deviations Proposed Method & Manual (%)
Foundation	1752394	289.80	289.80	289.80	289.80	0.00	0.00	0.00
Foundation	1752403	355.86	347.16	356.42	347.16	2.51	0.00	2.67
Walls	1805543	49.03	51.40	50.73	51.40	4.61	0.00	1.30
Columns	1766739	39.34	39.34	37.84	37.84	3.96	3.96	0.00
Columns	1766743	39.34	39.34	38.34	37.84	3.96	3.96	1.32
Beams	1773134	35.10	23.40	21.35	21.35	64.40	9.60	0.00
Beams	1773128	35.10	23.40	22.00	21.35	64.40	9.60	3.04
Slabs	1665201	1802.73	1599.37	1652.92	1599.37	12.72	0.00	3.35
Stairs	1762239	-	26.52	31.63	26.52	-	0.00	19.27

5.1.2 Evaluation of Building Expansion Joints

The case study structure includes three entrance structures and one main building. The entrance structures are separated from the main building with a 50 mm expansion joint. The main building is also divided into two structures by a 50 mm expansion joint, as shown in Figure 5.10. Generally, both sides of the expansion joint are not cast simultaneously due to constructability issues. Hence, this brings some advantages in formwork cost because the previously cast structure acts as formwork for the adjacent construction. Usually, one side of the expansion joint is cast, and then after the setting of concrete, an expansion filler material, which will be removed after both sides are cast, is placed in the expansion joint properly, and the other side is poured. For the time being, this logic cannot be implemented in visual code, and both sides of the expansion joint formwork are calculated and modeled.

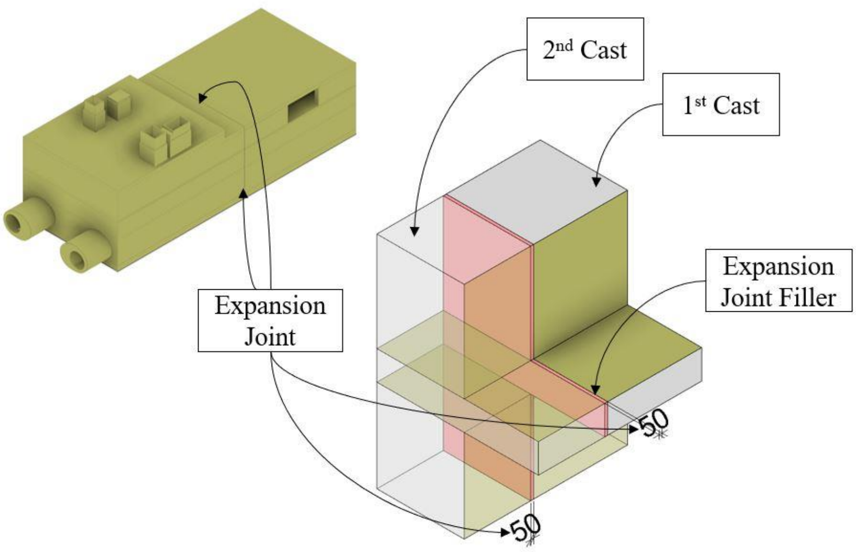


Figure 5.10. Expansion joints in the building and casting sequence

Table 5.4 shows how much area will be lost when casting concrete, as explained above. Accordingly, 503.58 m2 formwork area can be saved and should be deducted from the formwork calculations. Table 5.4 results are obtained using the paint option in Revit.

Table 5.4. Effect of expansion joint over formwork area

Expansion Joint Location	Area Loss (m2)
In between the foundations of main building blocks	23.80
In between the foundations of entrance structures and main building walls	42.80
In between the walls of main building blocks	75.00
In between the walls of main and entrance structures	191.82
In between the columns of main and entrance structures	11.72
In between the floors of main and entrance structures	38.68
In between the floors of main building blocks	119.76
Total	**503.58**

5.2 Results for Cladding Calculations and Modeling

The proposed framework for architectural claddings is tested with seven rooms in the case study building. Even though the building data could be in any format such as pdf or text file, this study considered that all data is stored in MS Excel. According to the framework and prepared Dynamo codes, rooms are placed in the 3D structural model, and then room parameters are filled, and new types of floors and walls are generated automatically per room data. After that, using the room geometry, floor, wall, wall bases, and ceiling components for each room are created and calculated. Hence, the building does not have any architectural components initially, and all architectural things are generated automatically after the placement of room elements. The findings are listed below, and the results are shown in Table 5.5.

