

BIM-based Automated Schedule Generation in Reinforced Concrete-framed Buildings

by

Ziwei Wang

A thesis
presented to Lakehead University
in fulfillment of the
thesis requirement of the degree of
Master of Science

Thunder Bay, Ontario, Canada, 2018

© Ziwei Wang 2018

Author's Declaration

I hereby declare that I am the sole author of the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

In the construction industry, project schedule has been regarded as a fundamental tool to complete a project under the targeted duration and cost. A sound schedule usually depends on schedulers' construction management knowledge, such as the principles and concepts of construction scheduling, as well as their enriched construction experience. However, as the complexity of projects increases, project scheduling has become demanding as well. In addition, traditional manual project scheduling methods are tedious, time-consuming, and error-prone. These methods, therefore, can hardly meet the requirement of the contemporary project management. With the prevailing trend of Building Information Modelling (BIM) in the Architecture, Engineering, and Construction (AEC) industry, many researchers in the construction research community have paid more attention on extending its capabilities into project management areas. Some of them have investigated automated schedule generation by utilizing BIM's versatility through buildings' lifecycle. The scope and capabilities of the developed systems, however, were limited, and they mainly demonstrated a simple proof of concept. In particular, there is a limited number of research efforts, which investigated automated scheduling of a certain type of structures, namely reinforced concrete-framed buildings. Accordingly, BIM has not reached its full potentials in the construction domain yet and the link between the design and construction stages is still underdeveloped.

This research investigates methods to develop a BIM-based framework to automatically generate schedules for reinforced concrete structures. In this framework, a BIM-enabled software has been connected with a project management tool, in which a bridge between the design and project planning stage was created. This framework firstly extracts the data that stored in the BIM, including elements' geometrical data, quantities, spatial information, material types, and other

related attributes. Secondly, it creates project activities, determines their sequences, and calculates their durations by applying construction sequencing rules and production rate data. At last, it organizes these figures into an applicable schedule, and then exports it to a project management software. Moreover, three samples are presented to further demonstrate the concept and feasibility of this system.

Acknowledgements

Over the past two years of master study in Lakehead University, I have received support and encourage from many individuals. First and foremost, I would like to express my deepest appreciation to my supervisor, Prof. Ehsan Rezazadeh Azar, for his patient guidance. During writing, he spent countless hours on proofreading my thesis, providing constructive suggestions, and helping me whenever I had issues on my thesis. I have learnt much through his teaching. I could not reach this stage without his supervision. It is such an honor to be his student.

I would also like to thank my friends and faculty members of the civil engineering department in Lakehead University for all the encouragements and supports they provided to me.

Especially, I would like to appreciate my parents, who are always on my side. They always support me and offer me the helps as possible as they could for many years. Thank them for giving me the endless love.

Table of Contents

BIM-based Automated Schedule Generation in Reinforced Concrete-framed Buildings.....	I
Abstract	3
Chapter 1: Introduction.....	13
1.1 . Background and Research Motivation.....	13
1.2. Research Objectives	16
1.3. Research Methodology.....	17
1.4. Thesis Organization.....	17
Chapter 2: Literature Review	19
2.1. Introduction	19
2.2. The Development History of Project Scheduling.....	20
2.3. Computer-Integrated Scheduling.....	22
2.4. Summary	42
Chapter 3: System Development.....	45
3.1. Introduction	45
3.2. Project Model Development.....	47
3.3. Project Data Extraction	52
3.4. Project Activities Package’s Generation and Durations’ Calculation.....	69
3.5. Project Schedule Export	79
Chapter 4: Case Study	81
4.1. Introduction	81
4.2. Information of Tested Models	81
4.3. Validation Process	83
4.4. Discussion	101
4.5. Conclusions	103
Chapter 5: Conclusion	104
5.1. Introduction	104
5.2. Conclusion and Research Contributions	105
5.2.1 Conclusions	105
5.2.2 Research Contributions	105
5.3. Limitations	107
5.4. Recommendations for Future Work	108
References	110
Appendix	116

List of Figures

Figure 1. Methodology of research	18
Figure 2. Scheduling methods' development history	21
Figure 3. Workflow of a typical knowledge-based method	23
Figure 4. The algorithm-based method	27
Figure 5. The model-based methods	31
Figure 6. The main differences between BIM and CAD systems	36
Figure 7. System development process	46
Figure 8. Revit interface	49
Figure 9. The model used in the project development step	51
Figure 10. The GUI of Dynamo (clearer pictures can be found in the Appendix)	54
Figure 11. The first part of Dynamo nodes for columns (clearer picture provided in the Appendix)	56
Figure 12. The Dynamo nodes of the first filter in the second part of columns	58
Figure 13. The Dynamo nodes of the second filter in the second part of columns (clearer picture provided in the Appendix)	59
Figure 14. The Dynamo nodes of the second filter in the second part of doors	60
Figure 15. The Dynamo nodes of the second filter in the second part of stairs	61
Figure 16. The rest Dynamo nodes of the second part of columns	62
Figure 17. The third part Dynamo nodes of columns	64
Figure 18. The beams' specified parameters are separated by levels (clearer picture provided in the Appendix)	65
Figure 19. The generated sheet of "B.O. Footing"	74
Figure 20. The filter's operation process	76
Figure 21. The first tested building model in Revit	82
Figure 22. The second tested building model in Revit	82
Figure 23. The third tested building model	83
Figure 24. Data extraction and organization module in Dynamo (clearer picture can be found in the Appendix)	85
Figure 25. Extracted data of "B.O. Footing" level in Dynamo (clearer picture can be found in the Appendix)	86
Figure 26. Data of foundations in Dynamo (clearer picture can be found in the Appendix)	87
Figure 27. A sample view of original data transformed by Dynamo	89
Figure 28. The "Task_Table" sheet generated in the Excel	91
Figure 29. A sample of the generated schedule for "B.O. Footing" level in Excel	92
Figure 30. A sample of the generated schedule for "Level 1" in Excel	93
Figure 31. A sample of the optimized schedule generated in the MS Project	95
Figure 32. A sample of the sequential schedule generated in the MS Project	96
Figure 33. A sample of the difference between two schedules	97
Figure 34. A sample of the critical task analysis from MS Project	98
Figure 35. Form working of a floor slab in sections	102

List of Tables

Table 1. The Level of Detail (LoD) of the model (Choi et al, 2015)	50
Table 2. Summary of nodes used in the system	66
Table 3. A sample of RS Means productivity	71
Table 4. Construction order of main components	72
Table 5. Detailed construction order of reinforced concrete components	73
Table 6. A sample of the validation of data extraction and exchange processes	100
Table 7. A sample of the validation process for the generated work packages and their sequences	101

List of Equations

Equation 1. Duration's calculation for concrete components 77
Equation 2. Duration's calculation for concrete components' formwork 77
Equation 3. Duration's calculation for reinforcement 77

List of Abbreviations

ADT	Architectural Desktop
AEC	Architecture, Engineering, Construction
AI	Artificial Intelligence
API	Application Programming Interface
BIM	Building Information Modeling
CAD	Computer Aided Design
CBR	Case-Based Reasoning method
CPM	Critical Path Method
DE	Differential Evolution
DEI	Duration Estimation Interface
FCDE	Fuzzy Clustering Chaotic Differential Evolution
GA	Genetic Algorithm
GPS	Global Positioning System
GUI	Graphical User Interface
HEA	Hybrid Evolutionary Algorithm
HVAC	Heating, Ventilation, Air Conditioning
IFC	Industry Foundation Classes
LoD	Level of Detail
LSM	Linear Scheduling Algorithm Method
MD	Multiple Dimension
MRCPSP	Multi-Mode Resource-Constrained Project Scheduling Problems
ND	N-Dimensional
OBDs	Object-Based Dependencies
OSM	Object Sequencing Matrix
PERT	Programme Evaluation Review Technique
PSM	Productivity Scheduling Method
PSO	Particle Swarm Optimization

RLP	Resource Leveling Problems
SBDs	Structural-Based Dependencies
SPLIT	Structural Planning Interpretable Templates Method
TCM	Time Coupling Method
VB	Visual Basic
VBA	Visual Basic for Applications
WBS	Work Breakdown Structure
XML	Extensible Markup Language
4DRs	4D Relationships

List of Symbols

A- Area of building component

F - Productivity of producing concrete components' formwork

K- Unit weight of reinforcement

P - Productivity of the producing concrete component

R- Productivity of producing reinforcement

U- Unit transform parameters

V- Volumes

Chapter 1: Introduction

1.1. Background and Research Motivation

The importance of effective scheduling has become more evident in the last few decades due to the increasing complexity of construction projects (Bryde et al., 2013). With a realistic schedule, project participants can finish their jobs without bearing too much pressure or get too much leisure (Oraee et al., 2017). A feasible plan can assist project managers to make proper resource allocation and cost estimation (Son et al., 2017). On the whole, a schedule is of the great importance to complete a project within the expected timeline and under a reasonable cost.

Until today, some construction schedulers still use the paper-based method to schedule, which is generally considered as time-consuming and problematic. Using this method, schedulers have to do many trivial tasks, such as writing and drawing a plan or calculating the start and finish times. All of these tasks could easily result in mistakes, such as miswriting or miscalculating. Subsequently, it is possible that these mistakes cause chain effects on the entire project's schedule, which are usually difficult to discover and correct. Schedulers have to examine every content on the schedule report, which are also time-consuming. Another drawback of this method is called fragmentation, that is, a kind of barrier to share and communicate project's information with other participants. Fragmentation is usually considered as one of the main contributors to the construction project's low efficiency (Nitithamyong and Skibniewski, 2004).

Since a number of commercial software products have been developed to facilitate project scheduling, more schedulers adopt computer-based scheduling. This approach can substantially simplify the scheduling process and eliminate some of the shortcomings of the paper-based scheduling method. For instance, computer programs can prevent some small problems, such as

missing hard copies, difficult in data transfer, and miscalculations. Because computer-based methods are practical in construction planning, they have superseded the original paper-based method (Hartmann et al., 2012). Nevertheless, the computer-based methods do not address all the problems, and the scheduling practice still requires considerable manual preparations that are error-prone and time-consuming. Most of the existing software products are able to calculate the schedule and resource histograms using well-known methods, namely critical path method (CPM); however, duration of the work packages, sequences, and required resources are still determined manually. Schedulers have to spend their time on making schedules for similar and repetitive projects (Chevallier and Russell, 1998), and mistakes can still occur as a result of engineers' mistyping or improper knowledge application.

The emergence of Building Information Modelling (BIM) has improved building data modelling and data exchange among project participants. BIM is considered as one of the most promising technologies in the AEC industry, where it can be a supportive tool during the entire lifecycle of a building project, including planning, design, construction, operation, and maintenance stages (Volk et al., 2014). Other main functionalities of the BIM include object-based 3D design, simulation, and building data analysis and process (Goedert and Meadati, 2008). Based on these features, the BIM is employed in this research to connect design and planning stages of a building project and also to connect software products from other domains, where they can save, exchange, and process project planning related data.

Thanks to the BIM's multi-functionalities, an increasing number of researchers from construction domain started to explore its abilities for automated schedule generation processes (Candelario-Garrido et al., 2017). On the one hand, BIM would be able to create a link to transfer building data from the design stage to the construction stage. On the other hand, by pre-defining

the construction sequencing rules and production rate data, it is possible to make BIM automatically generate task lists and calculate their duration, thus, realizing an automatic scheduling system. This way, the accuracy of schedule would increase, since the mistakes, such as mistyping, are normally occurred during the manual process of data entry. Furthermore, the schedulers can get rid of the tedious work of generating schedules for repetitive projects.

Unfortunately, existing BIM-based systems cannot satisfy the automated scheduling processes. For one reason, it is challenging to develop an automatic system to semantically extract and process building data from BIM. For example, using image-based method to automatically capture, integrate, and exchange semantic model information with BIM still requires more efforts (Klein et al., 2012). In addition, the complexity of linking a BIM platform with other domain's software to create and export schedules has impeded related research efforts. Hence, most of these efforts still require a certain level of manual interaction and the connection between the design and construction stages has not been fully implemented (Hartmann et al., 2012).

This research project proposes an innovative BIM-based system that can automatically generate project schedule for reinforced-concrete structures. An open-source programming tool, Dynamo, is used to enable automated data extraction and processing from the building information models. Besides, BIM's advanced compatibility enabled integration of several common programming tools and a spreadsheet platform to achieve project schedules' generation.

Reinforced concrete frames are among the most popular structural systems in the AEC industry. But this class of structural systems usually has complicated construction methods and sequencing rules, and reliable documentation and sources for construction methods and productivity data can be remarkably helpful in developing and testing this prototype. In order to increase the feasibility

of the developed model and make it more realistic, both cast-in-place and precast concrete elements are utilized during the design process. More details will be discussed in Chapter 3.

1.2. Research Objectives

The main purpose of this project is to create a framework that can automatically generate project schedules for reinforced concrete buildings. It integrates the BIM, Microsoft Project, Dynamo, Microsoft Excel, and Macros and VBA, to achieve an advanced and automated data exchanging, transforming, analyzing, and transferring procedure. In this research, detailed concepts, principles, assumptions, methodologies, and experiment results are presented. In particular, during the development process, the following main objectives were pursued:

- 1) Achieving an automated process that can directly extract building information from BIM, which mainly includes the components' quantity take-offs, material, spatial information, and other important projects data.
- 2) Developing of a practical and easy-to-use data processing system in order to correctly apply construction sequencing rules for reinforced concrete buildings, therefore, improving the accuracy of generated project activities.
- 3) Enhancing the availability of the schedules by applying reliable production rates to calculate project durations, as well as, applying more comprehensive construction sequencing rules.
- 4) Developing of a feasible data exchange procedure from BIM platform to a project management software. Consequently, build a bridge that connects the project design stage with the project management stage to generate project schedules.

1.3. Research Methodology

The methodology of this framework is presented in the following flowchart (Figure 1). It consists of three main phases: 1) Build BIM model; 2) Extract, analyze, and process model data; 3) Generate building schedule. Details are presented in Chapter 3.

1.4. Thesis Organization

This thesis consists of five chapters. Chapter 1 introduces the background, main concepts, and principles of scheduling and BIM. Then, it explains research motivations and objectives of this thesis, as well as a summary of the methodology. Chapter 2 presents the literature review related to this thesis. It illuminates the development progress of the paper-based scheduling methods and the main three computer-based scheduling methods (knowledge-based, algorithm-based, and BIM-based methods). Afterwards, details of the methods used to develop this framework are described in Chapter 3. In this chapter, a system that integrates a BIM-enabled software, two programming add-on tools, and one common project schedule software is presented in detail. Chapter 4 includes a case study on three reinforced-concrete buildings and discusses the results of this case study. Chapter 5 summarizes the findings of this research, highlights its limitations, and provides recommendations for future developments.

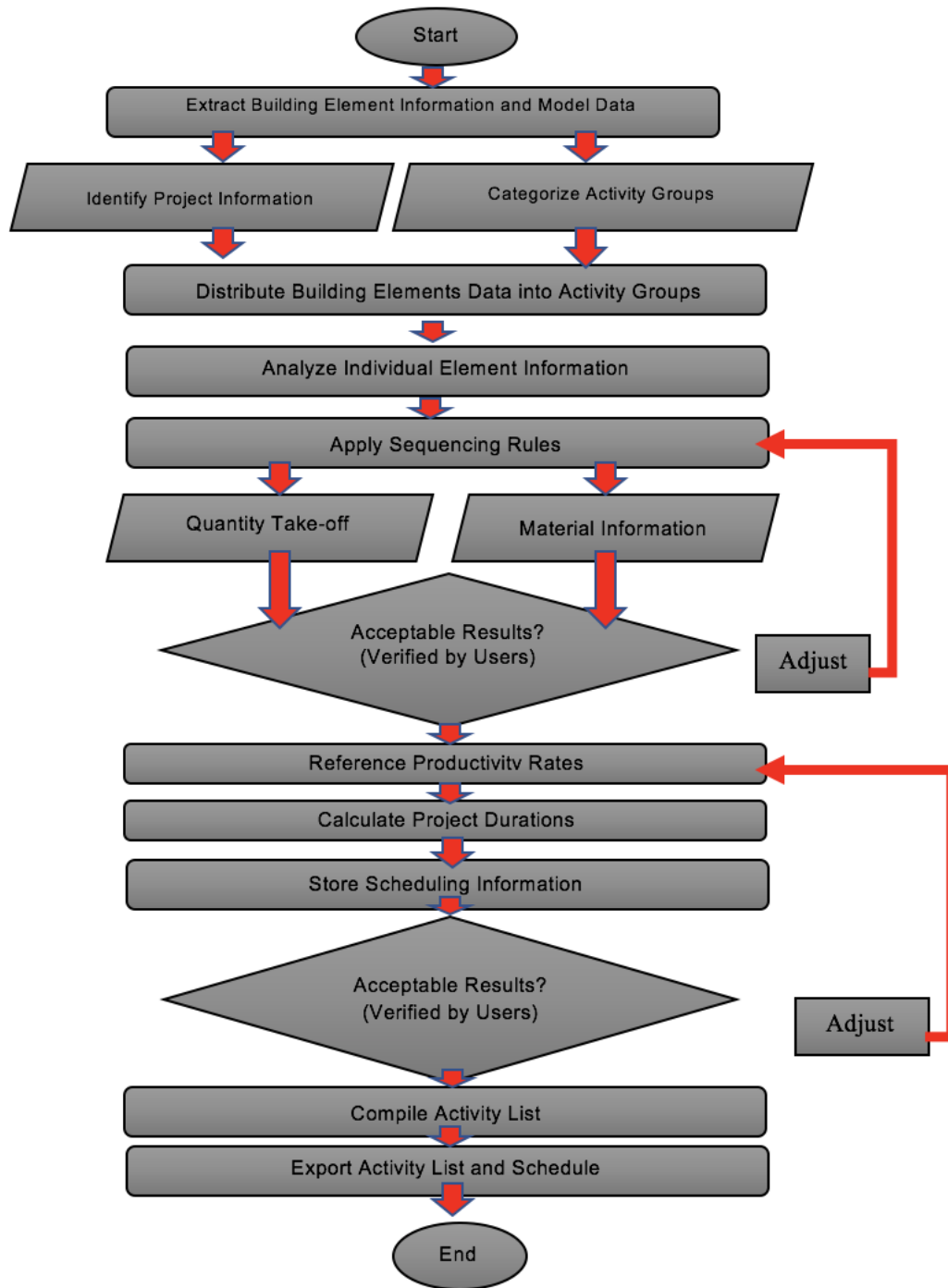


Figure 1. Methodology of research

Chapter 2: Literature Review

2.1. Introduction

Development of project scheduling techniques has a long history (Kim et al., 2013). The advancements of scheduling methods have made all project participants acknowledge the importance planning in supporting project management processes. Project schedules directly determine the start and duration of each activity and the entire project, and indirectly affect resource allocation, procurement, and the onsite spatial planning; therefore, they influence the cost of the project. Project schedulers relied on the paper-based methods to develop their plans before the appearance of computers. Subsequently, emergence of computers significantly changed the project management domain and computer-based scheduling methods took the place of paper-based methods. Among them, three approaches are noticeable: knowledge-based, algorithm-based, and model-based methods. In particular, CAD-based and BIM-based scheduling methods are the most common model-based methods and are widely adopted in the industry.

In this research project, an automated BIM-based scheduling system is designed and evaluated. BIM technology has become a dominant tool in the design, construction, and maintenance of buildings. It is widely used by various project members in different stages of the lifecycle of a building project. Because of the BIM's vast capabilities, a large number of research efforts investigate automated cost estimation, scheduling, 4D simulation (3D+Time), spatial planning, and safety assessment of building construction projects.

This literature review discusses the evolution of the construction scheduling techniques. First, it briefly introduces the development history of project scheduling techniques. Second, it defines three prevalent computer-based techniques used in scheduling generation, including knowledge-

based methods, algorithm-based methods, and model-based methods, as well as related research efforts. Besides, the studies related to BIM-based methods, including 3D BIM and 4D BIM, are emphasized in this section. At the end of this chapter, scheduling-related process, such as resource allocation and resource leveling, are briefly discussed.

2.2. The Development History of Project Scheduling

A few graphical scheduling tools emerged as early as 1912. Among them, the Bar Chart method, which is also called the Gantt Chart, was the most practical and prevalent technique (Hyatt and Weaver, 2006). Despite its simplicity, it has some drawbacks. In particular, this method heavily depends on expert judgment and it would become complicated when applied in big and complex projects. In addition, it could not display the relationships between activities. Despite these disadvantages, Gantt Chart method is still used for illustration of the schedules, but not for the calculations.

In 1957, Kelly and Walker created a fundamental scheduling method called Critical Path Method (CPM). The Programme Evaluation Review Technique (PERT) was also developed almost at the same time, and they were quickly merged into a network-based scheduling method (Hyatt and Weaver, 2006). In addition to the calculation of project duration, this network-based scheduling method was able to display the relationships between activities and predict the possibility to finish projects on time, which the original Bar Chart method failed to perform. Nowadays, both CPM and PERT methods have been utilized to develop popular project scheduling software products. Nevertheless, some researchers revealed that these methods lack sufficient flexibility to deal with alternative schedules scenarios (Qui, 2013). Therefore, more advanced and

intelligent approaches are required. Figure 2 presents a summarized timeline of the development of project scheduling methods.