i. Floor claddings are created, and takeoff is extracted perfectly, but for floor claddings at door sills, an additional door element is located so that the visual code understands that there is a door at specific locations. Hence, there is a disadvantage here since manual work is incorporated.
ii. Wall claddings are also generated, and takeoff is done, but wall covers should be manually edited after their placements for door and window openings. It is expected that previously located door, and window elements should automatically cut the newly added wall covers, but it does not work out since

door and window elements are created using the model-in-place option. All bottom and top elevations of wall covers are arranged automatically, allowing for the placement of wall bases without clashing with other components.

iii. Wall bases are created with wall elements, but it is observed that wall sweeps are utilized while modeling wall bases, which is more logical and appropriate since the software allows and is capable. Like wall elements, all top and bottom elevations of wall bases are automatically arranged with visual coding, as shown in Figure 4.24.

iv. Software features (Revit 2021.1) are not allowing to generate ceiling elements using Dynamo, so the generic model category is utilized to model ceiling components, as previously shown in Figure 4.25. Area information is also obtained and stored in the previously defined parameter.

It is confirmed that the framework enables material QTO for architectural claddings and also helps to generate 3D models automatically. Compared to the previous studies, this framework facilitates using spreadsheet data and 3D model geometry effectively because past research focuses only on the data extraction from 3D information models.

The main differences between the proposed method, Revit, and manual calculation results shown in Table 5.5 and Table 5.6 come from the shaft openings at floor and ceiling levels. Besides, there is a big difference between ceiling areas coming from Revit and Dynamo for the electrical and technical rooms. The ceiling for these rooms also includes some adjacent rooms, meaning that some portion of the ceiling quantity belongs to different rooms. There is a modeling mistake and lack of detailing in ceilings for these rooms. Other slight differences come from the overlaps eliminated in Dynamo.

Table 5.5. Room cladding quantification comparison using actual values

Room Name	Revit Floor Result (m2)	Revit Wall Result (m2)	Revit Wall Base Result (m2)	Revit Ceiling Result (m2)	Manual Method Floor Result (m2)	Manual Method Wall Result (m2)	Manual Method Wall Base Result (m2)	Manual Method Ceiling Result (m2)	Proposed Method Floor Result (m2)	Proposed Method Wall Result (m2)	Proposed Method Wall Base Result (m2)	Proposed Method Ceiling Result (m2)
WATER TANK	73.43	123.71	0.00	73.47	73.06	123.65	0.00	73.43	73.43	123.90	0.00	72.33
WATER TANK	73.43	123.42	0.00	70.36	73.06	123.36	0.00	70.32	73.43	123.90	0.00	72.33
ELECTRICAL ROOM	36.19	73.99	36.58	20.53	36.01	73.95	36.56	20.52	36.19	69.16	36.58	35.55
FIRE PUMP ROOM	67.59	79.97	33.16	69.88	67.25	79.93	33.14	69.85	69.75	73.32	33.16	69.02
WASTE WATER PUMP ROOM	16.53	40.09	14.98	16.64	16.45	40.07	14.97	16.63	16.72	36.53	14.98	16.35
ELECTRICAL ROOM	19.07	48.42	19.30	25.31	18.97	48.40	19.29	25.30	19.07	46.76	19.30	18.64
TECHNICAL ROOM	13.65	102.71	11.69	25.50	13.58	102.66	11.68	25.49	13.65	104.48	11.69	12.69

Table 5.6. Room cladding quantification comparison using mean absolute percent values

Room Name	Deviations Revit & Manual Method Floor Result (%)	Deviations Revit & Manual Method Wall Result (%)	Deviations Revit & Manual Method Wall Base Result (%)	Deviations Revit & Manual Method Ceiling Result (%)	Proposed & Manual Method Floor Result (%)	Proposed & Manual Method Wall Result (%)	Proposed & Manual Method Wall Base Result (%)	Proposed & Manual Method Ceiling Result (%)
WATER TANK	0.50	0.05	-	0.05	0.50	0.20	-	1.50
WATER TANK	0.50	0.05	-	0.05	0.50	0.44	-	2.85
ELECTRICAL ROOM	0.50	0.05	0.05	0.05	0.50	6.48	0.05	73.25
FIRE PUMP ROOM	0.50	0.05	0.05	0.05	3.71	8.27	0.05	1.18
WASTE WATER PUMP ROOM	0.50	0.05	0.05	0.05	1.66	8.83	0.05	1.69
ELECTRICAL ROOM	0.50	0.05	0.05	0.05	0.50	3.38	0.05	26.32
TECHNICAL ROOM	0.50	0.05	0.05	0.05	0.50	1.77	0.05	50.21

5.2.1 Evaluation of Case Study Model for Architectural Material QTO

Architectural material QTO requires high detail level for accurate results. Even though the proposed strategy can quantify wall claddings, wall bases, floor claddings, and ceiling covers, automation in complex architectural projects is challenging. It is because every project is unique, and there is no limitation behind architectural imagination and complex detailing, which is a natural and acceptable situation. Hence, models should be developed in a way that is comfortable to extract material quantities, and modeling guidelines should be provided, and 3D models should be information-rich and at the same time manageable. Figure 5.11 shows some details from the case study model, which is highly detailed and manageable based on the author’s experience, and the reasons are listed below.

i. Most importantly, the architectural model is created as separate from structural and mechanical models, making the model manageable and effective. Figure 5.11a shows a linked view of the structural and architectural model. Besides, expansion joints, wall bases, wall claddings, wall cores, and floor claddings are modeled with parametric objects which can be scheduled and quantified (Figure 5.11b).

ii. Covers on columns are modeled using wall elements, and column bases are modeled with wall sweeps, which again can be scheduled. This way, cladding or paint areas for columns can be extracted, and the accuracy of material quantification is increased (Figure 5.11d).

iii. Figure 5.11c shows railings in the architectural 3D model, and they have length parameters, which can be scheduled as well. The high accuracy of the 3D model can be proved by column bases in Figure 5.11c, which are not entirely surrounding the column, but only walkable side of the building.

iv. Figure 5.11b shows wall claddings and wall core modeled separately, making the material QTO of composite building components like walls and floors more accurate. Figure 5.11d shows the reinforcing columns for architectural walls, again demonstrating the high detail level in the 3D models.