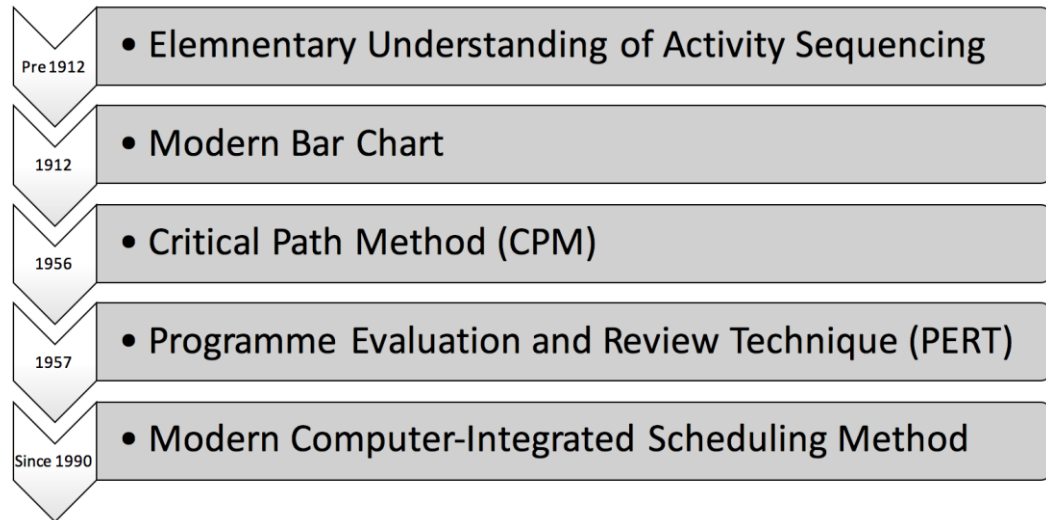


Figure 2. Scheduling methods' development history

Due to emergence of strong computing platforms, a number of computer-integrated techniques have been spawned in the AEC industry. In particular, Computer-Aided Design (CAD) and BIM are influential in the AEC industry and both of these approaches are heavily used in the design stage, but the BIM technology is able to achieve further competence in project planning, construction engineering, and maintenance (Azhar, 2011). In the construction industry, for example, BIM is capable of assisting scheduling generation, cost estimation, 4D simulation, resource allocation, spatial supervision, and other areas, therefore, many researchers are attracted to explore its potentials (Liu et al., 2015).

2.3. Computer-Integrated Scheduling

In this approach, schedulers must be familiar with the construction principles and methods to set up an achievable plan, and they need to possess the conscientiousness and patience to complete many trivial and tedious tasks. For instance, they are responsible to break down the project into manageable work packages, arrange and calculate each activity's duration, and determine the relationships among the work packages. However, with the assistance of some innovative approaches, these tedious scheduling processes can be simplified.

Most of the innovative approaches aimed at automated generation of schedules, therefore, helping users to get rid of the aforementioned trivial tasks. Among them, knowledge-based, algorithm-based, and model-based methods are adopted by the construction research community. The following subsections thoroughly discuss these three methods, which include basics of each method, relative studies, and shortcomings.

2.3.1 Knowledge-Based Scheduling Method

2.3.1.1 Introduction

The Knowledge-based schedule generation methods are developed based on the concept of sharing and using templates of past successful project to prevent the possible challenges of scheduling repetitive projects (Mikulakova et al., 2010). Although many companies regularly engage in a number of similar projects, whose activities and construction logic largely remain unchanged, only a few project schedulers record their schedules as templates for future convenience. Therefore, the recurring activities such as “casting concrete” have to be listed and analyzed every time, which can be time-consuming (Chevallier and Russell, 1998). In addition,

the knowledge-based approach allows all schedulers to communicate and exchange their scheduling knowledge and experience, in which, comprehensive learning opportunities are provided.

Knowledge-based scheduling systems are usually supported by a case-based reasoning method (CBR), which is a technique to determine similarities among several projects (Yau and Yang, 1998). It extracts critical attributes of the past cases to calculate, compare, and rank the best-matched cases based on the predefined attributes, their weights, and functions (Yau and Yang, 1998). This method can enhance estimating duration of construction tasks. Therefore, there was a substantial interest to use this method to develop knowledge-based scheduling systems. Figure 3 illustrates the workflow of a typical knowledge-based scheduling system. After users input the project's information, the system searches the most similar schedule template for the project, and then it generates the schedule based on the template of the similar project. Users can then tailor it to fit their project's conditions. At the end, the system will save and update the template in its database.

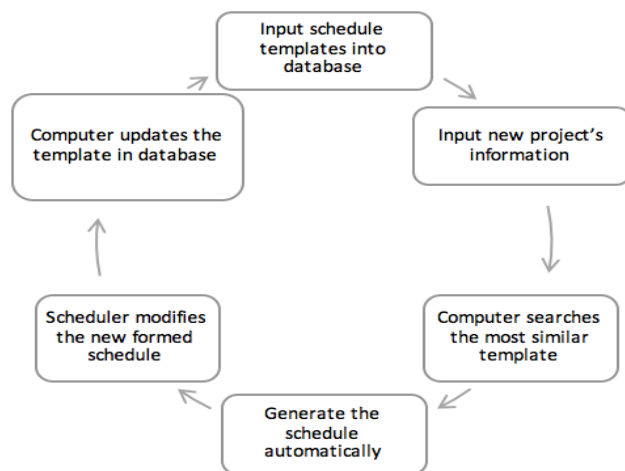


Figure 3. Workflow of a typical knowledge-based method

2.3.1.2 Related Studies

A growing number of scholars has focused on design and expansion of the knowledge-based method's capacities since 1990s. There are a variety of construction factors to be considered while scheduling, such as building components' relationships and construction regulations. To further understanding the influence of these factors, a comprehensive analysis was created (Echeverry et al., 1991). In this study, many construction constraints, including building components' physical relationships, construction trades, construction sequencing, and construction codes were categorized into three groups: flexible constraints, inflexible constraints, and time dependence constraints. A sophisticated knowledge-based system was then applied to generate schedules based on this analysis. Nevertheless, this system was only applicable for certain type of buildings. Hence, further developments were desired for determining more intricate projects.

A system was developed to demonstrate the possibility of generating project schedule based on the construction templates (Fischer and Aalami,1996). This system could determine the critical tasks of a project, arrange their sequences, and finally determine project duration. In addition, it allowed users to build up their own construction operation templates in the system's database. Increasing the number of templates in the database would enhance the chance of facing similar projects. However, this system was not able to address the need for frequent manual updating and organization of the database. This elementary system demonstrated the benefits of a knowledge-based method, though more experiments were necessitated.

Later, this knowledge-based system was combined with a CBR method to automatically generate project schedules (Mikulakova et al., 2010). There were mainly four steps in the CBR's process, including information retrieval, reuse, revise, and retain. In particular, several mathematical and information processing algorithms were applied in the reuse stage for the

filtering of similar project types, and consequently to generate schedules. Similar to the previous system, users were allowed to customize the templates' parameters or add their own. Furthermore, to evaluate the schedule's qualification, several criteria were added to the system. For instance, a fuzzy logic method of qualitative criteria could provide users with the schedules' ratings. At the end of the CBR's operation cycle, which is the retain phase, the system would automatically store the finalized schedule and project's attributes in the database for future use. This upgraded system, however, had some limitations. Firstly, it required considerable manual work where the users had to define the weight of each mathematical algorithm so that the filter in the retrieve stage could be performed. Moreover, the schedule's rating process was not transparent to the users.

Although using templates can save time, screening the similar project templates from the database is still troublesome. A novel pattern recognition system was proposed to address this problem (Sigalov and König, 2017). This system broke down schedule templates into a set of sub-schedules. The similar sub-schedules were subsequently identified and filtered out through a comparison process. In this process, a feature-based indexing system that had the capability of preselecting similar sub-schedules was designed. Finally, a matching algorithm was used for verifying the filter results. This system, however, could only work well when the detailed project information was provided. Also, researchers should ensure that the parameters are reliable, so they would not negatively affect the accuracy of the final schedule.

To improve the process of filtering project templates, a generic planning tool based on Case-based reasoning (CBR) was presented (Ryu et al., 2007). By using the CBR, which is efficient at reusing past schedules for similar future project, this system was able to assist decision-making related to construction planning. It screened the attributes of the project templates by applying similarity index associated with the weight factors, as well as ranking these similarity results. Also,

users were allowed to make modifications on the project schedule templates before generating the final results. However, this approach did not fulfill an automated process, since it required significant user intervention in the process.

2.3.1.3 Summary

Knowledge-based systems are template-based and depend on comprehensive databases for automated schedule generation. The advantages of this promising approach are summarized here. First, it greatly reduces the time that project schedulers spend on the recurring projects. Second, it improves the communication of engineers by sharing their valuable knowledge and experience. Third, it simplifies the project schedule process for project managers. This approach, however, does not fundamentally achieve a fully automated process, because it still requires manual work to customize and tailor the generated project schedules. For some projects, users might also need to calculate the attributes of projects, including the quantities of building components.

2.3.2 Algorithm-Based Scheduling Method

2.3.2.1 Introduction

Different algorithms were used to solve scheduling problems. Among these algorithms, Genetic Algorithm (GA) is the most commonly used method in the construction field. Genetic Algorithm is an advanced heuristic searching technique invented by John Holland in 1970s (Kumar et al., 2010). It is particularly useful in dynamic construction scheduling problems. In principle, this system is inspired by natural population genetics evolutions, where it chooses the best-matched solutions as chromosomes and makes them mate and crossover proportionately to produce new generations. A filter is applied to the new generations to ensure that they have a better fitness than the old ones. Afterward, the system repeats the process until it finds the optimum result. Because

of GA's core mechanism, it is usually practiced in the optimization problems, such as scheduling optimization. Furthermore, due to GA's capability of dealing with the dynamic and stochastic problems, it is also applied in the resource-constrained problems (Toklu, 2002). Figure 4 simplifies the main procedure of the algorithm-based methods.

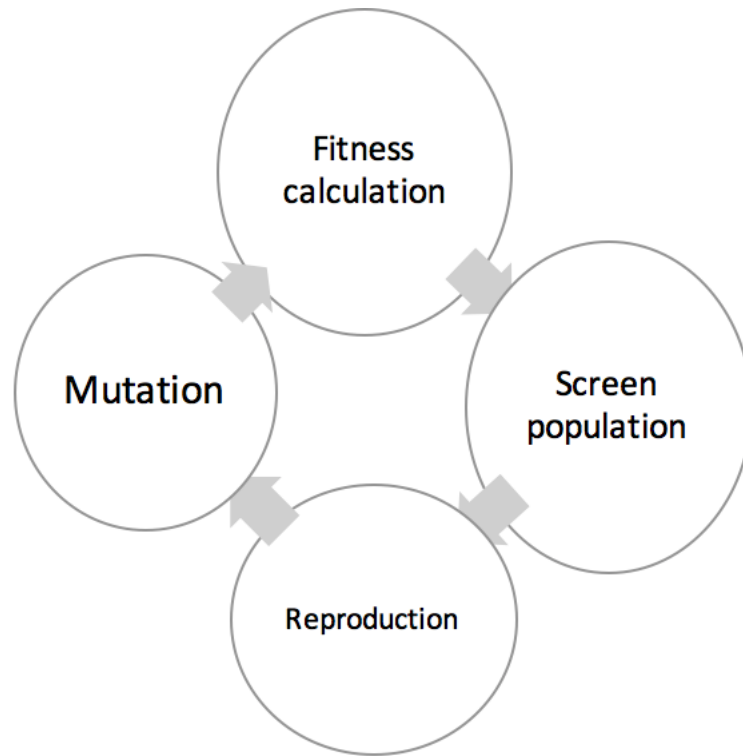


Figure 4. The algorithm-based method

2.3.2.2 Related Studies

A programming model to support project scheduling and material batch order was introduced in 2014 (Fu, 2014). A hybrid algorithm, consisting a harmony search method and a genetic algorithm, was applied to solve the multi-mode resource-constrained project scheduling problems (MRCPSP). This system was able to generate a comprehensive report of the project scheduling and material ordering plans.

Resource allocation is a fundamental part of project scheduling and there are challenges to solve resources-related problems, such as the time/cost trade-off problems, and the resource-constrained allocation problems, as well as, the unlimited resource leveling problems (Leu and Yang, 1999). As a result, many research efforts have focused on this topic.

A multi-criteria computational optimal scheduling model was created to solve such problems (Leu and Yang, 1999). It was mainly based on a genetic algorithm (GAs) stochastic searching operator. This model was able to generate an optimum plan of resource allocation and time/cost trade-off. A TOPSIS technique designed for finding the optimum solutions, based on defined conditions, was utilized to estimate the final results. However, this system could only work in small and simple projects, thus, more improvements were expected.

In addition to the GA, other algorithms were used in the scheduling generation process. For example, two heuristic algorithms were established in a system for generating schedule strategies (Li et al., 2014). One was a deterministic heuristics algorithm, which could facilitate stochastic resource leveling problems (RLP). The other one was a stochastic heuristic that could directly deal with stochastic RLP. In addition, the system utilized several pre-defined algorithms in the Visual C++ environment to help generate construction consequences. This process was supported by pre-defined activity priority regulations and deterministic formula in the system.

Overlapping tasks, referring to various activities executed simultaneously, frequently trigger problems such as resource leveling problems. Spotting such problems during project planning or project construction process could pose a challenge to project schedulers. In order to deal with these overlapping activities, a research effort investigated a system that included scheduling optimization algorithms, a risk simulation model, and a 4D CAD software (Moon et al., 2013). A

fuzzy algorithm was adopted in the process to identify and balance the required time of each activity. The system was able to evaluate the degree of overlapping risk based on the certain data, such as probability and intensity. To find the best schedule plan, the system used a schedule optimization procedure, which moved the overlapping activities back and forth in days and limited them in the range of their total float to reach the minimum overlapping level. This model had a real-time and on-time schedule changes capability, so the project managers were able to make onsite changes to the schedule, and then the system would change the original optimum schedules accordingly. Besides, managers could personally review and revise these generated schedules to check and ensure its practicality and accuracy. Nonetheless, this system did not consider the physical vicinity (spatial constraints) aspects of activities.

A fuzzy clustering chaotic differential evolution (FCDE) system was developed to solve the resource scheduling problems, in which a chaotic method was connected with a fuzzy c-means clustering method in differential evolution (DE) (Tran et al., 2016). The fuzzy c-means clustering method was a method that could categorize objects into classes based on their attributes. In addition, the differential evolution (DE) was a population-based and direct-search method, which was used to determine the optimum solution for resource scheduling. After inputting building's information and defining the number of loops required by the system to search, this DE was supported by the chaotic technique to mutate, crossover, and select the generated results. Afterward, a fuzzy clustering algorithm was utilized to track and evaluate the DE's performance. Finally, all results would be organized as a formal report for the users. This system could be upgraded by adding the function of optimizing the project cost estimation and trade-off durations.

In order to carry out an in-depth analysis of the relationships between cost and time to optimize construction schedules, a system that embraced three advanced tools was developed (Rogalska et

al., 2008). A time coupling method was used (TCM) to improve coordination between construction time and project cost under the resource constraints. Additionally, a hybrid evolutionary algorithm (HEA) was adopted to deal with the discrete optimization problems. Finally, the HEA would generate the optimum estimates and displayed them in a diagram format. However, this mathematical algorithm-based system was too complicated for end-users.

A linear planning algorithm also attracted some researchers' attention (Lucko, 2009). This Linear scheduling algorithm method (LSM) used a two-dimensional diagram: where one axis represented time and the other one showed activities, where the slope represented the task productivity. This method was able to detect activities interference and optimize their resource utilization. In order to calculate activity's productivity, a productivity scheduling method (PSM) was used. Although this system could estimate tasks' productivity and generate project schedule, users were required to have strong mathematical knowledge. Besides, this system did not take into account the aspects of activity's floats and the possibility of finishing tasks on time.

2.3.2.3 Summary

The algorithm-based methods are math-based and computer-integrated systems. They are able to handle dynamic scheduling optimization problems under resource-constrained situations. Their stochastic searching and evaluation features can tackle many complicated problems, including resource leveling, resource allocation, variable durations, and cost estimations. Significantly, they can perform better if combined with other computer-integrated methods, such as BIM or CAD-based methods. Because, the information and quantities of the building projects should be estimated and inserted to the systems manually. Thus, they are usually considered as supplement

to other scheduling methods. Nevertheless, the fact that they involve large mathematical knowledge could sometime discourage project schedulers to use this type of techniques.

2.3.3 Model-Based Methods in Automatic Schedule Generation

The emergence of the knowledge-based methods has demonstrated capabilities of the computers in the construction scheduling domain. However, as mentioned before, they have some limitations. Hence, methods were investigated to further develop computer's potential. The model-based methods, which usually refer to use model's information to accomplish some advanced functions, have been widely adopted (Faghihi et al., 2015). This type of methods allows users to analyze and process the model's data to generate schedule and 4D views. Figure 5 illustrates the simplified concept of model-based processes. After users input a digital model of the project, the computer program will perform its pre-defined functions and export the results for the user.

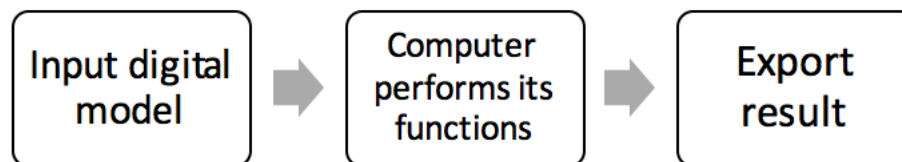


Figure 5. The model-based methods

Due to rapid development of CAD and BIM platforms, the model-based scheduling has been widespread in the modern construction practice. The fundamental function of this scheduling approach is to document construction information and generate accurate schedules and cost estimations (Fischer et al., 1994). In addition, since the emergence of 4D modeling, the model-based scheduling methods can visually simulate the entire construction process. By using BIM's

visualization and simulation abilities, the communication between all project participants can be improved, therefore, it is making the construction management processes more effective.

This section discusses some studies associated with CAD-based automated scheduling methods, including 3D CAD and 4D CAD models (3D+time). This will be followed by the correlated studies on the BIM-based scheduling methods.

2.3.3.1 CAD-Based Method

1) Introduction

CAD is a well-known designing tool, which is capable of fast and accurate model development, modification, and analysis. Furthermore, it has some advanced capabilities, such as 3D visualization of the design, basic calculations, recording building's information of components' materials, dimensions, and locations. Based to these capabilities, CAD-based scheduling methods were developed. They can arrange project activities, visualize and simulate the construction process, as well as integrate with other techniques, such as mathematical algorithms or computer programming.

2) Related Studies

A Builder system incorporated a knowledge-based planning method and a CAD-based model to generate a project schedule directly from its CAD model (Cherneff et al., 1991). This system consisted of two modules: Draw and Planner. The Draw provided CAD model with semantic knowledge and acted as an interpreter for the Planner module to translate the characteristics of CAD model. The Planner was designed by object-based programming method, in which several rules, such as work breakdown rules and precedence relationship rules, were set up. Its main functions were to calculate CPM, production rates, and schedules. Furthermore, by applying a

global CPM and a message propagating algorithm, this system could recalculate the parts where were affected by changes. This model could be improved by adding capabilities to solve resource allocation and resource leveling problems.

A CAD-based system was combined with GA method to automatically generate construction plans (De Vries and Harink, 2007). First, the attributes of building components were extracted from the project's 3D CAD model. Second, the algorithm categorized the relationships of components into three groups: the only horizontal adjacent, the only vertical intersects, or the both vertical and horizontal relationships, and recorded the results into a log file. A planning program, the MS Project, was used to import this log file to build up a planning scheme, in which the tasks of scheduling and resources allocation were completed accordingly. Finally, the Visual Basic for Applications (VBA) of AutoCAD was programmed to enable the system automatically calculates the project durations. This system demonstrated the feasibility of automated project duration's computation, as well as, the feasibility of combining CAD with algorithms.

A system that could produce schedules, quantity takeoffs, resource usage, and 4D visualization model was created (Kataoka, 2008). This system applied a structural planning interpretable templates method (SPLIT), which acted as an interpreter to recognize each model's construction method. It could analyze and transform project model's components, activities, construction methods, and activities sequences to calculate the duration of each activity and enable the 4D building simulation. This system was verified that it would take three hours to process a regular midsize building model and present the final results in a project management software, such as MS Project. Nonetheless, it used the longest estimated duration for each activity's standard duration, which may be inaccurate.

A novel method to automate schedule generation for bridge construction projects was presented (Wu et al., 2010). It considered available resource allocation and the interrelationships between tasks by using a constraint-based simulation (Monte-Carlo analysis) software. This approach allowed schedulers to use 3D model and input necessary data to assign construction patterns, consequently, generating activity packages with available resources. At the end, the results would be exported into an XML file for further analysis in other software products, such as MS Project.

A system that incorporated a 4D CAD-based method and the Line of Balance method was developed to address scheduling problems (Jongeling and Olofsson, 2007). The Line of Balance method could categorize project tasks based on the physical relationships of building elements. It was also functional in transforming the project plan into more understandable diagrams.

The model's data was initially obtained from an AutoCAD Architectural Desktop (ADT) software and exported into Microsoft Excel in order to identify building components' locations, and calculate project's cost and resources. The Line of Balance method was then exercised to determine activities and optimize resources plans. This system was able to help project managers check the accuracy of the project plan and detect resource allocation problems.

A 4D CAD system was presented to assist onsite construction management, cost estimation, and resource utilization (Chau et al., 2004). In this system, the AutoCAD, Microsoft Project, Microsoft OLAP, and C++ programming tool were utilized. It could update the data as soon as users made modifications to the original model, and also could generate or adjust the project schedules according to the users' requirements.

3) Summary

Although CAD was originally created to facilitate design processes, its capabilities were extended to many other fields, such as project planning and simulation. It can help project

engineers spend less time to make a reliable project plan and improve communication efficiency for all project participants. As scholars' study deeper, more advanced ideas have emerged. For example, a number of studies investigated the N-dimensional (ND) CAD-based methods. In these studies, a model-based method is usually practiced in the resource allocation, cost estimation, or dynamic scheduling generation. Compared to BIM-based systems, however, CAD-based methods have some drawbacks. Firstly, they have less functionalities than BIM, because building elements are not modeled as objects with attributes. Besides, they lack interoperability. Many CAD platforms cannot communicate with each other, which is troublesome while exchanging data among project participants.

2.3.3.2 BIM Scheduling

1) Introduction

Comparing to CAD, BIM platforms include data-rich and object-oriented models with more intelligent functions, such as quantity take-offs, cost calculation, clash detection, and energy analysis. Moreover, BIM platforms could have extended capabilities through connecting with other software or by using add-in tools. Figure 6 shows the main differences between BIM and CAD.

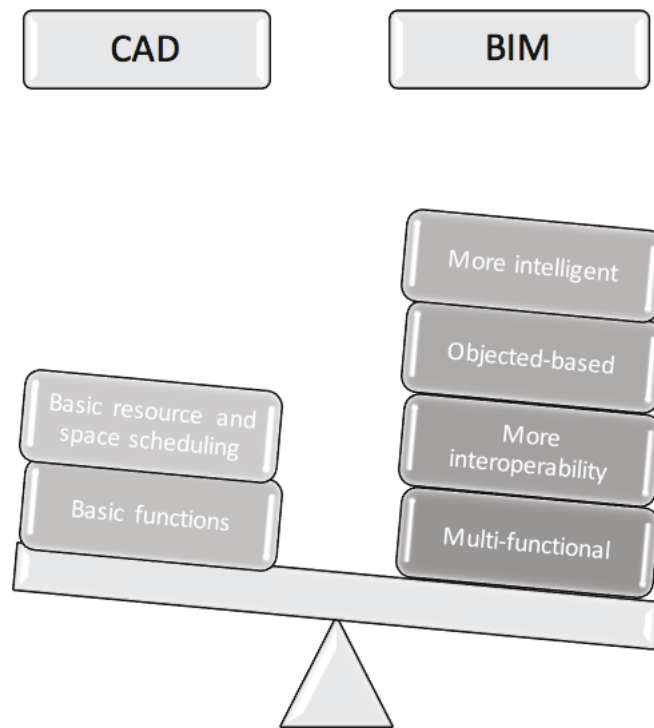


Figure 6. The main differences between BIM and CAD systems

Under this trend, all stages of a building lifecycle are more integrated and transparent. Project participants can attain or alter building model's parameters through BIM, since the building information are shared and can be quickly updated on a BIM platform. In terms of the BIM-based automated scheduling method, many applications were created. Some researchers have adopted computer programming method, others have tried to combine BIM with the algorithm-based method. More details are discussed in the following content.

2) Related Studies

A BIM-based framework for automated construction scheduling was generated (Kim et al., 2013). This system was able to create construction tasks based on sequencing rules, calculate activity durations by using activity production rates, and eventually producing a schedule. A model was built in Revit and exported into IFCXML format. After parsing this IFCXML data by using

IfcRelContainedInSpatialStructure system, all elements were categorized based on their spatial information. These grouped data were then converted into ID codes and applied production rate calculations. Finally, Microsoft Project was utilized for outputting the activity list, and displaying Gantt chart and critical path. However, this framework currently only considers the limited scale and complexity of building projects, more complicated cases are needed in order to test its feasibility.

A BIM-based system that could automatically create an onsite schedule for pre-fabricated construction was created (Liu et al., 2014). The pre-fabricated construction included manufacturing of building components in factories and then assembling them in the construction site. In this study, the Microsoft Access was utilized to extract BIM model data, in which the parameters of resource constraints and resources productivities were stored. With the help of Revit's Application Programming Interface (API), this system could arrange task orders based on building's structures. Consequently, the schedules and resource allocation reports of pre-fabricated buildings were generated. Nevertheless, the parameters of resources productivity in this system were set based on engineers' experience, which somehow might not be accurate.

There was a more complex model that used a combination of BIM and an algorithm-based method. This model not only generated an optimum schedule for the panelized construction, but also supported limited resource's allocation (Liu et al., 2015). Revit, MS Access, Work Breakdown Structure (WBS), Symphony simulation software, and an evolutionary algorithm were used in the development of this model. Firstly, the WBS was analyzed in MS Access to extract project data, such as the location of each pre-fabricated component. Secondly, a Particle Swarm Optimization (PSO) algorithm combined with a GA method was adopted to identify and prioritize the resource constraints in the simulation model. In the third step, the Symphony model was integrated with

Revit to recognize the constraints' priority values in order to search for the best project schedule. At last, the results were transformed to both an XML file and MS project file. Within this procedure, some shortcomings were noticed. Above all, this system was limited to the panelized construction method. Also, it required a large number of manual inputs. For example, the users had to manually set their projects' construction consequence during the simulation, which increased the complexity and time.

An innovative Multiple Dimension (MD) CAD model in AutoCAD Architectural Desktop (ADT) environment was developed to strengthen the BIM model's capability in project management (Feng et al., 2010). This MD CAD model was served as a database, where building's geometric elements, construction statistics, and control hierarchy were identified and saved. It was linked with an object sequencing matrix (OSM) and genetic algorithms (GAs) to output an optimum construction plan for project duration and cost. An evolutionary system was adopted to facilitate the optimum plan screening process. Though this MD CAD model could generate reports for cash flow, resources and cost estimation, and earned value analysis, it did not pay sufficient attention to resource productivity.

A BIM-based system combined with a supplemented algorithm was designed to read the project's data and build up a corresponding matrix in order to produce a practical project schedule (Wang and Song, 2015). Within the matrix, each row stood for each element, while each column meant the time unit or each activity's duration. Therefore, the matrix embodied the overall project's tasks and duration.

Similar to 4D CAD model, 4D BIM is known as adept in the visualized simulation. But 4D CAD has some shortcomings when it comes to the data interchange aspect. There are problems in data updating and data transferring between project's different life stages while using CAD-based

methods. For example, engineers have difficulties to make modifications on the models after design stage, because they might have to re-evaluate and re-adjust all the relevant models' data. Similarly, project engineers are required to produce practical schedule before construction starts, but this is a challenging task. As a consequence, 4D CAD models are only used as a static description, which hindered the functionality of 4D CAD's simulation (Dang and Bargstädt, 2015). In contrast, 4D BIM has superior capabilities in data updating during the building's lifecycle, thus, some researchers explored BIM's capability in automated scheduling simulation by performing data exchange between project's design and construction stages.

A prototype that could update project schedules based on model's 4D Relationships (4DRs) was presented (Dang and Bargstädt, 2015). Two basic relationships based on activity scheduling were defined: the technical requirement, and the nontechnical issues. The 4DRs mainly focused on the technical requirements. For instance, in this system, the beginning of concrete slabs' construction would correspond to the finish of concrete columns or beams' construction, rather than resources usage, which belonged to nontechnical issues. Two kinds of dependency relationships were also defined: object-based dependencies (OBDs) and structural-based dependencies (SBDs). An add-in program with the aforementioned pre-defined functions was then designed in C# language and applied in Revit. By testing this prototype on a simple project, it was able to update the schedule automatically.

A BIM-based interface system that supported site-level operations' simulation and project schedule generation was developed (Wang et al., 2014). This system was competent to collect, save, and transfer data among various software, and solve dynamic resource allocation problems. It would create a suitable construction plan and link it to a 4D model simulation method. In this system, a BIM model and a duration estimation interface (DEI) module were designed to support

the project schedules' generation and 4D simulation. Although it was able to automatically generate site level schedule and proper resources allocation plans, it had some limitations. Firstly, it could only operate in reinforced concrete structure, secondly, it did not achieve full automatic simulation. For one thing, it could not generate 4D simulation file and import it into 4D software automatically. Plus, users had to manually input data while executing DEI system.

The 4D BIM can also facilitate solving on-site project scheduling problems. A BIM-based framework to develop optimal project schedule was put forward (Chen et al., 2013). In this system, a BIM database, a scheduling simulation system, as well as a multi-dimensional (MD) CAD model creator was utilized. The generated MD CAD model was able to monitor and manage activities, resources usage, and cost.

A few researchers broadened 4D BIM potentials in some studies, including site layout planning and space management. Site layout planning includes on-site spatial management of temporary facilities, materials, and equipment. Sometimes, this can be an intractable task to project managers due to the difficulty of updating changeable information during construction. A dynamic model that utilized 3D and 4D BIM, an automatic rule checking algorithm, and Industry Foundation Classes (IFC) was presented to support site layout's planning under resources-constrained situations (Schwabe et al., 2016). It embraced a rule-based algorithm to interpret construction rules into computer language, a simulation process of project's installation, operation, and dismantling in order to generate onsite layout, and ultimately generate a 4D BIM-based system to assist onsite spatial arrangement.

Space interference is regarded as an obstacle in project management processes. For example, it can trigger schedule overlaps, which might decrease the whole project's productivity, and can also result in resource shortage problems and cause additional cost. A system that could both detect the

degree of spatial overlapping and suggest an optimum solution of project scheduling was developed (Moon et al., 2014). The space interferences were grouped into two types: full overlapping and partial conflicts. Critical Path Method (CPM) based schedule templates were inserted into a customized algorithm to determine the level of overlapping based on the schedule overlap ratio, workspace adjacency, and schedule-workspace interference. Another location constraint-based genetic algorithm was designed especially for the activities that did not have a CPM format. These algorithms were then combined with a roulette wheel selection operator to find the spatial overlapping results.

Safety detection is an important part of the construction processes, since it affects well-being of all construction team members. A new BIM-based system was designed to check the safety of project's construction plan, which was based on several official regulations (Zhang et al., 2013). This system included four stages: interpret rules into a programming language, provide model attributes for the system, compare the rules with the model data, report danger information and offer possible solutions to the users. This system was also equipped with fall protection assessment, which was a common danger in the construction field. This model was able to automatically detect potential hazards of the project's schedule and construction methods, therefore, ensure workers' safety, and indirectly saving time and cost for the whole project.

3) Summary

BIM's appearance has led all project participants into a new world, where it is equipped with automatic and intelligent capabilities. For one thing, it is a parametric modelling system, which allows every building component has its specific attributes. When building's elements are changed, BIM automatically makes corresponding modifications on relevant elements. Consequently, it enables easy data changing, data updating, and data integrating processes. BIM provides a more

transparent and transferable information platform through project lifecycle, in which the communication of all project participants has improved. These capacities have promoted people's work efficiency in the AEC industries. In addition, BIM is compatible with other domains' software or add-ins. BIM platforms also have a number of advanced functions, such as calculating project's quantity take-offs and cost estimation, as well as, performing energy analysis and simulation.

Despite these advantages, the BIM's capability in schedule generation area is far from reaching its full potentials. The data transferring process within the BIM platforms still remains problematic. There is no systematic framework for the project engineers to apply BIM technology in solving resource leveling and dynamic cost estimation problems. Furthermore, there is a necessity of finding a way to sufficiently utilize 4D BIM. By integrating 3D BIM with 4D BIM, it is possible to estimate the feasibility of project's schedule, generate budget distribution plan and resource allocation plan before the real construction starts. The 4D BIM can also be used to support the automated schedule generation process rather than just a visual simulation tool. Therefore, more forward-thinking studies of BIM technology should be done.

The mentioned drawbacks of BIM will be partially addressed in this thesis. This research effort provides a comprehensive BIM-based system that achieves an automated schedule generation process. It focuses on the data exchanging between a number of software products from different domains. More details are discussed in chapter 3.

2.4. Summary

This chapter primarily discusses computer-integrated methods used to automate schedule generation. At the start, it briefly introduces the development history of scheduling methods. Three

computer-integrated scheduling methods are presented, including knowledge-based, algorithm-based, and model-based methods. Each class of methods is explained by its introduction, correlated studies, and limitations. In particular, this chapter discusses the BIM-based methods in detail. Some scheduling related areas, such as onsite spatial management, are also described in this chapter.

Knowledge-based methods are operated by screening and adopting similar project schedule templates from a database, and consequently, generating a feasible project schedule. This method is able to reduce the time of rescheduling similar projects. Usually, a CBR system is embedded in this method to support templates selection process.

The algorithm-based methods are capable of math-based searching methods, which are skilled at finding optimum results for dynamically resource-constrained scheduling problems. The algorithm-based methods work as supplement of another scheduling methods. The knowledge-based methods sometimes can be error-prone, especially when the templates search tool is not well-designed. On the other hand, the mathematical algorithms applied in the algorithm-based methods are too complicated for the end-users. Thus, many engineers prefer to adopt model-based scheduling methods, which include one of these technologies: the CAD-based and the BIM-based methods. Both of them can simplify the design, visualization, and simulation processes. However, BIM's parametric modelling has much more capabilities than CAD, such as object-oriented modelling, quantity take-offs, clash detection, and energy analysis.

In summary, BIM technology has changed the traditional approaches that engineers used in project planning. In terms of the automatic scheduling generation, BIM owns several innovative capacities, which can be functional in this field. For example, the Application Program Interface (API) enables schedulers to program BIM to perform some extensive tasks. Despite the recent

advances, there are a number of areas that should be improved. First, the relationships of 3D BIM and 4D BIM can be further enhanced. Second, there is a need to improve BIM data's transparency and transferability. Correspondingly, the system presented in this paper is designed to deal with some of these limitations. More details are presented in the following chapter.

Chapter 3: System Development

3.1. Introduction

This chapter presents the methods used to develop a prototype system to automatically generate a schedule for reinforced concrete buildings using their building information model, construction sequencing rules, and a construction productivity database. In order to achieve this goal, the prototype focuses on three aspects: data extraction, data processing, and data exchange. The development process of this prototype is divided into these steps: 1) Project Model Development, 2) Project Data Extraction, 3) Project Durations Calculation, 4) Project Schedule Export. Figure 7 summarizes the entire system development process.

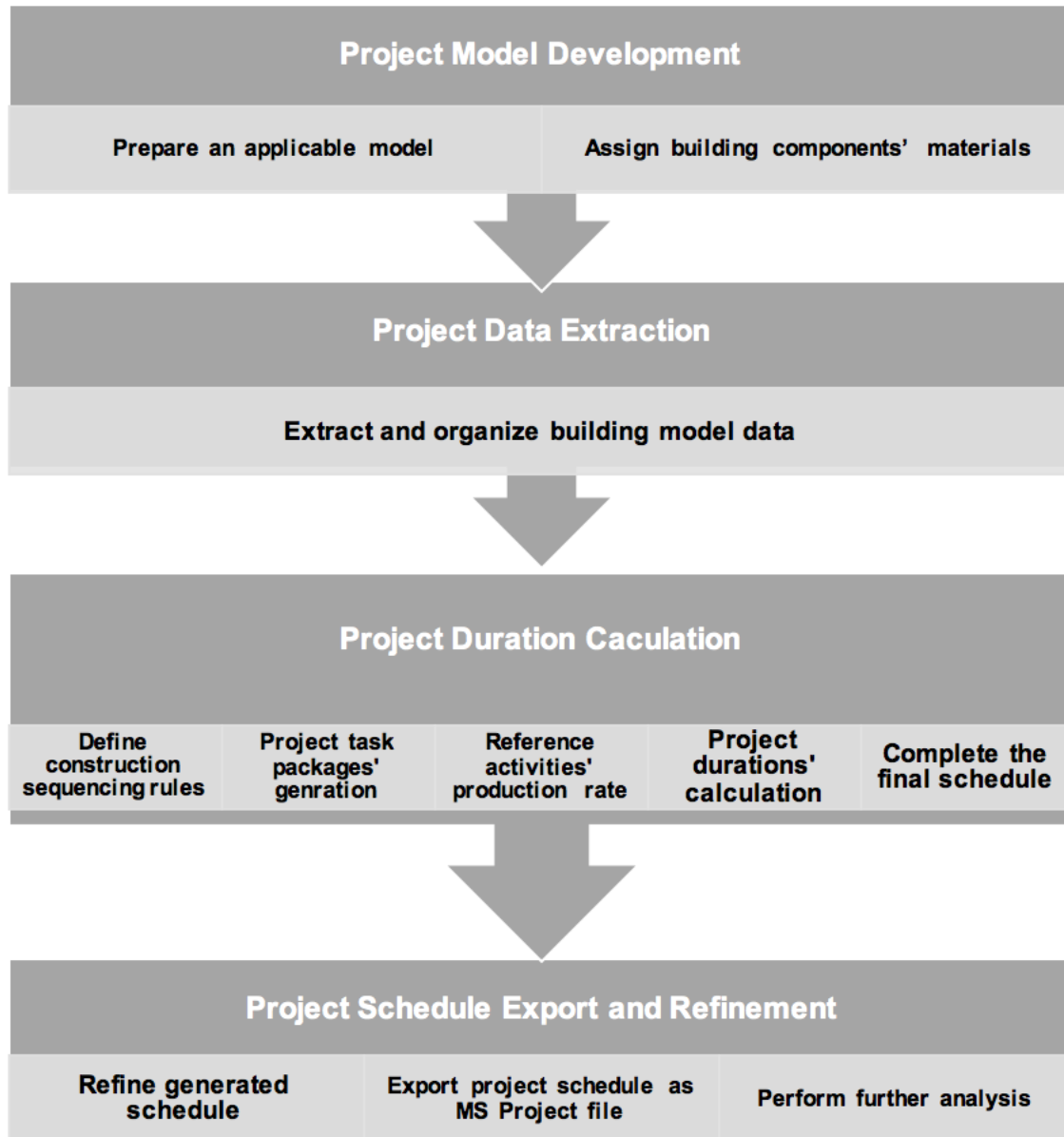


Figure 7. System development process

In this procedure, reinforced-concrete buildings should be modeled with their main building elements in a BIM platform. Subsequently, the building element's data, such as family type, spatial information, assigned material, and geometric information, are extracted by a script developed in Dynamo environment. Dynamo is an open-source graphical programming environment that works together with Revit as an add-in tool (Dynamo, 2018). It is able to extract the targeted data and

group them into different classes according to the components' attributes, and construction sequencing rules. Then the grouped data could be exported to a data processing platform, namely spreadsheet, for further processing.

A combination of Macros and Visual Basic for Applications (VBA), which is a common programming add-in system of Excel, was used to support Excel automatically generate the project schedule. In the last stage, this system transforms project schedules into the Microsoft Project's format, therefore, users can further process the project schedule, such as calculations of early start or finish, total and free floats, identifying the critical path, generating Gantt Chart, and other processes.

The project durations are computed based on an industry-recognized productivity database, called RSMeans, that is, a comprehensive construction cost and productivity provider (RSMeans, 2018). The proposed system is currently limited to Revit platform, but the same architecture can be implemented on other BIM-enabled platforms. In order to ensure the accuracy and feasibility of generated schedule, users are able to check and change the parameters set in this system based on their project conditions.

The whole development process of the framework is described in this chapter. It explains the methods and systems that adopted in each step, including their concepts, functions, and purposes. More details are described in the following subsections.

3.2. Project Model Development

3.2.1 Introduction

Development of the project model in the BIM platform is the first step of creating an automated scheduling framework. Because of the widely application of CAD and BIM in building design

field, the project models can be directly obtained from such software. A building model, that has detailed building elements, is essential to develop and verify the system's capabilities. For example, it can provide sufficient information for the system to not only generate a feasible project schedule, but also to support developers test the system's capacity by comparing with real projects' schedules, consequently, identifying and eliminating this framework's problems to make it more applicable.

3.2.2 Revit

Autodesk Revit, a popular BIM-enabled software product (by Autodesk Company), was used in this step. The Revit platform is able to assist design, drawing, quantity take-off, and documenting projects' data, such as project quantities, project structures, and mechanical and electrical systems. It is capable of identifying interface conflicts, making corrections and modifications, and checking the conformance of the designed building with building codes and regulations.

In addition to these functions, Revit is a parametric modelling software, which can automatically coordinate the changes made on the model and maintain building components' consistency. Engineers do not need to update drawings or connections when changes are applied in a certain model view, drawing sheet, section, or plan. Revit will determine what items are affected by the changes and will apply that change to the affected elements (Revit users' guide, 2011). For example, outside of a door frame is fixed on a perpendicular partition. If the partition is moved, the door will retain this relationship to the partition (e.g. will be moved/modified accordingly).

Revit is also compatible with some external software or add-in tools, such as Macros, and Application Programming Interface (API). This capability allows users to exchange building data

between Revit and some external software products. By integrating with computer programming, external tool can modify model's parameters, create or delete elements, and apply other modification.

Many of Revit's capabilities are useful in designing an automated scheduling process, which makes Revit a suitable BIM platform for this step. The Revit interface is displayed in Figure 8.