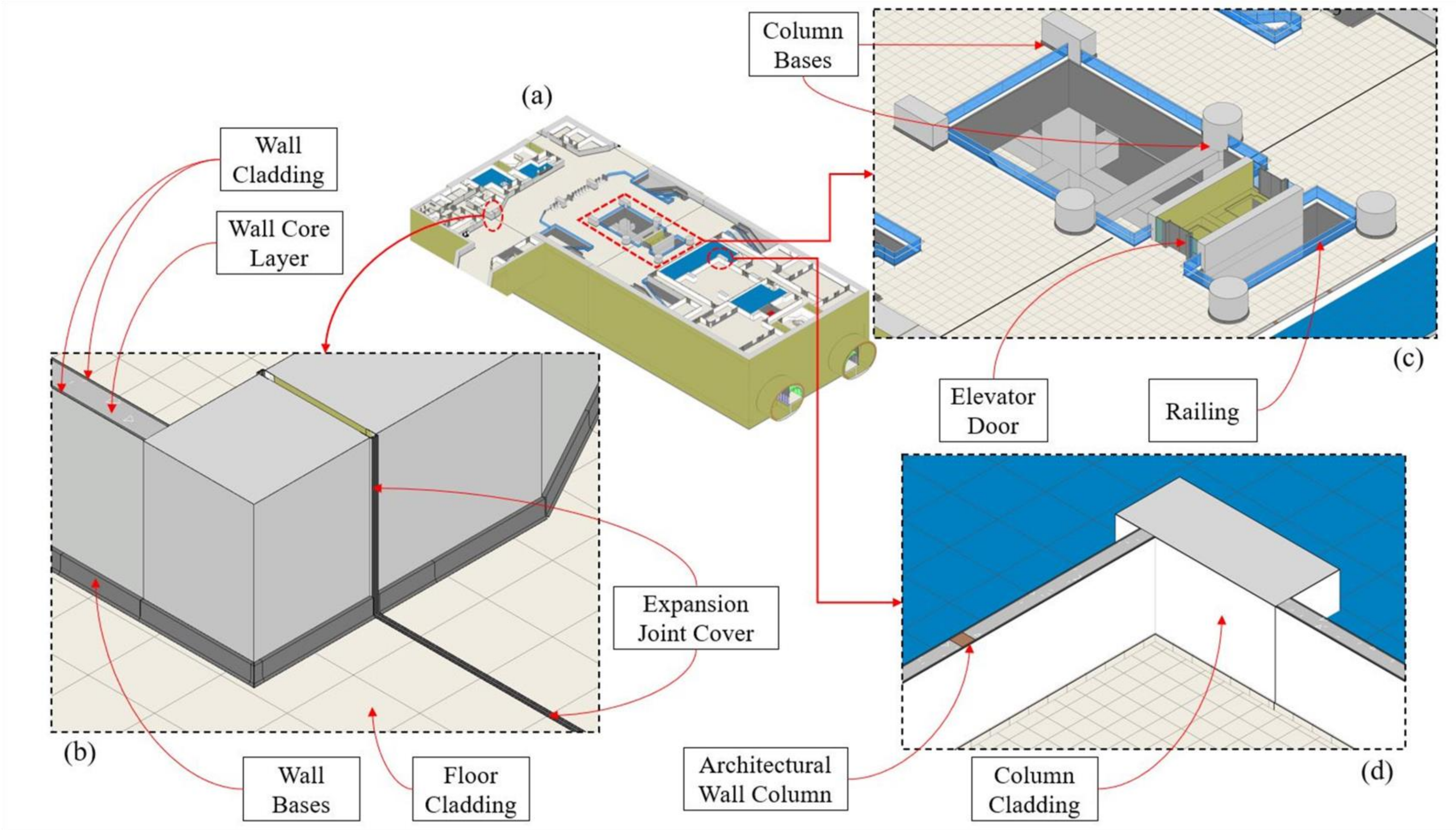


Figure 5.11. Architectural details from case study model

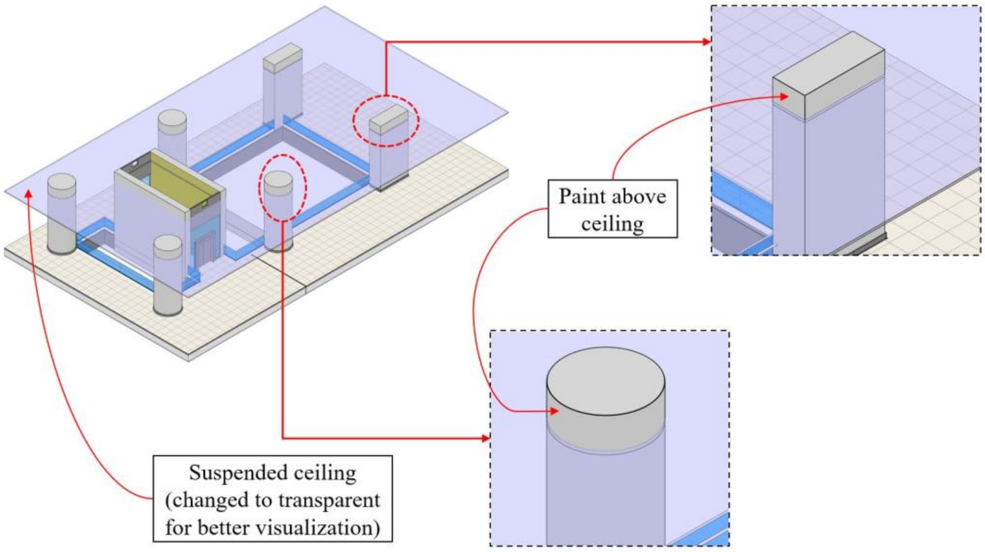


Figure 5.12. Unnecessary material claddings above ceiling level

On the other hand, Figure 5.12 demonstrates a sample case resulting in high paint material quantity results. Accordingly, the design model includes column and wall paints extending too much above the suspending ceilings. This extension is generally limited between 100 mm and 200 mm in practice since it is not architecturally visible. In this case, modeling details should be improved following the architectural desires and at the same time to achieve cost-efficiency.

5.3 Major Challenges and Evaluation of Visual Programing

Programing and coding play a prominent role in the construction industry. Most of the time, engineers and architects utilize programing to reduce their time over repetitive tasks. For example, replacing page numbers or creating new ones with an order might be time-consuming and easy to handle with programing applications. In the context of BIM, Dynamo helps manipulating such data, especially for those who lack knowledge in textual programing. It is because Dynamo has visual code blocks which are understandable, and input and output logic are apparent. It also allows for implementing textual codes and creating new custom nodes, which is not investigated in this study. However, there are some considerable challenges in visual codes prepared in Dynamo. These inferences are based on the difficulties coped within this study, and they are listed below.

i. List structure in Dynamo can get complex and challenging to manage. For example, a floor element with too many faces results in many surfaces, and some surfaces are left as polysurfaces (having two or more surfaces) in the first geometric explosion (Figure 5.13). In this case, these polysurfaces need to be divided again, increasing the number of nodes and sublists, which is not easily manageable.