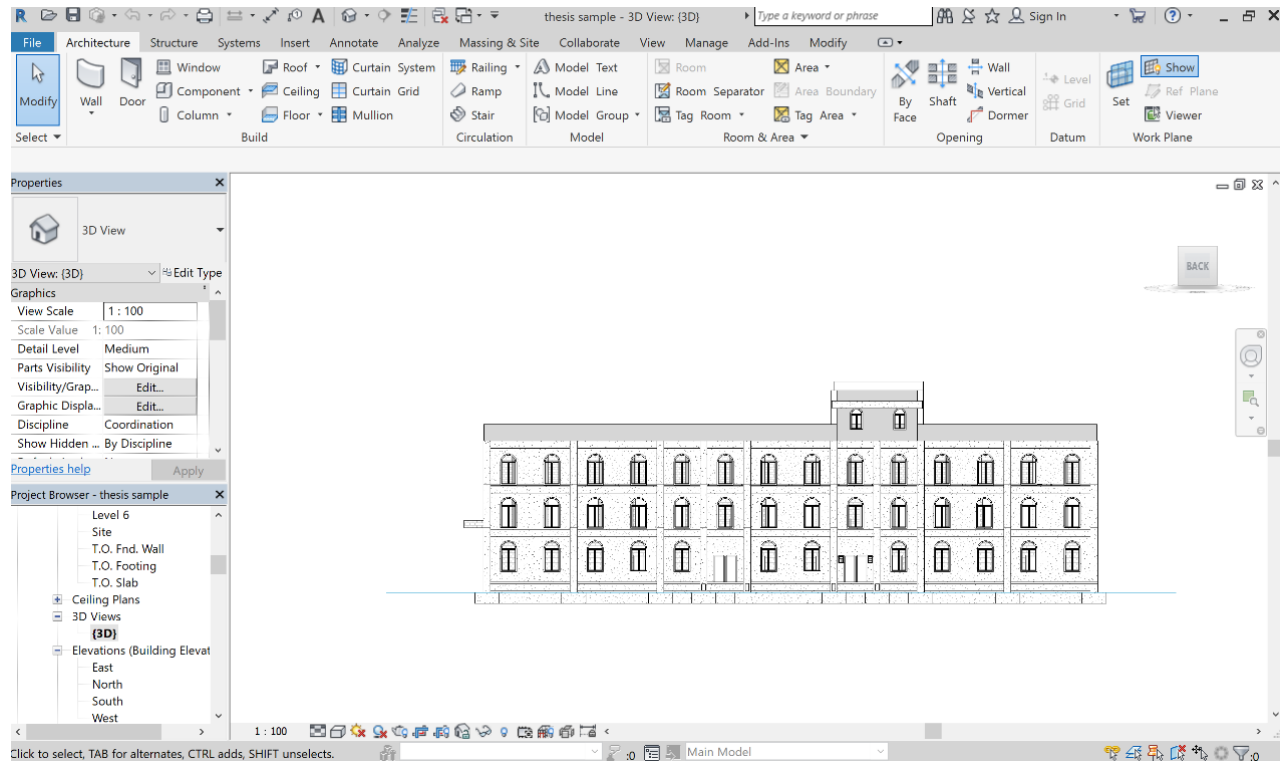


Figure 8. Revit interface

3.2.3 Prepare Building Model

With the use of Revit, a building model was developed for the case study. The Level of Detail (LoD) of the model directly affects the outcome of the process (Choi et al., 2015). The LoD of the model indicates the scope and purpose of different phases of building project and depends on the user requirement.

Table 1 shows different LoD classes, and the LoD3 is needed for an effective schedule generation.

Table 1. The Level of Detail (LoD) of the model (Choi et al, 2015)

	AIA document E202: building information modeling protocol display	BIM standards and production technology	Singapore BIM guide
LoD1 (conceptual design)	Non-geometric or line work, areas, dimensions, etc.		Building mass analysis dimensions, area, volumes, and spatial data
LoD2 (schematic design)	3D basic elements	Rough dimensions, figure, quantity, and spatial data	<ul style="list-style-type: none"> • Non-geometric characteristics, • Approximate dimensions, figure, and spatial data
LoD3 (detailed design)	3D object-based elements' geometry dimensions, capabilities, and links	Dimensions, figure, spatial data, quantity identified components, and facilities	<ul style="list-style-type: none"> • Exact dimension, figure, spatial information, and quantity • Non-geometric characteristics
LoD4 (construction)	Procurement data manufacture, and delivery	Modeling to assembly information: material, figure, color, etc.	Completed fabrication and assembly information
LoD5 (O & M)	As-built model	<ul style="list-style-type: none"> • Finished production and assembly information • Review material, dimensions, etc. 	Renew the modified data

The models used in this research are reinforced concrete-framed buildings with main structural and architectural elements, including foundations, columns, beams, floors, exterior walls, interior walls, doors, windows, and stairs. Figure 9 presents a building model designed in this step.



Figure 9. The model used in the project development step

3.2.4 Assign Building Components' Attributes

This step is carried out during the developing of the model, as the user can select/modify the details of building elements while they are using them in the model. This step is important because the name of the components and their family type and materials will later be used by the system to create work packages of the project. In addition, system uses these attributes to identify a proper activity productivity rate from the RSMeans database.

In order to assess the capability of the system to process complex building models, different materials are assigned to the model's components. Various material types were assigned to the structural elements, such as cast-in-place concrete and precast concrete.

3.2.5 Conclusion

Since the system extracts required data from the BIM model, a certain LoD is essential to generate a reliable schedule. The models that are mainly developed for visualization of the concept (LoD1 and LoD2) do not include the information that are required for subsequent processes.

3.3. Project Data Extraction

3.3.1 Introduction

Once the model is developed and the main attributes are assigned to the elements, the system would be able to extract project data to calculate project's construction schedule. This step is proposed to extract data from the BIM platform and exchange data with the software from other domains. Since the existing BIM platforms are not able to directly generate and transfer project schedule spreadsheets into a project management software, such as MS Project, other tools were used to create this link.

The objected-oriented, parametric, documentation, and interoperability characteristics of Revit enable the access to each building components' attributes and process them into useful information. The information, such as components' family types, spatial data, quantities, geometric data, and material, are required to create project work-packages, determine sequences, and to calculate the duration of projects' activities

3.3.2 Dynamo

The process of data access, extraction, and transformation from BIM can be challenging. In order to achieve it in a systematic and generic way, which is applicable to different building models, Dynamo, a novel graphical programming tool, was adopted.

Dynamo is an open-source graphical programming environment for building information modelling. It can work as a plug-in application for data management and data exchange. Users can access Dynamo directly through Revit graphical user interface (GUI) and develop their own programs based on their requirements. The Dynamo script is saved separately to the original BIM

file; therefore, the dynamo script could be applied to process other building models (Dynamo Guideline, 2017).

Furthermore, Dynamo has the ability to connect BIM with other software, such as Microsoft Excel. The data that stored in the building information model can be transferred to Microsoft Excel for further processing through Dynamo. Unlike other programming tools, such as Visual Studio, Dynamo allows users to insert and organize their codes using graphical nodes, which is helpful to people who are new to computer programming. It contains a large number of predefined nodes, which some were created by Dynamo developers and some by its community members, and users can simply drag them into the main interface and integrate them with their algorithm. Moreover, the users can create their customized nodes, using direct programming such as Python, and utilize within their main script.

Dynamo is utilized in this system to extract and organize data directly from the BIM, which then exports the processed data into MS Excel for generating project's work packages and durations. Figure 10 illustrates the graphical user interface (GUI) of Dynamo.

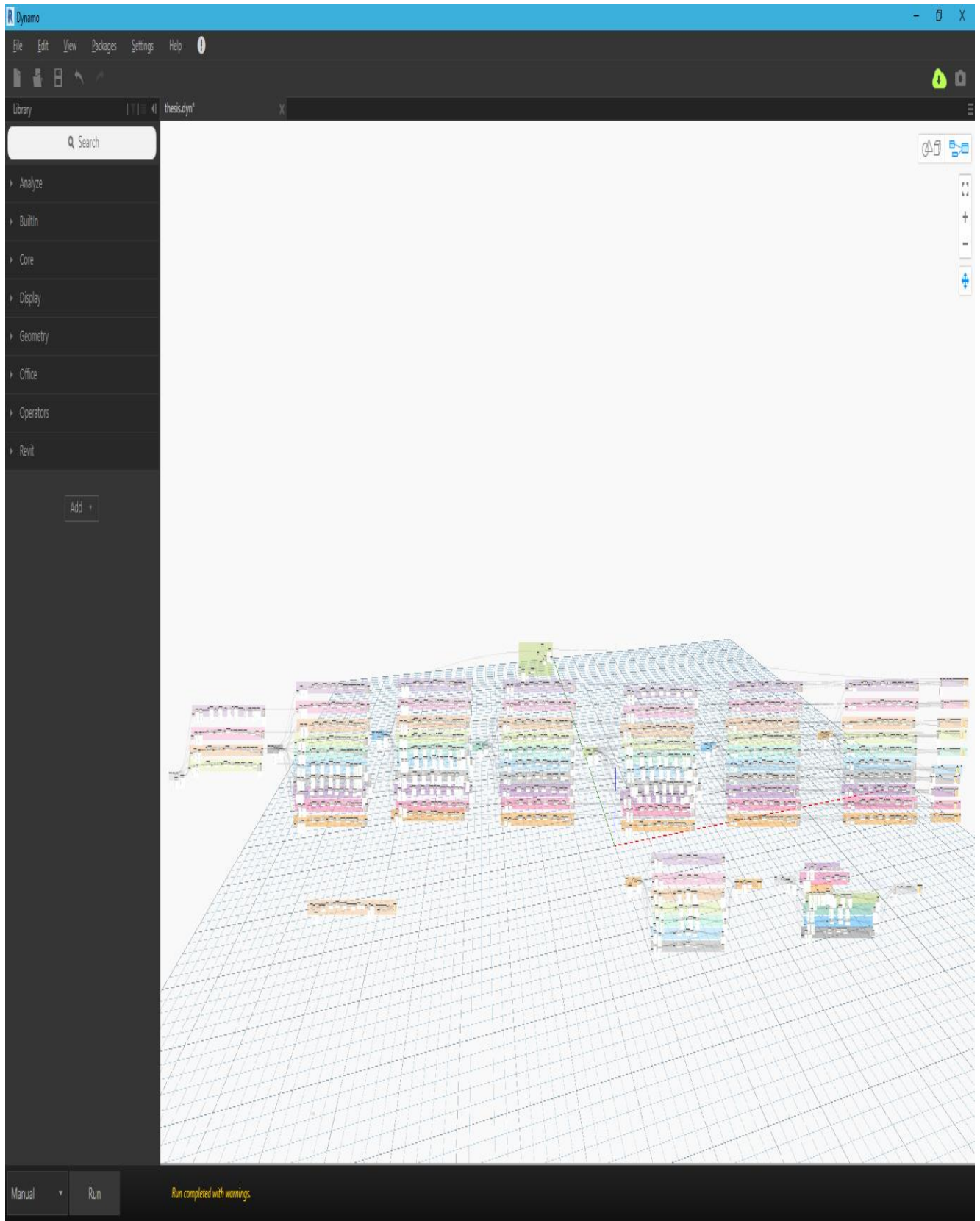


Figure 10. The GUI of Dynamo (clearer pictures can be found in the Appendix)

3.3.4 Extract Building Data from Revit

To extract the building data through Dynamo, related function nodes should be selected and properly connected. In this approach, target nodes are dragged into the main interface to obtain the attributes of the building elements from all levels, including the nodes of “Categories”, “All Elements of Category”, “Element. Parameters”, “Element.GetParameterValueByName”, and “Code Block “embedded with the “levels”. After linking these nodes, the parameters of each component’s class, such as beam, column, can be selected and displayed under the Watch node. Figure 11 displays a sample chain of nodes designed to extract the information of structural columns based on building levels. After selecting structural columns in the “Categories” node and linking it with the node of “All Elements of Category”, the algorithm will select all the structural columns in the model. By connecting these two nodes with “Element.GetParameterValueByName” node through the “Code Block” of “Levels”, information of all columns is obtained and organized by their levels.

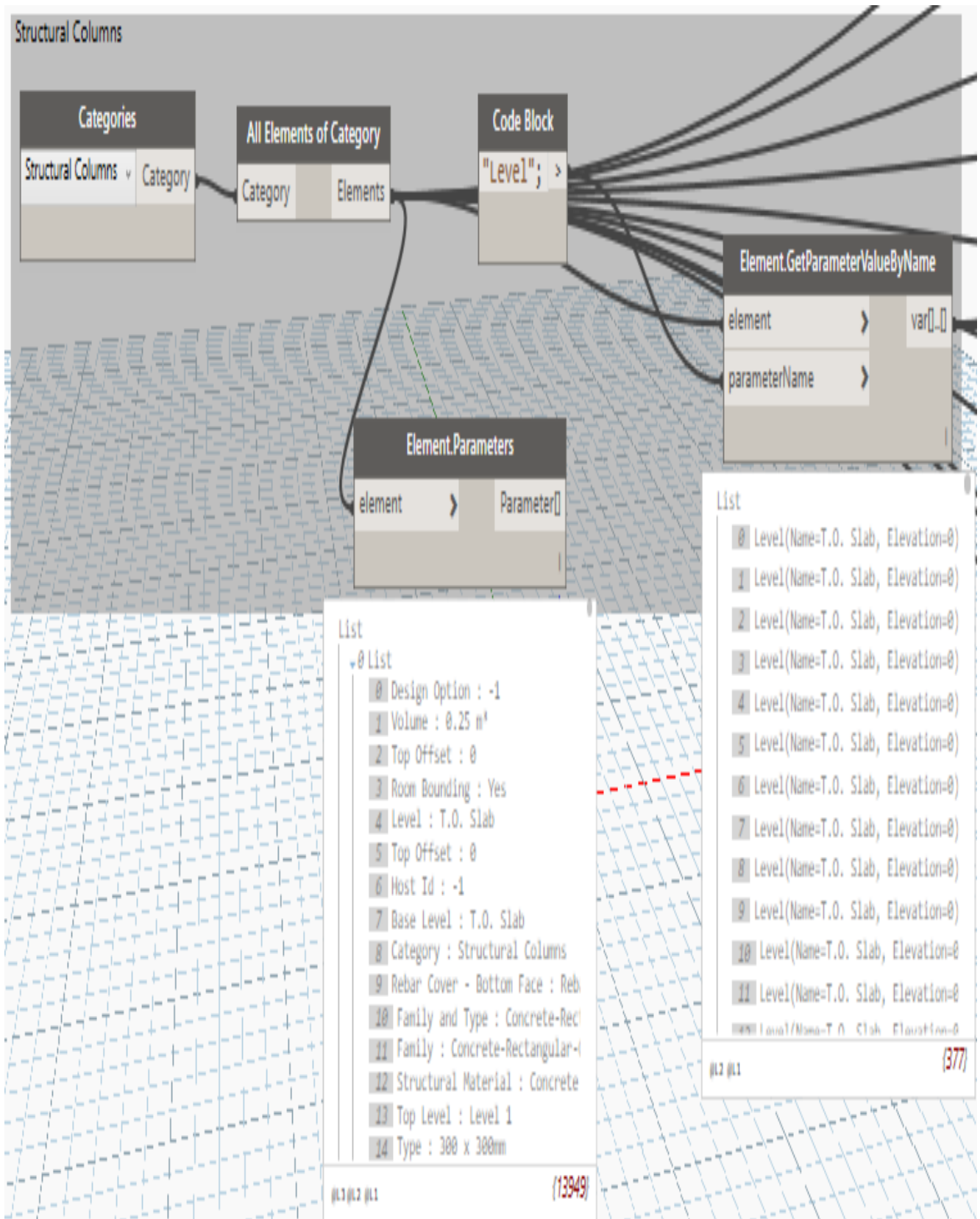


Figure 11. The first part of Dynamo nodes for columns (clearer picture provided in the Appendix)

To generate a project schedule, several parameters are required, such as the project components' volumes, assigned material types, elements' spatial data, categories, areas, and reinforcement volumes. The elements' areas and reinforcement volumes are required for generating the durations of concrete form-working and reinforcements, respectively. The components' volumes and areas are used to compute the durations of elements' concrete casting. Moreover, elements' spatial data (i.e. location), categories, and assigned material types are applied to sort the project activities, as well as identifying elements' production rate.

In the second part, a number of nodes are integrated to extract these parameters' values and group them by levels, where the nodes of "Levels", "Equals", "List.FilterByBoolMask", "Code Block", "GetParameterValueByName", "Material. Name", "List. Create", "List. Combine" are utilized. The nodes of "Levels", "Equals", and "List.FilterByBoolMask" constitute the first filter to divide the elements into specific levels. Figure 12 presents the nodes in the first filter of the second part for columns.

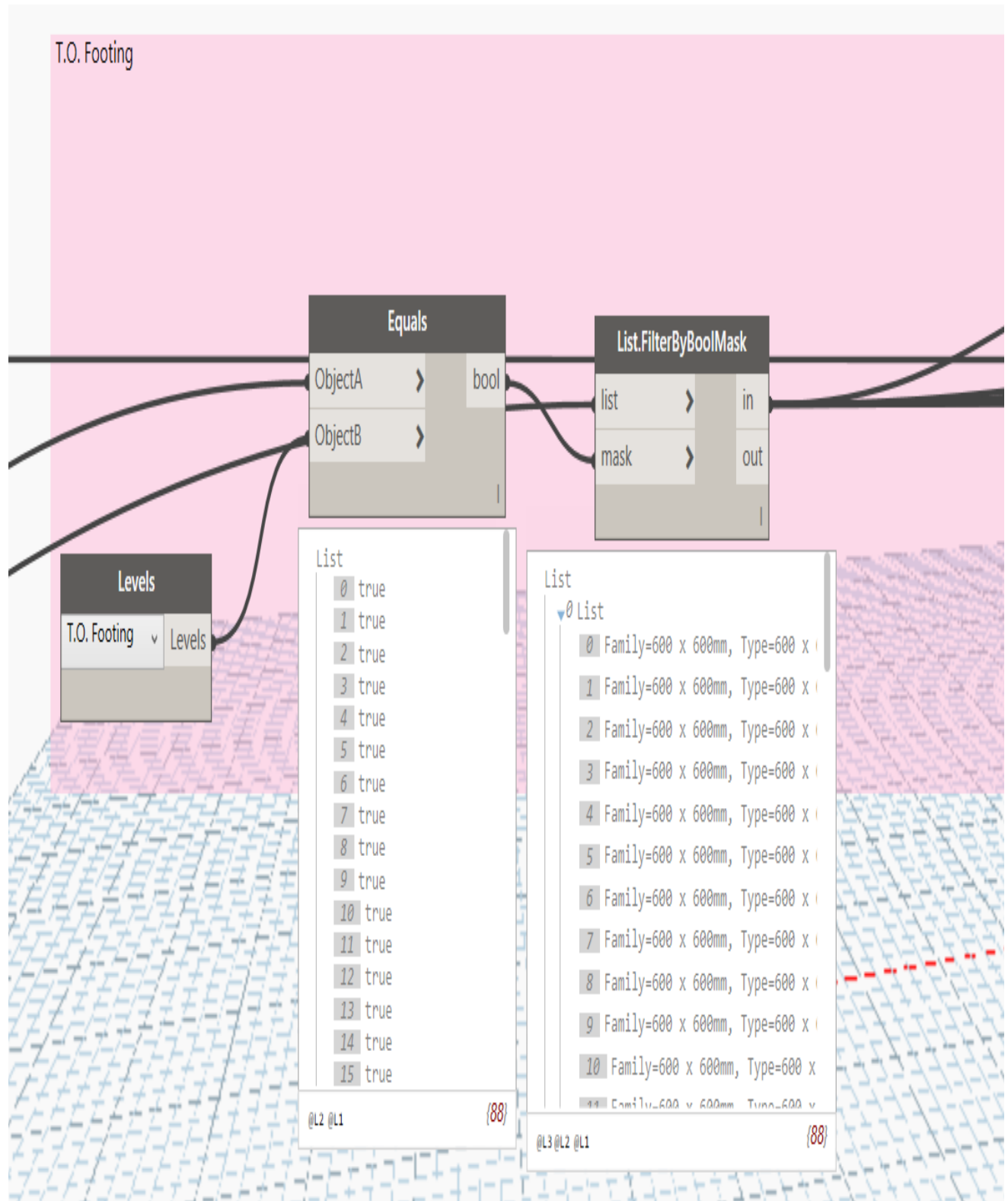


Figure 12. The Dynamo nodes of the first filter in the second part of columns

The nodes of “Code Block”, “GetParameterValueByName”, and “Material. Name”, have comprised the second filter, which is aimed to attain the needed parameters types and their values. The parameters of components’ levels, categories, area, volumes, estimated reinforcement volumes, and materials are defined in the “Code Block” individually. After linking with these nodes, the values of these parameters are showed under the watch nodes. Figure 13 displays the nodes of second filter applied in the second part for columns.

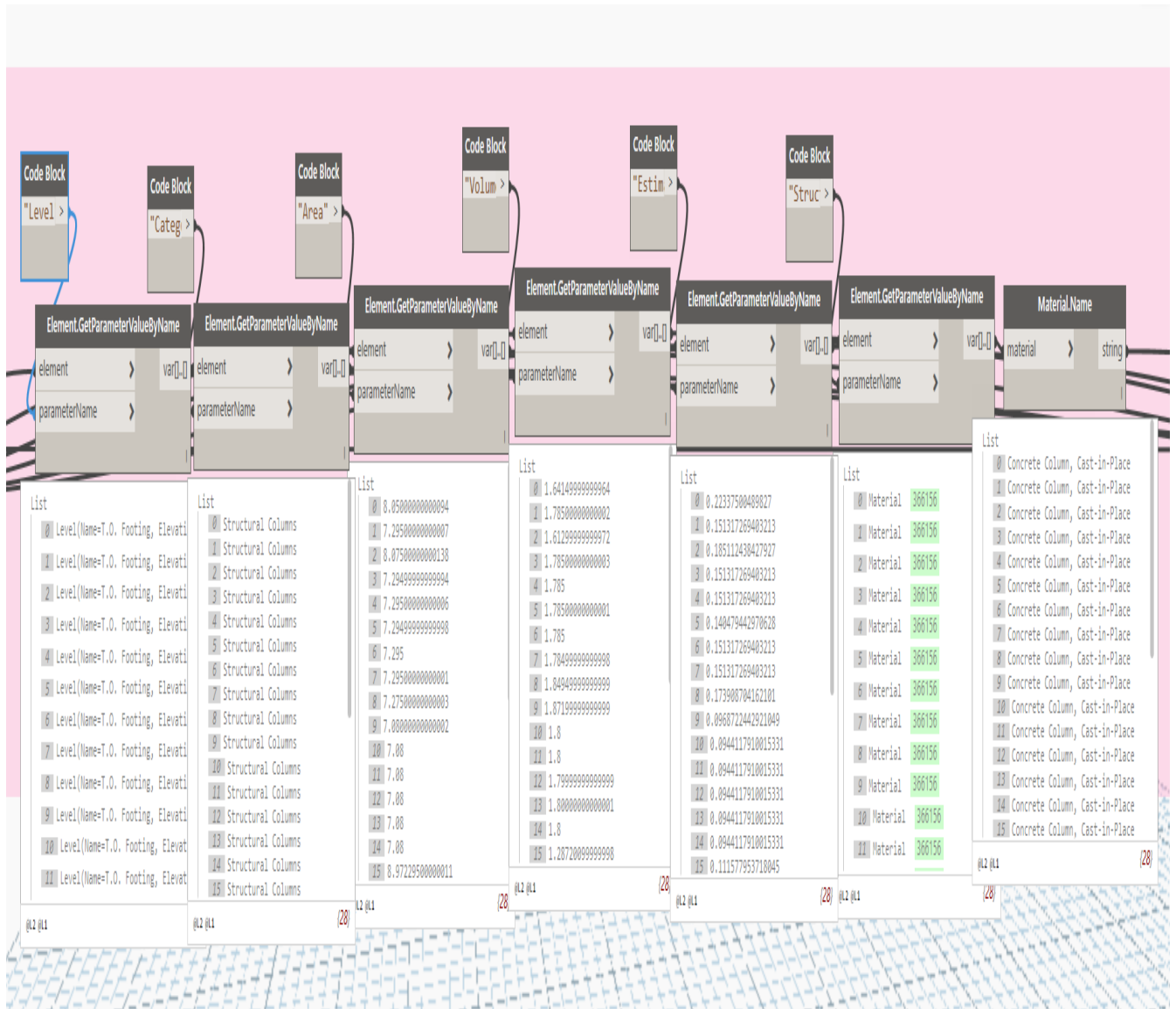


Figure 13. The Dynamo nodes of the second filter in the second part of columns (clearer picture provided in the Appendix)

The filter for the doors and windows, however, are different, which are made of the nodes of “Family Types”, “Equals”, “List. FilterByBoolMask”, “Code Block”, “GetParameterValueByName” “Levels” and “Element”. There is no need to get the windows and doors’ parameters such as reinforcement volumes or dimensions. A new “Family Types” node is utilized to identify windows or doors based on family types. To generate the windows and doors’ schedule, in addition to the needs of knowing their categories, families and levels, the number of their total amount is required, which is calculated in the Excel in the next step. Figure 14 displays the second filter of Doors’ second part.

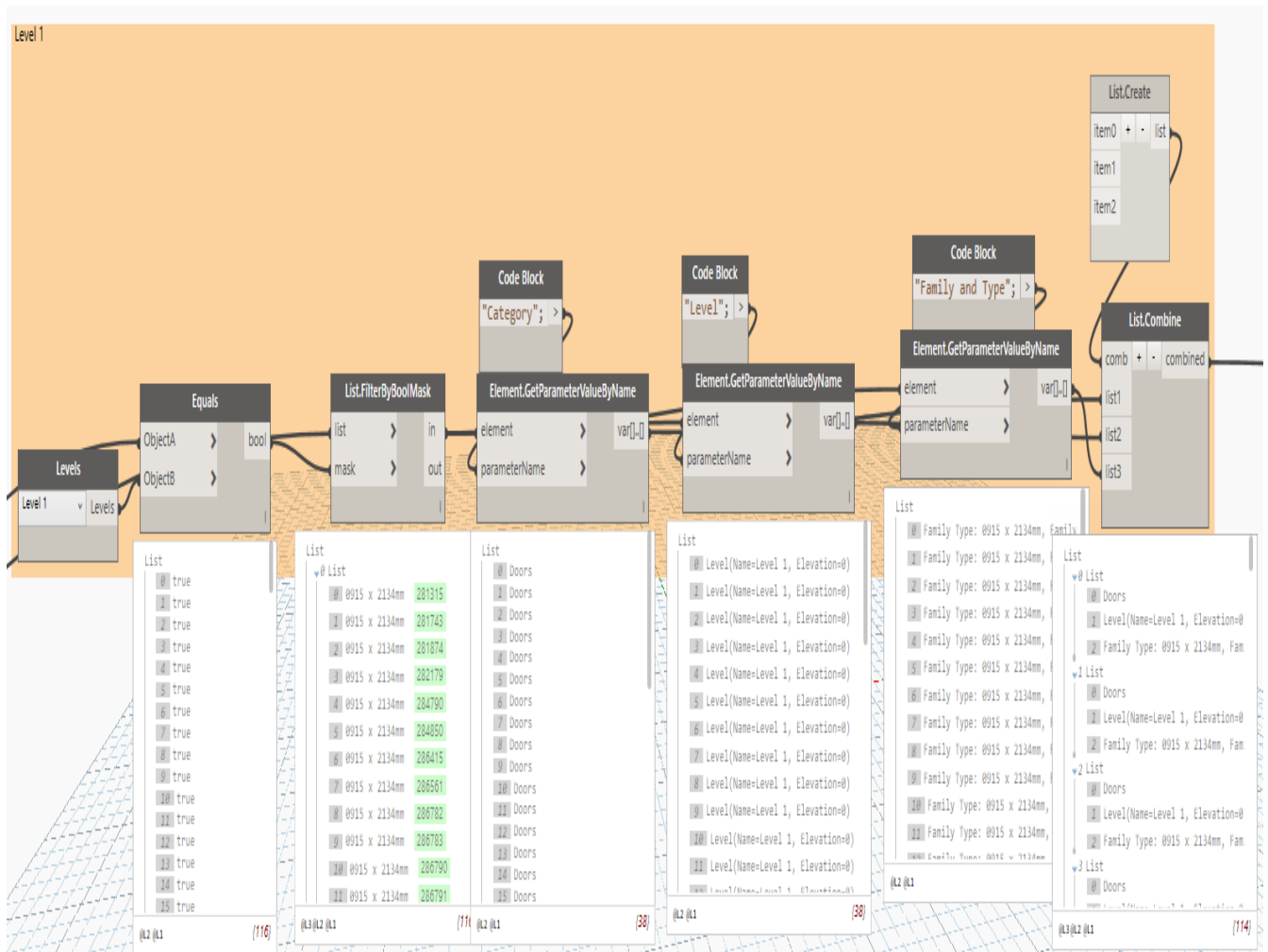


Figure 14. The Dynamo nodes of the second filter in the second part of doors

In terms of stairs, the parameters of base level, top level, desired number of risers, estimated reinforcement volume are demanded. The Figure 15 displays the second filter of stairs' second part.

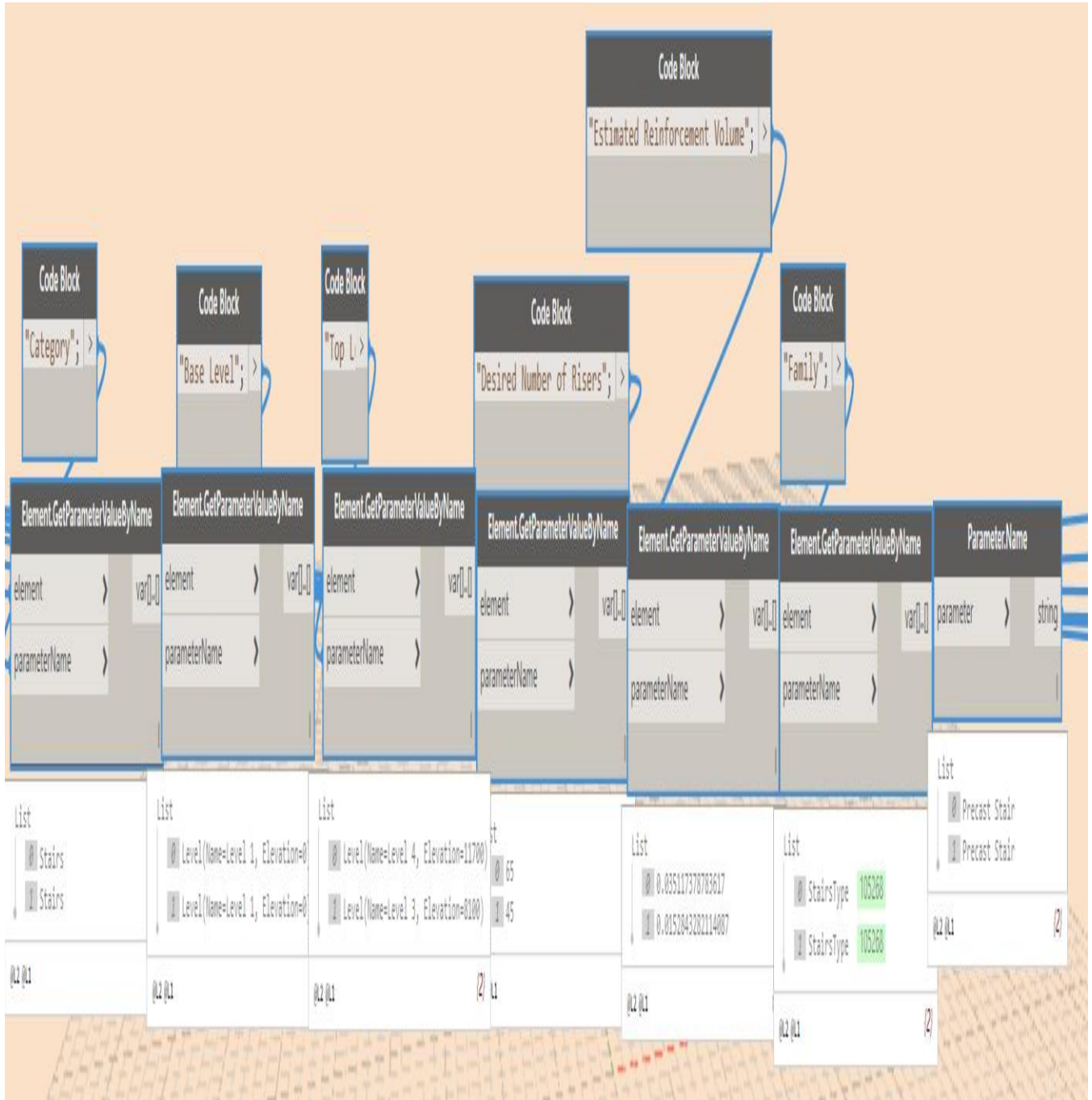


Figure 15. The Dynamo nodes of the second filter in the second part of stairs

The purpose of the rest nodes in the second part, which includes the nodes of “List. Create” and “List. Combine”, are to organize these data and to facilitate data transfer to Microsoft Excel.

Figure 16 illustrates the rest nodes of the second part for columns.

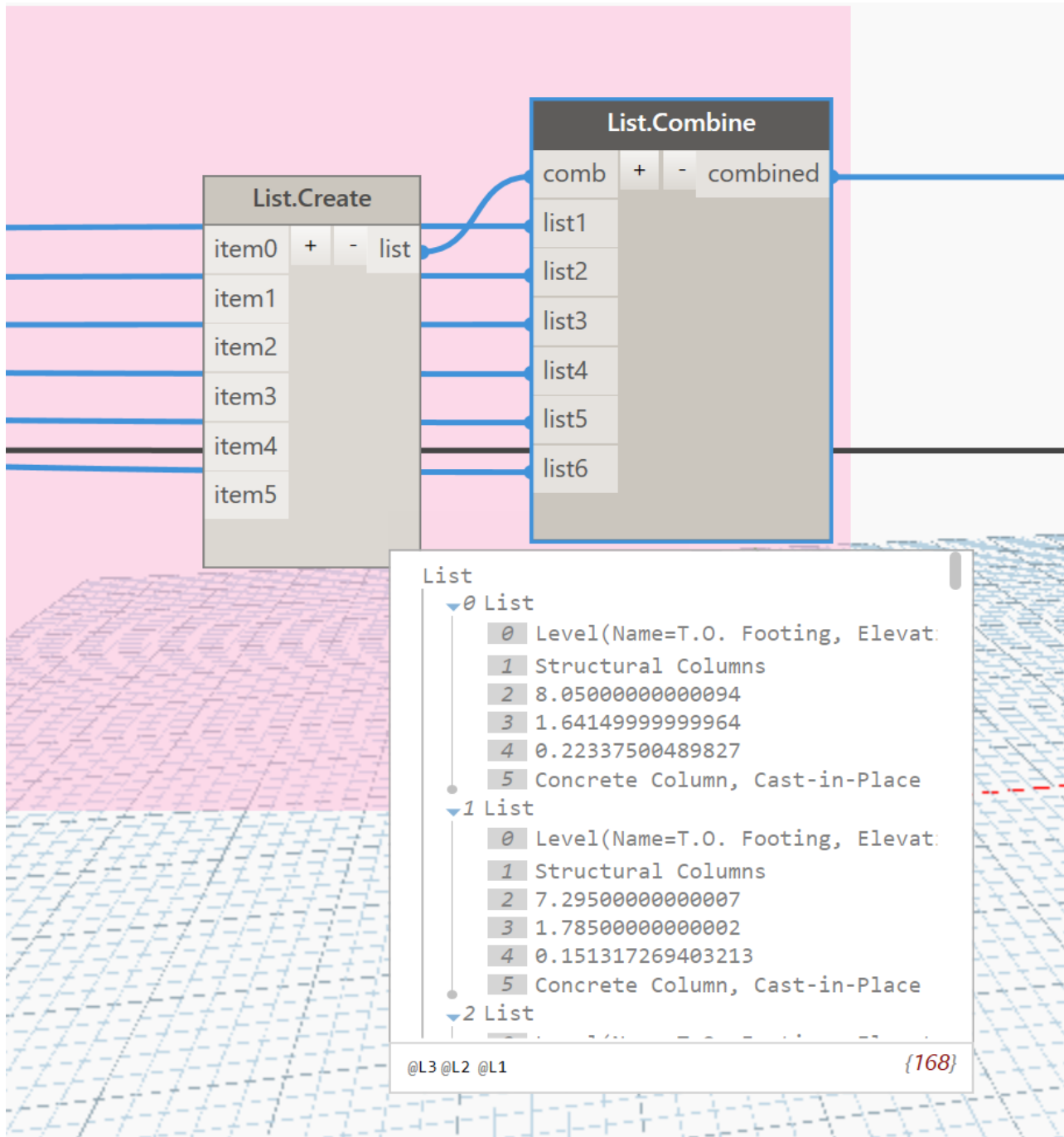


Figure 16. The rest Dynamo nodes of the second part of columns

Because a node is usually able to tie with only one other node, the first part can only get one kind of building element information, such as beams, or columns. The nodes from the second part are only able to get one level's data for the defined element. As a consequence, a series of iterations are needed to extract all the building elements' information.

The third part of the script is made of the nodes of "List. Join", "Code Block", "Boolean", "List. AddItemToFront", "Excel. WriteToFile", and "File Path". These nodes enable the third part to further organize the obtained data. The "List. Join" node combines all building components within the same level. The "Code Block" and "Boolean" nodes are used here to enable the "Excel. WriteToFile" node to transfer data into Microsoft Excel automatically. The "List. AddItemToFront" is used to organize the sheets, where a "Code Block" with the content of "Level; Category; Area; Volume; Estimated Reinforcement Volume; and material" are attached. With these nodes, the title of the sheets, the name of the Excel file and its position are all customized. The names of sheets are set based on the level's names, from the "B.O. Footing", "T.O. Footing", "T.O. Fnd. Wall", "T.O. Slab", to the Level N. The sheets of "Stairs", "Windows" and "Doors" are separated from other sheets since they would be installed separately. Eventually, all the needed data of the project's components is extracted and organized by levels and types and being transferred to Microsoft Excel for later use. Figure 17 shows the algorithm of the third part for columns. A rather similar approach is used for the beams and the process of the beams' data extraction is represented in the Figure 18.

Table 2 summarizes the names, functions and the outcome of all the nodes used in the system.

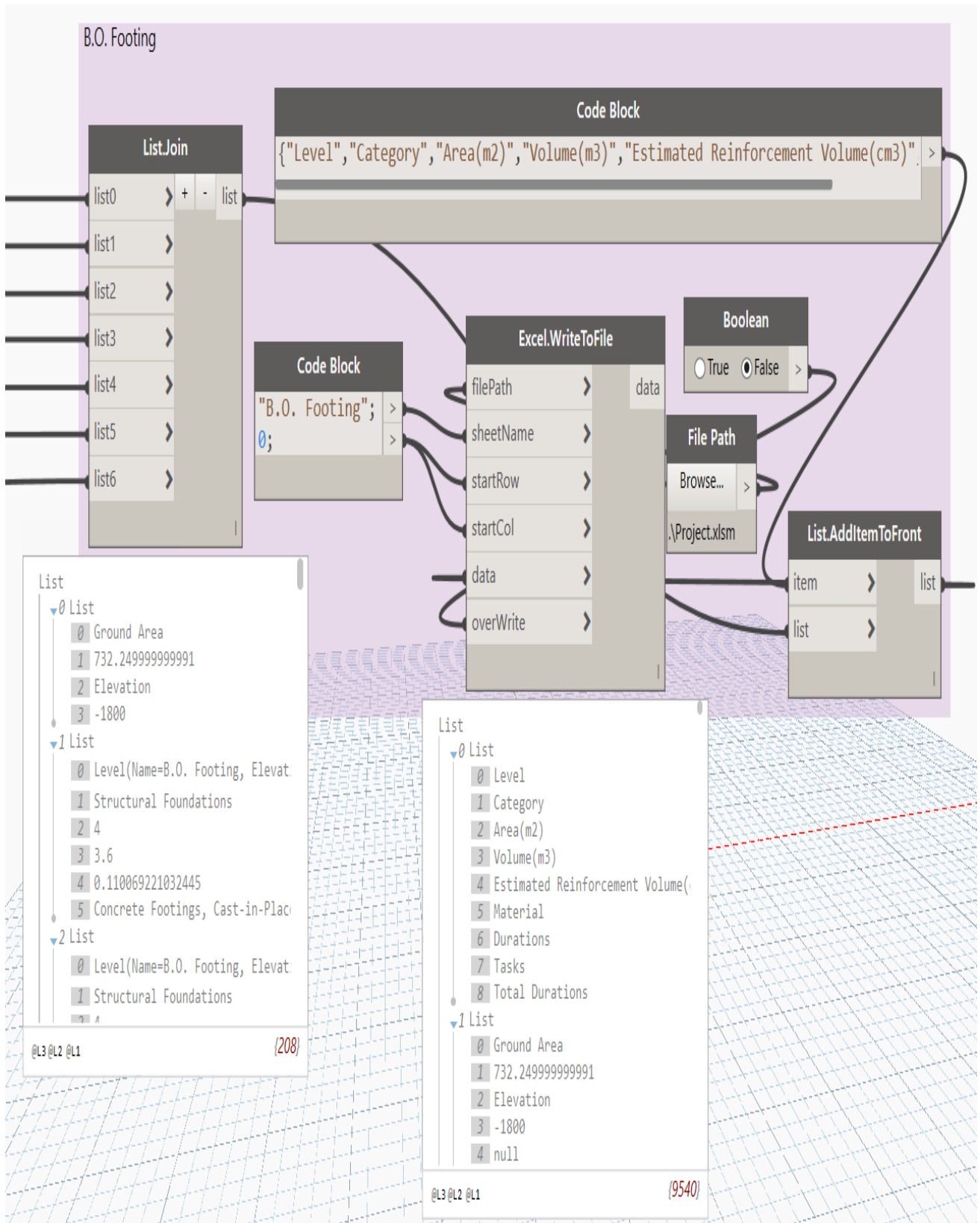


Figure 17. The third part Dynamo nodes of columns

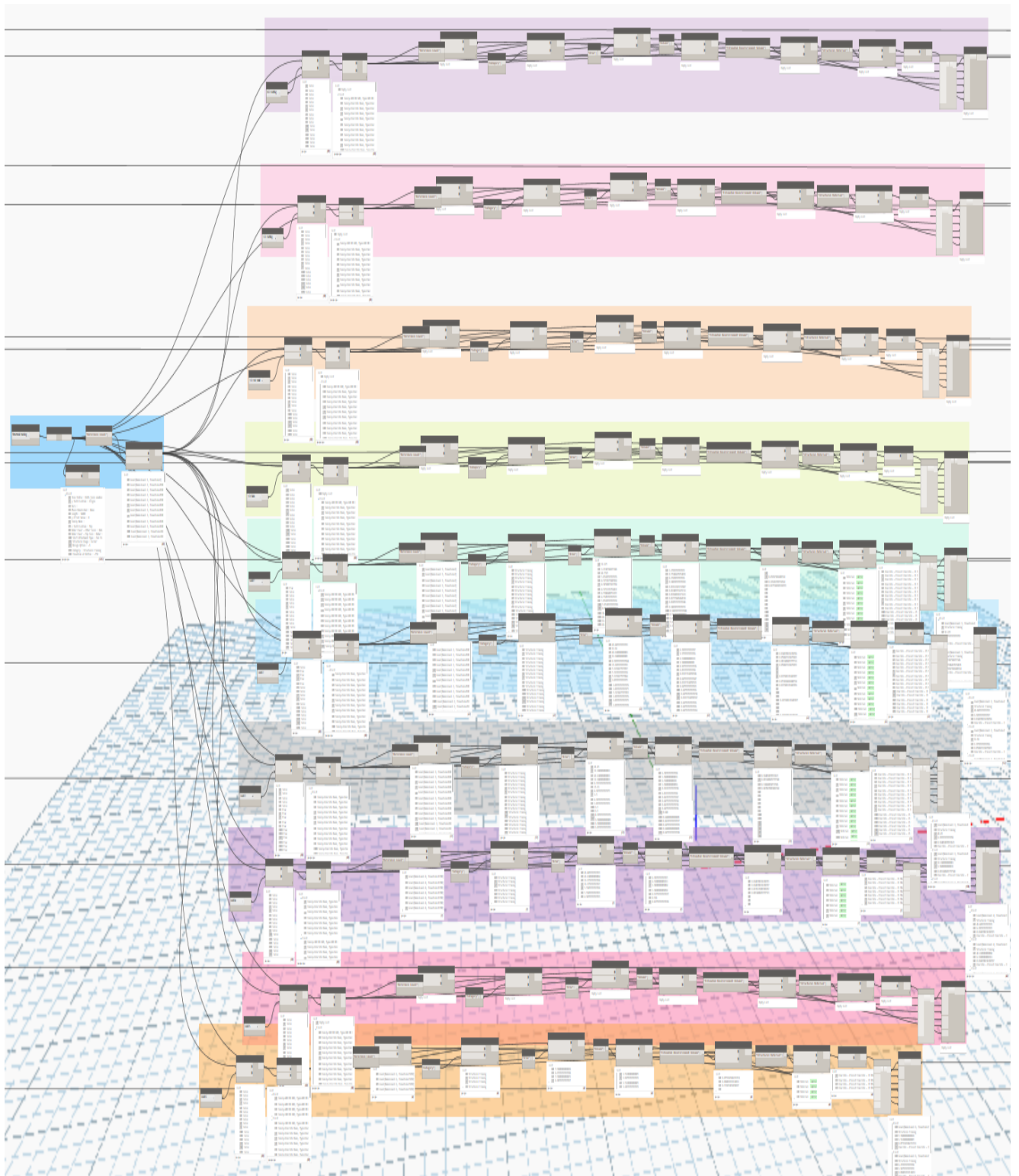
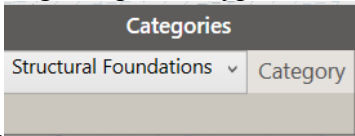
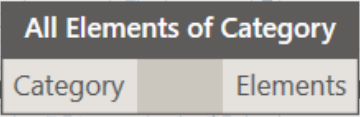