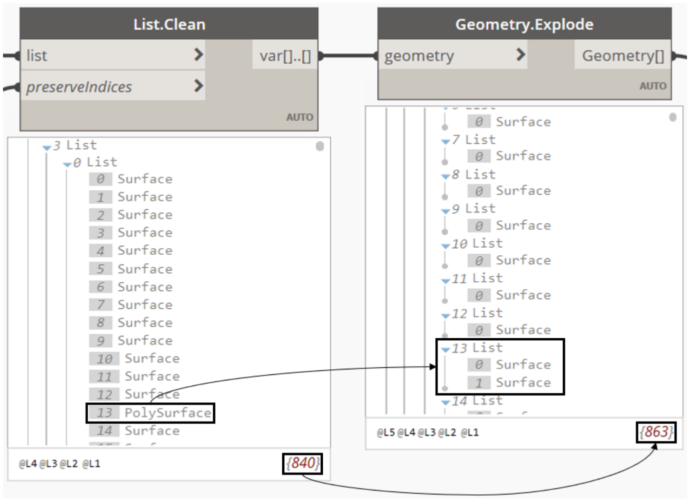


Figure 5.13. PolySurface problem and increase in sublists for surfaces

ii. As explained in section 4.1.5, some floor elements cannot be converted into solid geometry because of floor complexity and software bugs as searched on the internet. Even though the problem is solved by implementing additional code, this is a random error, making Dynamo unstable for complex geometries.

iii. In addition to the above item, one surface of the problematic floor elements cannot be converted to Revit geometry, and the reason cannot be understood. The surface area can be extracted for this specific surface, but it cannot be converted to a formwork element.

iv. Even though Dynamo is fast in architectural cladding quantification and modeling, formwork quantification and modeling takes longer, and Dynamo gets slow while converting surfaces into generic models. Table 5.7 shows the total times for completing formwork quantification and modeling processes. Architectural parts are not included since they are significantly less compared to formwork operations. However, for better evaluation of the performance of Dynamo, this study should also be done with another visual programing tool like Rhino Grasshopper and results should be compared. According to Table 5.7, the number of panels for stairs is high compared to its number, and the main reason is that Dynamo calculates every riser and side of risers separately. The highest processing time belongs to wall elements, and it might get higher if bottom surfaces of wall openings are also calculated.

It is important to note that some floor elements are considered in the foundation category in section 4.1.1. Therefore, the same thing is applied while preparing Table 5.7. This is why there is an explanation under the number of elements in the foundation category. Consequently, 13 floor elements are deducted from floor formwork calculation and added to foundation formwork calculation.

Table 5.7. Dynamo processing times for formwork quantification and modeling

Building Category	**Number of Elements**	**Number of Formwork Panels**	**Processing Time**
Foundation	24 -11 from foundation category -13 from floor category	178	10 min 01:28 s
Walls	301	1341	240 min 05:36 s
Columns	73	274	43 min 07:20 s
Beams	56	187	32 min 04:15 s
Floors	105	939	110 min 03:31 s
Stairs	11	1784	120 min 08:36 s

CHAPTER 6

CONCLUSIONS

6.1 Summary

Construction projects require detailed QTO results for every component in the project scope since quantities affect the cost and schedule activities. However, area-based quantification with BIM for materials like formwork and architectural claddings still has problems. For this reason, this study focuses on the accurate quantification of formwork and architectural cladding materials and applies a visual programing approach to an underground metro station building. There are reliable results, gains, and learning outcomes in this study. First of all, a detailed literature review is performed, and various approaches in the past research are discussed in detail for BIM-based QTO, visual programing, and QTO of formwork and architectural claddings. Although there are different methods to improve BIM-based material QTO, this study is structured to enhance visual programing approaches. Secondly, it is comprehended that Revit QTO features are limited for formwork quantification since the software does not account for the intersection between different elements, and quantifying the formwork area of a complex structure takes time and requires attention. Hence, Dynamo helps extracting area quantities accurately and creates a 3D geometry that might be useful for other construction activities like 4D simulation. Thirdly, it is confirmed that architectural quantities can be extracted with Dynamo, and a 3D model can be generated, and a link can be maintained between spreadsheet data and Autodesk Revit. However, this part of the study needs further improvement because of the high detail requirements in architectural materials. At this point, automation of importing room data, creating cladding materials, and locating cladding materials in the correct places is achieved.