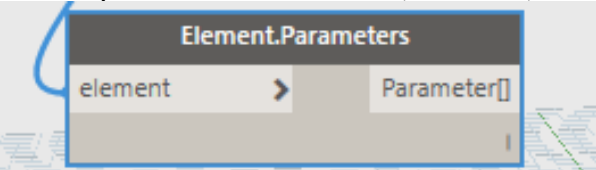
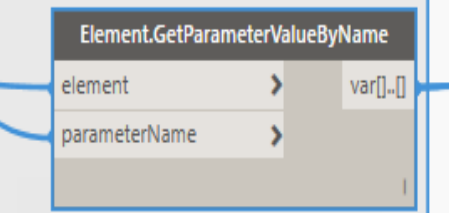
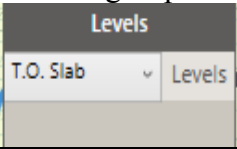
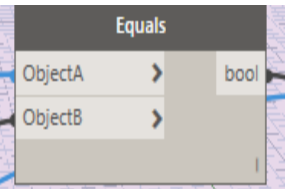
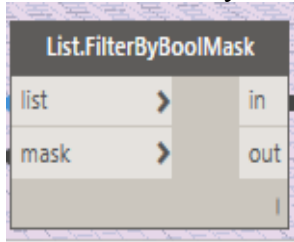
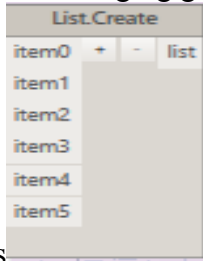
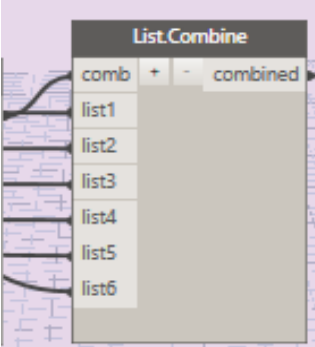
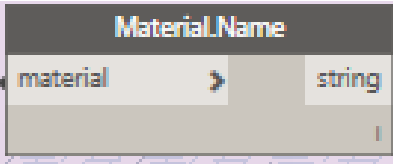
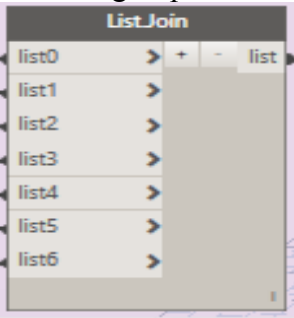

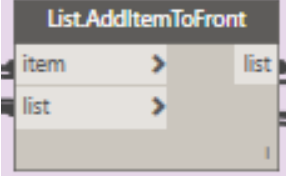
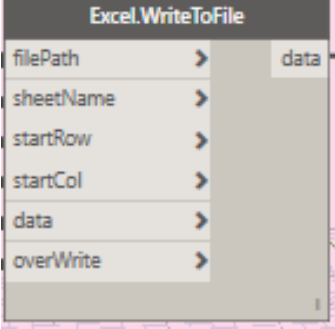
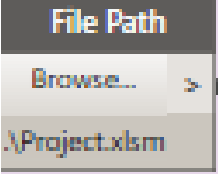
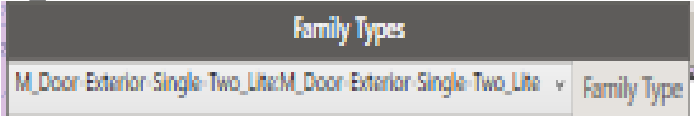



Figure 18. The beams' specified parameters are separated by levels (clearer picture provided in the Appendix)

Table 2. Summary of nodes used in the system

Node	Function	Outcome
Categories	Select all built-in categories	Select building component types, such as columns, beams, etc. 
All Element of Category	Get all elements of the specified category from the model	Work with “Categories” node to select all elements of that specified category 
Code Block	Allows users to input authorized Design Script code directly	Input text-scripting, variables, numbers, strings, etc. 
Element.Parameters	Obtain all the parameters from an element	Extract parameters such as area, volumes, etc. 
Element.Get-ParameterValueByName	Get the value of one of the element’s parameters	Work with “Element.Parameters” node to extract specified parameters of an element 
Levels	Select a level in the active document	Used to group elements based on their levels 
Equals	Determines whether two object instances are equal	Used to form the filters 

List.FilterByBoolMask	Filters a sequence by looking up corresponding indices in a separate list of Booleans	Work with “List.FilterByBoolMask” node to form filters 
List.Create	Makes a new list out of the given inputs	Create list for arranging generated elements’ parameters 
List.Combine	Applies a combinatory to each element in two sequences	Combine and group elements’ parameters 
Material.Name	Get material name	Get material name, such as cast-in-place concrete 
List.Join	Concatenates all given lists into a single list	Join and group elements’ parameters 
Boolean	Selection between a true and false	Work with “List.FilterByBoolMask” to form filters 

List.AddItemToFront	Add an item to the beginning of a list	Work with “Code Block” to add titles such as “Categories”, “Volumes”, etc., to organize generated elements’ parameters 
Excel.WriteToFile	Write data to a MS Excel spreadsheet.	Extract data to Excel file 
File Path	Allows users to select a file on the system to get its file name	Select file for data export 
Family Types	All family types available in the document	Select family types for building components, such as M Fixed 0406 x 1220mm 
List.Transpose	Swaps rows and columns in a list of lists.	Transpose and group elements’ parameters 

3.3.5 Conclusion

This module was set to extract useful data from the BIM platform, and then organize and transfer them to other software for further processing. This step verifies the BIM’s capability in

documenting and accessing building components' parameters, and also explores the BIM's capability of connecting with other software products in other domains. The Dynamo can also be used for checking building's performance and select and change the building elements. In summary, this step automatically extracts data from BIM and organizes them for the next step, which are the activity packages' generation and activity durations' calculations. More details are discussed in the following sections.

3.4. Project Activities Package's Generation and Durations' Calculation

3.4.1 Introduction

The next step after is to generate work-packages and to calculate their durations. In this step, the transferred data will be automatically used to generate activity packages based on predefined construction rules and to calculate their durations using the RSMeans productivity database. The combination of Marcos and Visual Basic Application (VBA) was used in this module, which are add-in applications of the Microsoft Excel. This step has explored the potentials of connecting a BIM platform with Microsoft Excel by programming. Also, BIM's potential in automated construction management has extended by creating a link between a BIM platform and a project management tool. First, the employed tools in this step are introduced, and then the details of the processes are discussed.

3.4.2 Visual Basic for Applications (VBA)

VBA is an event-driven programming tool that used in many Microsoft Office applications. It utilizes the Visual Basic (VB) language to program and can compile with the Macros, which is also attached to the Excel (Chapra, 2010). By using VBA, Microsoft Excel is able to achieve many

advanced functions, such as automatically generate data, modify, and export spreadsheets. In this system, VBA is integrated with Macros to program the system to rearrange the data that exported by Dynamo, calculate the durations of different building components, generate project schedule, and export it to Microsoft Project.

3.4.3 Macros

Excel Macros is designed to save the trouble for people to do repetitive tasks (Chapra, 2010). It has the function to record the tasks that users have performed on the Excel and automatically transform these tasks into codes, which VBA can understand, save, and repeat. Thus, users only need to perform tasks once. Macros can improve the efficiency of users' work, as well as helping them to get rid of the tedious work.

In addition, Macros can support users in writing their codes. Users can use the Macros to record their tasks, where the corresponding codes will be generated. They can then study these codes and make modifications on them to program similar tasks. The combination of these two tools would enable the system in automated schedule generation. More details will be described in next section.

3.4.4 RSMeans

The activity production rates are critical to estimate the duration of tasks. This data should be reliable and reasonable enough to calculate each task's duration, consequently, generate the total project's schedule. The productivity rates were adopted from RSMeans, which is a construction cost data source that covers all aspects of the construction (RSMeans, 2018). It provides data of productivity rates, crew composition, city cost indexes, contractor's overhead and profit rates, and unit costs for different project participants, including the owners, designers, architects, engineers, and contractors. It updates the statistics every year based on the data collected from North

American AEC industry and organizes the data into an easy-to-use format for the end-users. Therefore, RS Means is used as the production rate database for this system. Table 3 shows a sample of productivity obtained from RS Means.

Table 3. A sample of RS Means productivity

Category	Daily Output	Unit
Excavation	120	Cubic Yard
Formwork		
Foundation formwork	290	Square Feet
Mat foundation formwork	290	Square feet
Column formwork	165	Square feet
Beams formwork	395	Square feet
Slabs formwork	1200	Square feet
Foundation Walls formwork	240	Square Feet
Walls formwork	280	Square Feet
Partition walls formwork	265	Square Feet
Cast-in-place Concrete		
Foundation footings	28	Cubic Yard
Mat foundation	38.67	Cubic Yard
Columns	13.77	Cubic Yard
Beams	15.62	Cubic Yard
Slabs	50.99	Cubic Yard
Walls	27.26	Cubic Yard
Foundation walls	66.2	Cubic Yard
Reinforcement		
Foundation footings	2.1	Ton
Mat foundations	2.1	Ton
Columns	1.5	Ton
Beams	1.6	Ton
Slabs	2.9	Ton
Exterior walls	3	Ton
Partition walls	3	Ton

3.4.5 Construction Sequencing Rules

To develop construction schedules, a logical way to sort all the building elements is by level. In this prototype, the level is considered as a work zone to define the sequencing of construction areas. Construction workers generally start a project's construction from the lowest level to the

highest one. They are more likely to start from the foundation to the ground level, then to the higher level, such as the second floor, third floor, and finish the structural construction tasks at the tallest level. Within the floor that above the foundation level, the columns are normally the first elements to be built. The beams, slabs, and walls will then be constructed one by one. The common construction order of reinforced concrete foundation, slabs and beams is: assembling the formwork, properly placing the reinforcement and casting, and finally removing the formwork. For the construction of the reinforced concrete columns and walls, however, the reinforcements are installed before the formwork. This research adopts these construction sequence rules to generate the project schedule. **Table 4** and **Table 5** illustrates the adopted construction sequence rules of main components and reinforcement works, respectively.

Table 4. Construction order of main components

Levels	Construction order				
	→				
Below the ground	Foundation	Columns	Beams	Slabs	Walls
Level 1		Columns	Beams	Slabs	Walls
Level 2		Columns	Beams	Slabs	Walls
Level 3		Columns	Beams	Slabs	Walls
...		Columns	Beams	Slabs	Walls
Top level	Stairs and Roof				
Others	Windows and Doors				

Table 5. Detailed construction order of reinforced concrete components

Main components	Construction order			
	→			
Foundations	Assembling formwork	Placing reinforcement	Casting & Curing	Removing formwork
Columns	Placing reinforcement	Assembling formwork	Casting & Curing	Removing formwork
Walls	Placing reinforcement	Assembling formwork	Casting & Curing	Removing formwork
Beams	Assembling formwork	Placing reinforcement	Casting & Curing	Removing formwork
Slabs	Assembling formwork	Placing reinforcement	Casting & Curing	Removing formwork

There are some points need to be mentioned. First, precast concrete components are directly installed without the need of installing formwork, pouring concrete, and others. Second, precast-concrete stairs can be installed after construction of the building frame. Third, installations of windows, doors are usually scheduled at the late stages of the project construction. This system also considers delivery durations of these prefabricated materials, the delivery durations are pre-set as two weeks for these components. Users are able to change it based on their projects' conditions in later processes.

The construction order is critical to generate a correct schedule. The accuracy and feasibility of generated project schedule highly depends on the correct sequences. After the data extraction procedure in Dynamo, it will automatically group the extracted data based on the customized ordering rules. Building components and their attributes are arranged by their levels. When the

The first step of this stage is to make these sheets more organized for Excel to calculate the durations automatically. This is a data preparation step to carry out the calculations accurately. New columns of Tasks, Durations, and Total Durations are generated in each level's sheet automatically. In the window's and doors' sheets, the new columns named Numbers, Tasks, and Durations are generated, since the construction duration of them is based on the total number of items and their installation productivity. Similarly, the stair sheet generates new columns for Tasks and Duration.

After this preparation process, the second step is to identify activity types and determine the duration associated with each activity. The activity identification is based on the types of elements. The system uses predefined task names for each building components, which is based on element's family types, location and material types. RSMeans is used to calculate the duration of each task based on its correlated material to find its specific production rate. A filter is created by programming to identify the matched component's type and its material composition with RSMeans data. Figure 20 demonstrates the algorithm used to develop this searching process. It checks each element's family types and material types until find a match production rate. The parameters "v", "x", "y", "w", "l", "e" are representing the table cells' content from the column A to the column E in the spreadsheet file (see Figure 19), which are the attributes of the extracted concrete elements. In addition, the parameter "z" is defined as the calculated durations of concrete works, the parameter "r" is defined as the calculated duration of components' reinforcement, and the parameter "m" is defined as the calculated duration of the components' formwork.

```

Range("a1").Offset(i, 0).Select
v = ActiveCell.Value
Range("b1").Offset(i, 0).Select
x = ActiveCell.Value
Range("f1").Offset(i, 0).Select
y = ActiveCell.Value
Range("d1").Offset(i, 0).Select
w = ActiveCell.Value
Range("c1").Offset(i, 0).Select
l = ActiveCell.Value
Range("e1").Offset(i, 0).Select
e = ActiveCell.Value

If x = "Structural Foundations" And y = "Concrete Footings, Cast-in-Place" Then

    z = w / 0.7646 / 43
    Range("g1").Offset(i, 0).Select
    ActiveCell.Value = z

    Selection.EntireRow.Resize(1).Insert
    Range("b1").Offset(i, 0).Select
    ActiveCell.FormulaR1C1 = "Concrete Reinforcement Footings"

    r = e * 7.85 / 2.1
    Range("g1").Offset(i, 0).Select
    ActiveCell.Value = r

    Selection.EntireRow.Resize(1).Insert
    Range("b1").Offset(i, 0).Select
    ActiveCell.FormulaR1C1 = "Forms in place, Footings"

    m = l / 0.0929 / 440
    Range("g1").Offset(i, 0).Select
    ActiveCell.Value = m

```

Figure 20. The filter's operation process

The corresponding production rate of the element is then applied in the formulas embedded in the filter to calculate duration of each activity, in which the component's quantity take-offs and unit conversions factors are included.

Equation 1. Duration's calculation for concrete components

$$\text{Duration} = V / P * U$$

Where: V= Volumes

P = Productivity of the producing concrete component

U= Unit transform parameters

Equation 2. Duration's calculation for concrete components' formwork

$$\text{Duration} = A / F * U$$

Where: A= Formed area of building component

F = Productivity of producing concrete components' formwork

U= Unit transform parameters

Equation 3. Duration's calculation for reinforcement

$$\text{Duration} = V * K / R * U$$

Where: V: Volume of reinforcement

K: Unit weight of reinforcement

R: Productivity of producing reinforcement

U: Unit transform parameters

Equation 1 is used to calculate the durations of casting concrete components. Equation 2 represents the durations of forming for concrete components. Equation 3 is designed to calculate

the duration of installing concrete reinforcement.

A filter was also created to avoid generating same task name. It checks the components information of their locations, categories and material components, then groups them to generate their task names as well as calculates their total durations. It is also applied for generating the windows, doors and stairs' tasks names.

After the task lists are produced, the Excel will calculate the total durations of these tasks. Similar to the functions of the second filter, the last filter is designed to ensure Excel only calculate durations for each individual activity, which checks the content in the categories and material's columns.

For improving the accuracy of this system, users are allowed to check and modify the activities list before running the combination of Macros and VBA, such as add or delete tasks. Plus, after Macros and VBA are lunched, users can examine and adjust the results. They are able to modify the tasks names, their durations, and their relationships. For example, this system does not take into account the weather influences, therefore, users can personally apply factors to correct durations. They can also add the durations of contractor preparation, resource purchase, as well as, correct the mistakes of Revit designing, such as the mistakenly assigned material to some components.

3.4.7 Conclusion

This stage enables a BIM-based automated schedule generation process by programming, in which data organization, calculations of tasks lists and durations, schedule refinement, and results export have completed. The capability of BIM platform is extended to integrate with Microsoft Excel and Microsoft Project, which proves BIM's capability of supporting project management. It

broadens the BIM's capabilities into automated construction. The use of the combination of Macros and VBA has assessed the possibility of extending BIM's skills by programming. Macros can record tasks as VB language, repeat tasks for users, and provide users coding templates. In order to strengthen the applicability of this prototype, this step allows users to examine and supervise computer's performance and make adjustments on the results.

3.5. Project Schedule Export

3.5.1 Introduction

The purpose of this step is to complete the entire schedule generation process and present the schedule in a common format (i.e. bar chart) for the users. In this step, the bridge between the design and the project planning stage has formed.

3.5.2 Microsoft Project

Microsoft Project is a program designed for planning and managing project (Chatfield & Johnson, 2010). It is functional in scheduling project duration, resource allocation, budget estimation, and other project planning and control processes. It is also able to generate cash flow charts, Gantt Chart, and CPM, perform earned value analysis, resource leveling, as well as tracking project progress and sharing plans with collaborators. In this system, MS Project is adopted to receive the schedule generated by MS Excel to perform further calculations.

3.5.3 Project Schedule Export

Once the task lists and durations are generated, the next step is to arrange them into a new sheet in a usable format for MS Project without losing or messing data. The generated new sheet is called "Task_Table", it summarizes the activities and durations generated in each sheet and applies two

basic predecessor rules for each task. One is the sequential predecessor rule, which means all the activities are scheduled sequentially. The other one is the optimized predecessor rule, in which some overlapping rules are programmed. At the final stage, therefore, two schedule options will be generated for the users to select. Based on the project's conditions and applied methods and equipment, users will be able to modify activities' predecessors on the selected schedule to arrange activities' priority and refine the selected schedule. The Excel will then save this sheet as useable file for launching the MS Project, in which the user can use all of its functions and scheduling tools. Users can use MS Project to generate Gantt Chart, CPM, set start/finish dates and project calendar, analyze resource allocation, cash flow, and earned value analysis.

3.5.4 Conclusion

The development procedure of this prototype has completed in this step. The end user can review the automatically generated construction schedule and will be able to refine the tasks' names, types, and durations, based on the conditions of their project.

Chapter 4: Case Study

4.1. Introduction

To assess the performance of this system, three reinforced-concrete building models were used to generate their construction schedules. This chapter describes the information of the experimental models, validation procedure, discussion of the results, as well as the conclusion of this case study.

4.2. Information of Tested Models

The first test model is a four-story residential reinforced-concrete building, which consists of main building components: foundations, walls, columns, beams, floors, reinforcements. The area of each floor in this model is about 1435 m², with the total area of 5740m². The foundation of this model is 2.9m below the ground. Above the ground, the height of each level is three meters and the total height of this building model is 14.9 meters.

In the B.O. Footing level, pad foundations and columns are all made of reinforced concrete. Above the ground, each level consists of beams, columns, walls, floors, stairs, doors, and windows, in which the structural elements are made of cast-in-place reinforced concrete, including the concrete beams, concrete columns, and concrete slabs. In detail, there are three types of slab designs: 225mm, 150mm, and 210mm concrete slabs. The walls are sorted into four types: brick walls, curtain walls, reinforced concrete generic walls, and reinforced concrete partition walls. In addition, the doors are assigned to four types: two-lite wood doors, overhead-sectional doors, double wood doors, and passage single wood doors. The model includes two types of windows: 406 × 1220 mm fixed windows and 915 × 1220mm double hung windows. The stairs are made of precast concrete material. Figure 21 displays the building model.



Figure 21. The first tested building model in Revit

Another model is a three-level reinforced concrete building. Its gross area is 2116.4 m^2 , and its floor area is 778.4 m^2 . The height of the first level is 4.5 meters, the second and third levels are 3.6 meters high. Figure 22 presents a 3D view of this building model.



Figure 22. The second tested building model in Revit

Different materials are assigned to the model's components. Most of structural elements are made of cast-in-place concrete, such as columns, floors, and foundations. The model also includes

concrete masonry walls, precast concrete beams and stairs. In the architecture part, it contains basic architectural elements, such as windows, doors, ceiling, and roof. The validation process was carried out using these model and details are discussed in the next section.

Finally, a “L” shape’s 5-level model was used to validate the system’s performance in a building with an asymmetric plan. The total area of this model is 2200 m² with an floor area of 440 m². The height of this building is 16 m. Similarly, it is a reinforced concrete structure with basic components, such as the beams, columns. Figure 23 shows this building model.

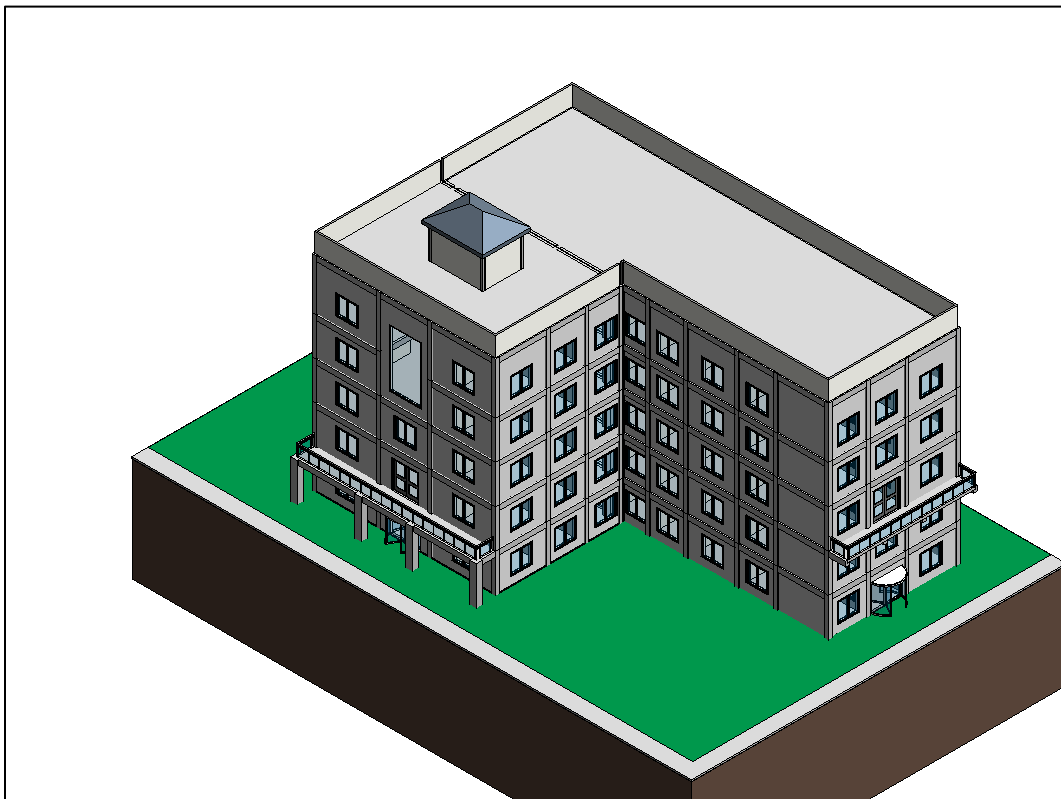


Figure 23 The third tested building model

4.3. Validation Process

These building models were developed in Autodesk Revit environment, and the Dynamo module was employed to retrieve, organize and export required building information to the Excel

environment. With the use of predefined algorithms described in chapter 3, all required information are retrieved by Dynamo. It extracts dimensions, area, volume, material, spatial, and reinforcement (if applicable) data of the building elements. It then groups these data into different levels based on the components' locations and family types. Figure 24 shows all the nodes designed in Dynamo. Figure 25 illustrates the extracted data of B.O. Footing level in Dynamo. Figure 26 presents the extracted data of foundations in Dynamo.

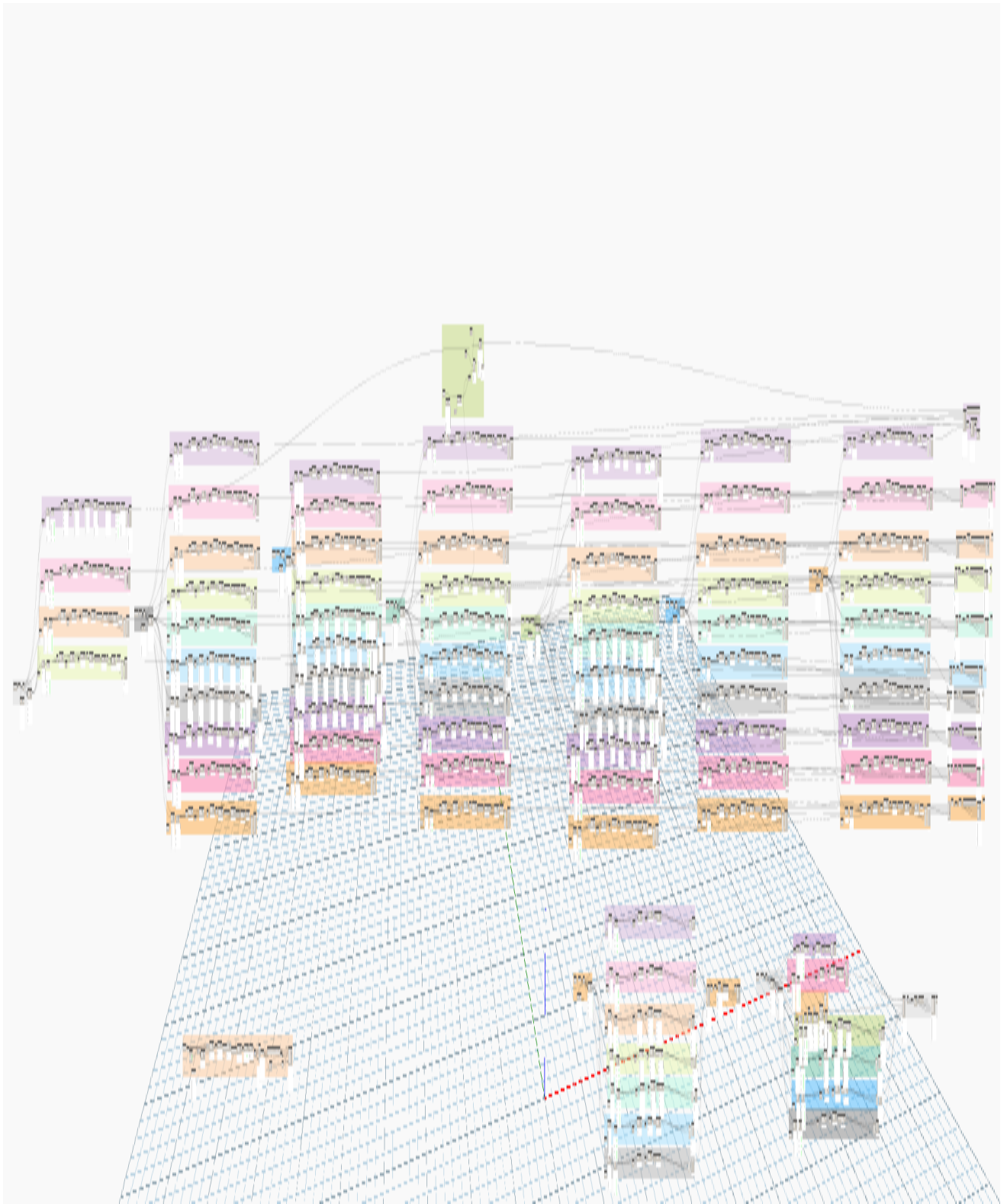


Figure 24. Data extraction and organization module in Dynamo (clearer picture can be found in the Appendix)

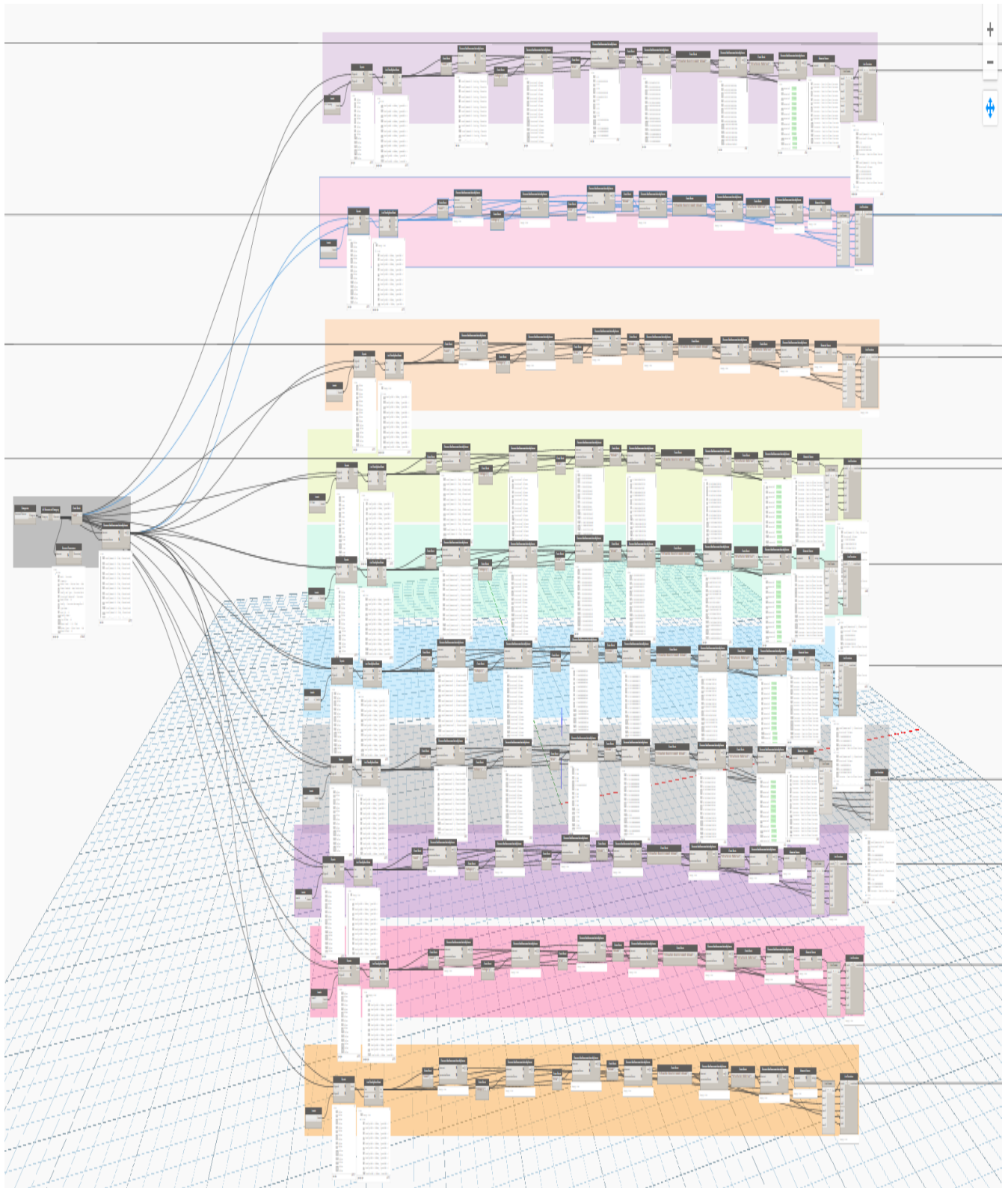


Figure 25. Extracted data of “B.O. Footing” level in Dynamo (clearer picture can be found in the Appendix)

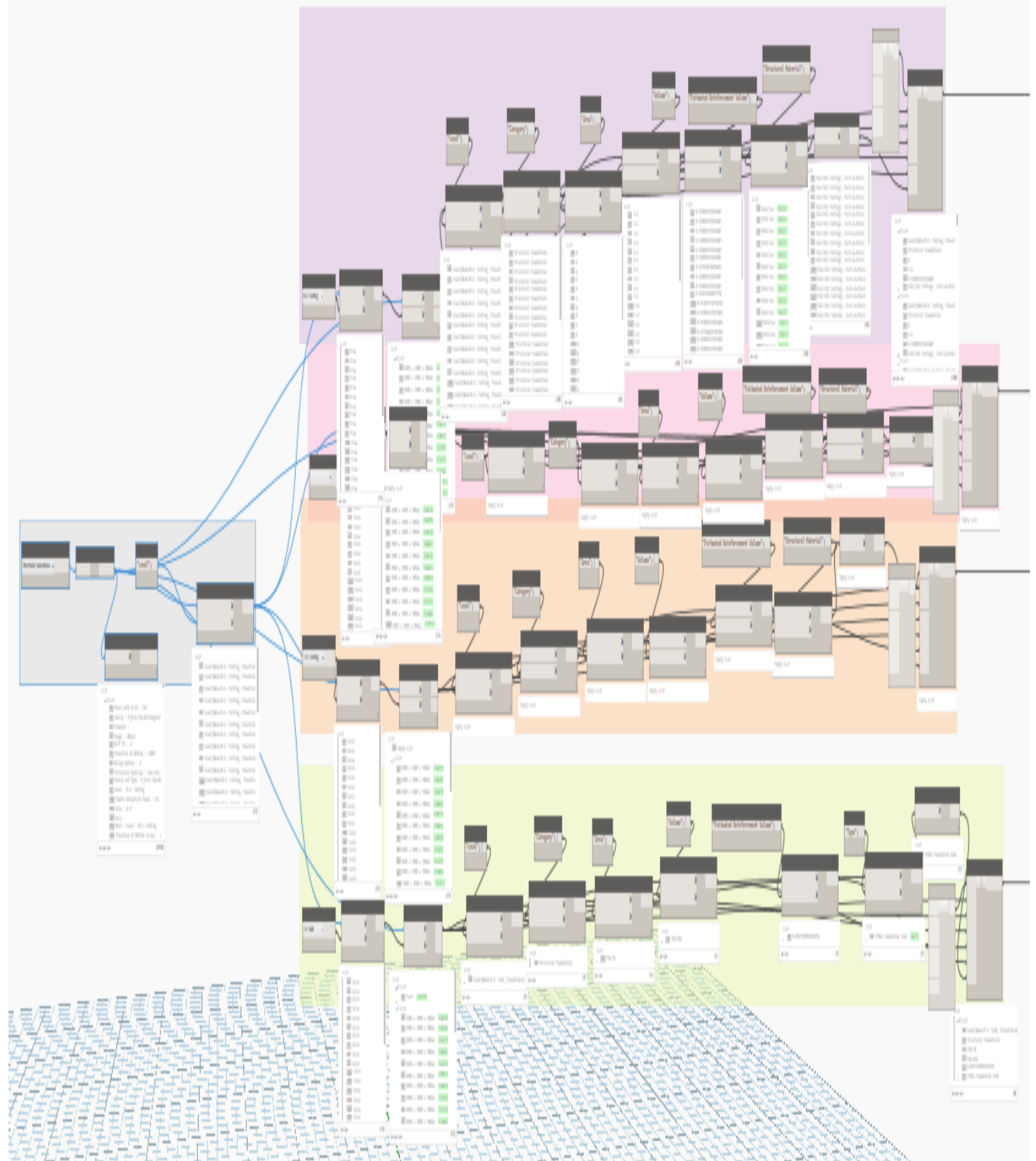


Figure 26. Data of foundations in Dynamo (clearer picture can be found in the Appendix)

After Dynamo organizes and transfers data into Excel, building information sheets are generated automatically for both projects, including the sheets of B.O. Footing level, T.O. Footing, T.O. Slab, Level 1 to Level 4, windows, doors, and stairs. A final schedule sheet that includes summarized work packages and durations is also generated for each project. In the next step, this sheet will be transformed into a file that is used by the MS Project. Figure 27 illustrates a sample view of the data that retrieved by Dynamo.

As described before, the Excel was programmed to match each component's material and type with its corresponding productivity rate to calculate its construction duration. Next, the Excel generates task packages based on their family types and summarizes duration of each task. It then transfers this organized data into the aforementioned final schedule sheet called "Task_Table" to generate a completed schedule. Figure 28 illustrates the final result of schedule sheet. Figure 29 and Figure 30 represent the B.O. Footing level and level 1's construction schedule in Excel, respectively.

Name	Duration
Excavation	32.1
Forms in place, Footings	11.5
Concrete Reinforcement Footings	5.0
Level(Name=B.O. Footing, Elevation=-2900),Structural Foundations,Concrete - Cast-in-Place Concrete & Curing	12.3
Removal of formwork	1.0
Concrete Reinforcement Columns	4.8
Forms in place, Columns	10.2
Level(Name=B.O. Footing, Elevation=-2900),Structural Columns,Concrete - Cast-in-Place Concrete & Curing	8.0
Removal of formwork	1.0
Concrete Reinforcement Columns	5.2
Forms in place, Columns	9.0
Level(Name=T.O. Slab, Elevation=0),Structural Columns,Concrete - Cast-in-Place Concrete & Curing	6.8
Removal of formwork	1.0
Forms in place, Beams	12.9
Concrete Reinforcement Beams	5.1
Level(Name=T.O. Slab, Elevation=0),Structural Framing,Concrete, Cast-in-Place gray & Curing	11.7
Removal of formwork	1.0
Forms in place, Floor Slabs	13.7
Concrete Reinforcement Slabs	0.0
Level(Name=T.O. Slab, Elevation=0),Floors,Insitu Concrete 150mm & Curing	12.4
Removal of formwork	1.0
Concrete Reinforcement Partition Walls	4.0
Level(Name=T.O. Slab, Elevation=0),Walls,Exterior - Brick on Mtl. Stud	0.1
Concrete Reinforcement Walls	0.0
Forms in place, Generic Walls	5.3
Level(Name=T.O. Slab, Elevation=0),Walls,Generic - 200mm	6.1
Removal of formwork	1.0
Concrete Reinforcement Columns	5.8
Forms in place, Columns	8.7
Level(Name=Level 1, Elevation=3000.103380924),Structural Columns,Concrete - Cast-in-Place Concrete & Curing	6.8
Removal of formwork	1.0
Forms in place, Beams	13.0
Concrete Reinforcement Beams	4.9
Level(Name=Level 1, Elevation=3000.103380924),Structural Framing,Concrete, Cast-in-Place gray & Curing	9.7

Figure 28. The “Task_Table” sheet generated in the Excel

Level	Category	Area(m2)	Volume(m3)	Estimated Reinfon	Material	Durations	Tasks	Total Durations
Ground Area		1372.8	Elevation	-2900				
	Excavation	1372.8	3981			32.1	Excavation	32.1
	Forms in place, Footings					0.1	Forms in place, Footings	11.5
	Concrete Reinforcement Footings					1.3	Concrete Reinforcement Footings	5.0
Level(Name=B.O. Footing, Elevation=-2900)	Structural Foundations	4	2	0.34	Concrete - Cast-in-Place Concrete	0.1	Level(Name=B.O. Footing, Elevation=-2900),Structural Foundations,Concrete - Cast-in-Place Concrete	12.3
	Forms in place, Footings					0.1	Concrete Reinforcement Columns	4.8
	Concrete Reinforcement Footings					1.3	Forms in place, Columns	10.2
Level(Name=B.O. Footing, Elevation=-2900)	Structural Foundations	4	2	0.34	Concrete - Cast-in-Place Concrete	0.1	Level(Name=B.O. Footing, Elevation=-2900),Structural Columns,Concrete - Cast-in-Place Concrete	8.0
	Forms in place, Footings					0.1		
	Concrete Reinforcement Footings					1.3		
Level(Name=B.O. Footing, Elevation=-2900)	Structural Foundations	4	2	0.34	Concrete - Cast-in-Place Concrete	0.1		
	Forms in place, Footings					0.1		
	Concrete Reinforcement Footings					1.3		
Level(Name=B.O. Footing, Elevation=-2900)	Structural Foundations	4	2	0.34	Concrete - Cast-in-Place Concrete	0.1		
	Forms in place, Footings					0.1		
	Concrete Reinforcement Footings					1.3		
Level(Name=B.O. Footing, Elevation=-2900)	Structural Foundations	4	2	0.34	Concrete - Cast-in-Place Concrete	0.1		
	Forms in place, Footings					0.1		
	Concrete Reinforcement Footings					1.3		
Level(Name=B.O. Footing, Elevation=-2900)	Structural Foundations	4	2	0.34	Concrete - Cast-in-Place Concrete	0.1		
	Forms in place, Footings					0.1		
	Concrete Reinforcement Footings					1.3		
Level(Name=B.O. Footing, Elevation=-2900)	Structural Foundations	4	2	0.34	Concrete - Cast-in-Place Concrete	0.1		
	Forms in place, Footings					0.1		
	Concrete Reinforcement Footings					1.3		
Level(Name=B.O. Footing, Elevation=-2900)	Structural Foundations	4	2	0.34	Concrete - Cast-in-Place Concrete	0.1		
	Forms in place, Footings					0.1		
	Concrete Reinforcement Footings					1.3		
Level(Name=B.O. Footing, Elevation=-2900)	Structural Foundations	4	2	0.34	Concrete - Cast-in-Place Concrete	0.1		
	Forms in place, Footings					0.1		
	Concrete Reinforcement Footings					1.3		
Level(Name=B.O. Footing, Elevation=-2900)	Structural Foundations	4	2	0.34	Concrete - Cast-in-Place Concrete	0.1		
	Forms in place, Footings					0.1		
	Concrete Reinforcement Footings					1.3		