Lastly, this study provides an insight into visual programing, and the steps utilized in this work can be implemented for other visual programing applications.

6.2 Limitations of the Study

In this study, BIM-based material QTO is investigated using the visual programing tool Dynamo for Revit. Due to construction sequence, applied methods, and software tools, there are some limitations of the study, and they can be summarized as the followings:

- ✓ The investigated structure is an underground structure, and it is considered that the excavation is wide enough to build this structure like an ordinary building. In deep excavations without side slopes, formwork activities significantly change such that perimeter walls are probably cast with one-sided formwork, meaning that the formwork area of those walls is cut in half. Moreover, foundations do not require any side formworks in this case. The visual script should further be developed for such cases.
- ✓ While calculating column and beam formwork calculations, beam areas touching the column faces cannot be deducted from column and beam formwork calculations in the first code trials. Codes are investigated, and it is realized that trim and extend command should be applied for the problematic areas to ensure the beam and column faces are touching each other. It brings a considerable limitation to the proposed framework. Hence the visual codes should be further improved such that a tolerance gap should be provided among different elements. For example, column surfaces should be evaluated with the elements located 10 mm away from the face of the columns. This way, beam surfaces not touching the column due to modeling approaches can also be considered in the estimation process.
- ✓ Stairs are considered cast after adjacent construction is performed, so if stairs are cast integrated with other building components, some formwork area is to be reduced from the adjacent building components.

- ✓ The architectural material QTO is performed using the structural 3D model. Therefore the architectural calculations and modelings should be studied in more detail considering the additional conditions such that the existence of non-structural building elements like partition walls and the orientation of walls should be taken into account to distinguish material layers on different walls of a room boundary.
- ✓ Another limitation for the architectural quantification is the sample size due to the architectural complexity in the case study. As mentioned in section 4.2, there are 131 rooms in the case study building, but only seven rooms, including two water tanks, two electrical, one fire pump, one waste water pump, and one technical room, are studied within the scope of this study. As the number of rooms increases, the results might deviate; therefore, more rooms with different details and complexity should be investigated.
- ✓ This study is performed with Autodesk Revit 2021.1 and Dynamo 2.6.1.8850 versions, so performing similar studies with older versions may yield difficulties such that some nodes and features might not be available due to frequent updates of nodes and packages.

6.3 Recommendations and Future Works

Visual programing tools for the AEC industry are open source and developing perpetually. Moreover, the ability of BIM tools is also increasing each year and new releases are solving the problems encountered previously. For this reason, the following are suggested as recommendations and possible future works.

- ✓ This study is based on the implementation of Autodesk Revit, and it is a vendor-dependent software tool and is considered a barrier for open-BIM applications in the AEC industry. Hence, this study should be implemented with IFC (Industry Foundation Classes) schema using visual programing tools Dynamo and Rhino Grasshopper to create a neutral and open framework while still enforcing visual programing approaches, which is user-friendly and easy to grasp.

- ✓ These frameworks should be tested with other building types and infrastructure projects to draw a better conclusion about the benefits of visual programing tools for BIM-based QTO. It is considered that the building used in this study is sufficiently complex, especially from the architectural standpoint, so the proposed method for the architectural part might work better in more standardized residential buildings, and it should be investigated in more detail.
- ✓ Revit can also provide more accurate results if the model is correct and detailed sufficiently. Thus, the Revit Schedule/Quantities option results can be further improvedby forcing the boundaries of calculated schedule parameters in the software. Similarly, accuracy of results obtained from Revit Material Takeoff can also be further increased by pushing software boundaries by adding additional parameters to column and beam families. For example, paint parameters can be added to column and beam families for formwork quantification, and these adaptive paint dimensions can be arranged according to the connected beam, column, and wall dimensions. However, it takes a significant amount of time, and it requires great attention to prevent mistakes.
- ✓ For the formwork part, the created formwork models represent the panel (plywood) part of the formwork systems, and it is known that formwork systems are more complex and require more detailed models. It is proposed that a formwork library from the market can be integrated with Dynamo, and panels can be generated with actual details according to extracted formwork surfaces that account for all element connections and casting sequences.
- ✓ For the architectural part of the thesis, more manual work is performed while placing room elements and organizing spreadsheets. Hence, the automated or faster ways of doing these tasks should be searched further.

- ✓ Even though process time is not verified in this study, the results show that Dynamo should be compared with another visual programing tool since the generation of panels take significant time, and processing surfaces get complicated, especially for floor elements. The algorithm might need to be improved as well for reducing processing time.

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