Figure 29. A sample of the generated schedule for “B.O. Footing” level in Excel

Level	Category	Area(m2)	Volume(m3)	Estimated f Material	Durations	Tasks	Total Durations
	Concrete Reinforcement Columns				1.38	Concrete Reinforcement Columns	5.8
	Forms in place, Columns				0.12	Forms in place, Columns	8.7
Level(Name=Level 1, Elevation=3000.103380924)	Structural Columns	1.8	0.3	0.3 Concrete - Cast-in-Place Concrete	0.02	Level(Name=Level 1, Elevation=3000.103380924),Structural Columns,Concrete - Cast-in-Place Concrete	6.8
	Concrete Reinforcement Columns				2.35	Forms in place, Beams	13.0
	Forms in place, Columns				0.11	Concrete Reinforcement Beams	4.9
Level(Name=Level 1, Elevation=3000.103380924)	Structural Columns	1.7	0.2	0.4 Concrete - Cast-in-Place Concrete	0.02	Level(Name=Level 1, Elevation=3000.103380924),Structural Framing,Concrete, Cast-in-Place gray	9.7
	Concrete Reinforcement Columns				2.35	Forms in place, Floor Slabs	14.4
	Forms in place, Columns				0.12	Concrete Reinforcement Slabs	7.0
Level(Name=Level 1, Elevation=3000.103380924)	Structural Columns	1.8	0.3	0.4 Concrete - Cast-in-Place Concrete	0.02	Level(Name=Level 1, Elevation=3000.103380924),Floors,Insitu Concrete 225mm	13.5
	Concrete Reinforcement Columns				2.88	Concrete Reinforcement Partition Walls	5.6
	Forms in place, Columns				0.12	Level(Name=Level 1, Elevation=3000.103380924),Walls,Exterior - Brick on Mtl. Stud	0.7
Level(Name=Level 1, Elevation=3000.103380924)	Structural Columns	1.8	0.3	0.6 Concrete - Cast-in-Place Concrete	0.02	Level(Name=Level 1, Elevation=3000.103380924),Walls,Curtain Wall 1	0.4
	Concrete Reinforcement Columns				2.88	Concrete Reinforcement Partition Walls	1.0
	Forms in place, Columns				0.12	Level(Name=Level 1, Elevation=3000.103380924),Walls,Exterior - Brick on Mtl. Stud	0.5
Level(Name=Level 1, Elevation=3000.103380924)	Structural Columns	1.8	0.3	0.6 Concrete - Cast-in-Place Concrete	0.02	Forms in place, Generic Walls	3.5
	Concrete Reinforcement Columns				2.35	Level(Name=Level 1, Elevation=3000.103380924),Walls,Generic - 200mm	5.7
	Forms in place, Columns				0.12		
Level(Name=Level 1, Elevation=3000.103380924)	Structural Columns	1.8	0.3	0.4 Concrete - Cast-in-Place Concrete	0.02		
	Concrete Reinforcement Columns				2.89		
	Forms in place, Columns				0.12		
Level(Name=Level 1, Elevation=3000.103380924)	Structural Columns	1.8	0.3	0.6 Concrete - Cast-in-Place Concrete	0.02		
	Concrete Reinforcement Columns				2.89		
	Forms in place, Columns				0.12		
Level(Name=Level 1, Elevation=3000.103380924)	Structural Columns	1.8	0.3	0.6 Concrete - Cast-in-Place Concrete	0.02		
	Concrete Reinforcement Columns				2.07		
	Forms in place, Columns				0.12		
Level(Name=Level 1, Elevation=3000.103380924)	Structural Columns	1.8	0.3	0.4 Concrete - Cast-in-Place Concrete	0.02		
	Concrete Reinforcement Columns				1.38		
	Forms in place, Columns				0.12		
Level(Name=Level 1, Elevation=3000.103380924)	Structural Columns	1.8	0.3	0.3 Concrete - Cast-in-Place Concrete	0.02		
	Concrete Reinforcement Columns				1.38		
	Forms in place, Columns				0.12		
Level(Name=Level 1, Elevation=3000.103380924)	Structural Columns	1.8	0.3	0.3 Concrete - Cast-in-Place Concrete	0.02		
	Concrete Reinforcement Columns				1.38		
	Forms in place, Columns				0.12		
Level(Name=Level 1, Elevation=3000.103380924)	Structural Columns	1.8	0.3	0.3 Concrete - Cast-in-Place Concrete	0.02		
	Concrete Reinforcement Columns				0.84		
	Forms in place, Columns				0.12		
Level(Name=Level 1, Elevation=3000.103380924)	Structural Columns	1.8	0.3	0.2 Concrete - Cast-in-Place Concrete	0.02		
	Concrete Reinforcement Columns				0.84		
	Forms in place, Columns				0.11		

Figure 30. A sample of the generated schedule for “Level 1” in Excel

Once the data are transferred from Excel to MS Project, users are able to set the start/ finish time

and working calendar. They can use MS Project to perform CPM, resource allocation, and cost analysis. In addition, since this system uses common construction rules, it may not perfectly fit with some special projects. Professionals can modify the generated schedule in MS Project. More considerations will be added on this system to fit more real-world projects in the future development. Figure 31 and Figure 32 are samples of the optimized schedule and the sequential schedule respectively. The marked circle in each figure displays the difference between two schedules' Gantt Chart. Figure 33 specifically shows a sample of the difference between two schedules. In the sequential schedule, all tasks are scheduled sequentially, differently, in the optimized schedule, several tasks are scheduled simultaneously. Figure 34 presents the critical task analysis in the MS Project.

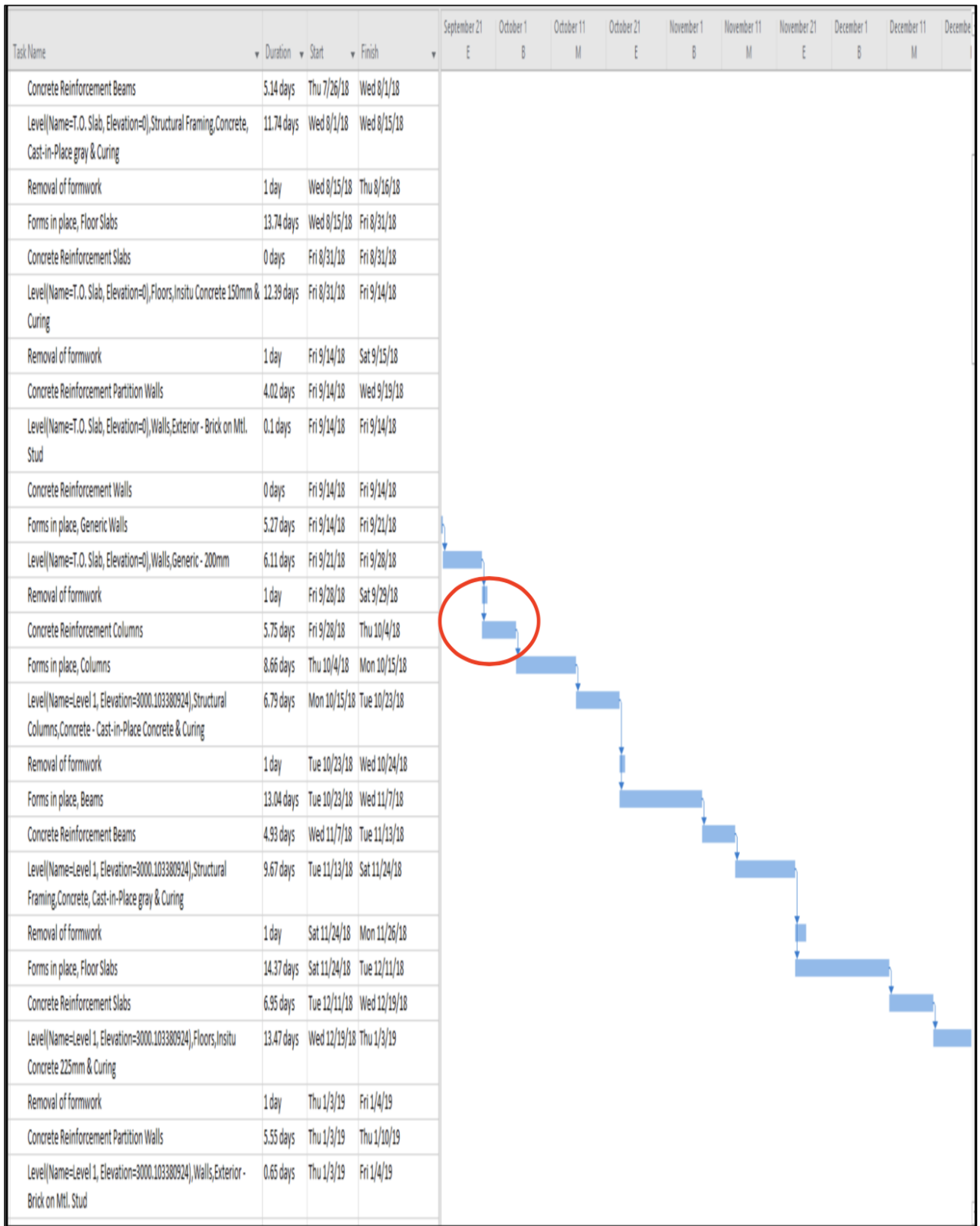


Figure 31. A sample of the optimized schedule generated in the MS Project

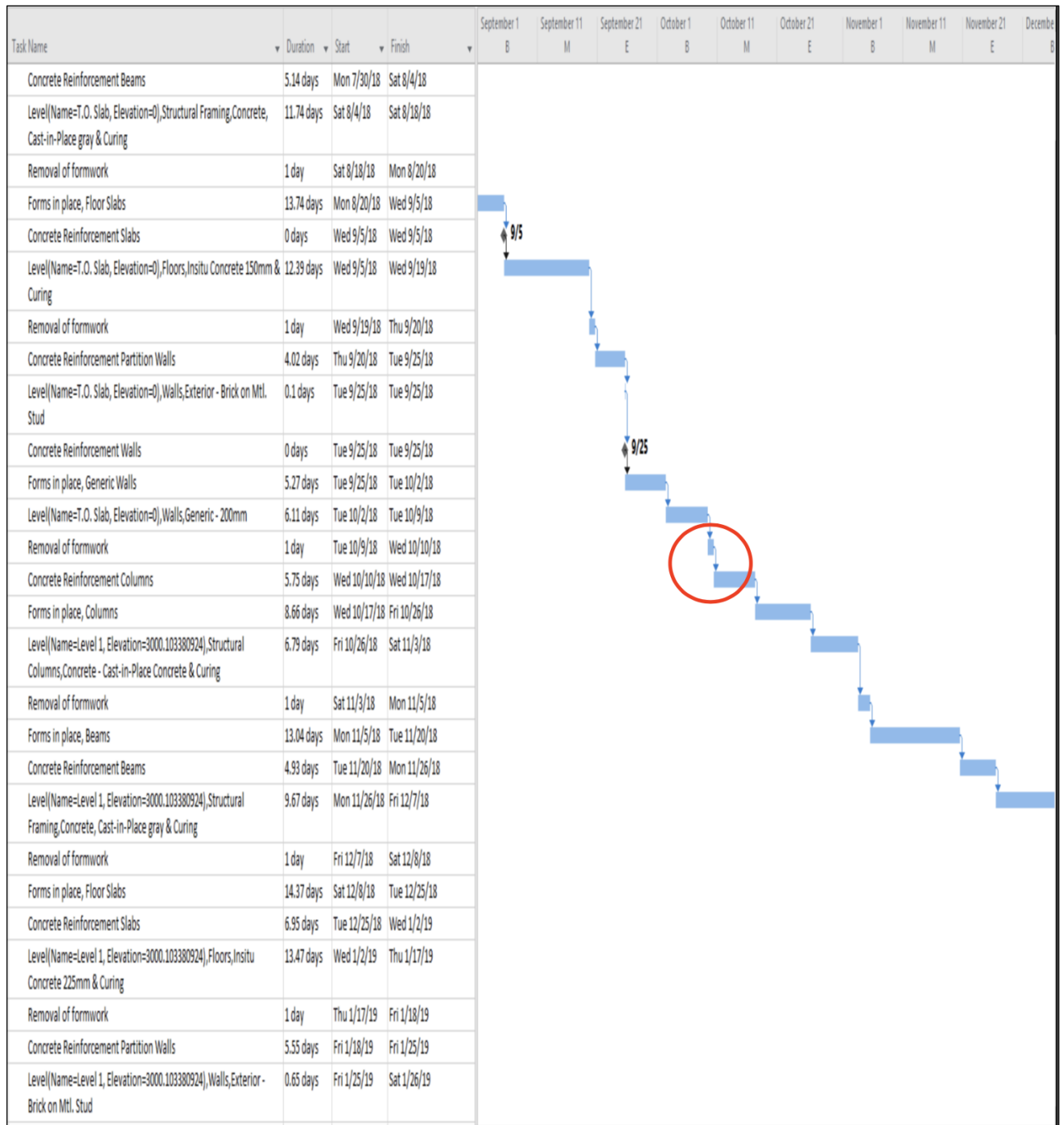
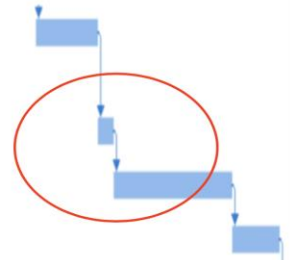


Figure 32. A sample of the sequential schedule generated in the MS Project

Sequential schedule

Level(Name=Level 1, Elevation=3000.103380924),Structural Columns,Concrete - Cast-in-Place Concrete & Curing	6.79 days	Fri 10/26/18	Sat 11/3/18
Removal of formwork	1 day	Sat 11/3/18	Mon 11/5/18
Forms in place, Beams	13.04 days	Mon 11/5/18	Tue 11/20/18
Concrete Reinforcement Beams	4.93 days	Tue 11/20/18	Mon 11/26/18



Optimized schedule

Level(Name=Level 1, Elevation=3000.103380924),Structural Columns,Concrete - Cast-in-Place Concrete & Curing	6.79 days	Mon 10/15/18	Tue 10/23/18
Removal of formwork	1 day	Tue 10/23/18	Wed 10/24/18
Forms in place, Beams	13.04 days	Tue 10/23/18	Wed 11/7/18
Concrete Reinforcement Beams	4.93 days	Wed 11/7/18	Tue 11/13/18

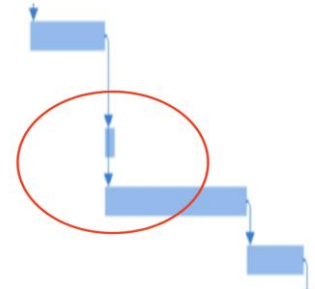


Figure 33. A sample of the difference between two schedules

Concrete Reinforcement Columns	Fri 9/28/18	Thu 10/4/18	0%	0 hrs
Forms in place, Columns	Thu 10/4/18	Mon 10/15/18	0%	0 hrs
Level(Name=Level 1, Elevation=3000.103380924),Structural Columns,Concrete - Cast-in-Place Concrete & Curing	Mon 10/15/18	Tue 10/23/18	0%	0 hrs
Forms in place, Beams	Tue 10/23/18	Wed 11/7/18	0%	0 hrs
Concrete Reinforcement Beams	Wed 11/7/18	Tue 11/13/18	0%	0 hrs
Level(Name=Level 1, Elevation=3000.103380924),Structural Framing,Concrete, Cast-in-Place gray & Curing	Tue 11/13/18	Sat 11/24/18	0%	0 hrs
Forms in place, Floor Slabs	Sat 11/24/18	Tue 12/11/18	0%	0 hrs
Concrete Reinforcement Slabs	Tue 12/11/18	Wed 12/19/18	0%	0 hrs
Level(Name=Level 1, Elevation=3000.103380924),Floors,Insitu Concrete 225mm & Curing	Wed 12/19/18	Thu 1/3/19	0%	0 hrs
Concrete Reinforcement Walls	Thu 1/3/19	Thu 1/3/19	0%	0 hrs
Forms in place, Generic Walls	Thu 1/3/19	Tue 1/8/19	0%	0 hrs
Level(Name=Level 1, Elevation=3000.103380924),Walls,Generic - 200mm	Tue 1/8/19	Tue 1/15/19	0%	0 hrs
Concrete Reinforcement Columns	Tue 1/15/19	Mon 1/21/19	0%	0 hrs
Forms in place, Columns	Mon 1/21/19	Thu 1/31/19	0%	0 hrs
Level(Name=Level 2, Elevation=6000.10338091655),Structural Columns,Concrete - Cast-in-Place Concrete & Curing	Thu 1/31/19	Thu 2/7/19	0%	0 hrs
Forms in place, Beams	Thu 2/7/19	Fri 2/22/19	0%	0 hrs
Concrete Reinforcement Beams	Fri 2/22/19	Wed 2/27/19	0%	0 hrs
Level(Name=Level 2, Elevation=6000.10338091655),Structural Framing,Concrete, Cast-in-Place gray & Curing	Wed 2/27/19	Sat 3/9/19	0%	0 hrs
Forms in place, Floor Slabs	Mon 3/11/19	Fri 3/29/19	0%	0 hrs

Figure 34. A sample of the critical task analysis from MS Project

The generated schedule for the first model consisted of 137 activities, including 17 initial site works, 23 activities for installation of doors, windows, and stairs, and 100 activities are completed above ground. Activities list includes: cast-in-place for the foundations, columns, beams, floors, stairs, external walls, interior walls, and windows and doors' delivery time. The system estimated 581 working days to complete the construction under the optimized scheduling rule, which was assumed to start on March 12th, 2018 and will finish on January 18th, 2020. By using the sequential predecessor rule, the project will be completed in 646 working days, which starts on March 12th, 2018 and will finish on April 3rd, 2020. The calendar of this project was set to include 48 hours per workweek (Sundays are non-working day).

The second model schedule included 89 activities in total, in which 10 of them are for initial site works, 18 tasks are for the installation and delivery of doors, windows, and stairs, as well as 61 above-ground tasks. The system calculates the duration for the main structure's construction would be 350 days in sequential construction rule, which was assumed to start on March 12th, 2018, and finish on April 23th, 2019. By applying the optimized construction rule, the project will be finished in 310 days, which will start on March 12th, 2018, and will finish on March 8th, 2019. Similar to last model's project, the working hours for this project is set as 48 hours per workweek (Sundays are non-working day). The Gantt Chart, milestones, as well as the critical tasks analysis are also displayed in the MS Project.

The generated schedule of the third model included 99 activities totally, including 15 site works and 10 tasks for delivering and installation of the doors and windows. The sequential duration is estimated as 524 days, which is shorted to 479 days under the optimized construction conditions.

After generating the schedules for these three models, the accuracy of the results was evaluated. Firstly, the conformance of extracting data from Revit, as well as, exchanging the data between

several software programs were validated. For the 1st level of the 1st model, for example, the system detected and exported 75 columns to the Excel, which matched the quantity and properties of the corresponding columns created in the original model. Table 6 shows a sample of the validation process for the accuracy of data extraction in the first experimental model. It includes the quantity of each level's columns in the Revit and compared this data with the quantity of the matched levels' columns exported to the Excel.

Table 6. A sample of the validation of data extraction and exchange processes

Columns' number	Revit	Excel
B.O. Footing Level	77	77
T.O. Slab	77	77
Level 1	75	75
Level 2	75	75
Level 3	75	75

Next, the accuracy of generated work packages was checked against the defined rules. The conformance of the sequences of the generated activities was also checked with the defined construction orders. Table 7 presents a sample of the validation process for these steps. In this table, the construction sequences generated in the schedule were compared with the construction order defined in the system.

Table 7. A sample of the validation process for the generated work packages and their sequences

Components	Defined Construction Order	The Construction Order in Generated Schedule
Foundation	Assembling the Formwork	Forms in Place, Footings
	Placing Reinforcement	Concrete Reinforcement Footings
	Casting & Curing	Concrete-Cast-in-Place Concrete & Curing
	Removing Formwork	Removal of Formwork
Columns	Placing Reinforcement	Concrete Reinforcement Columns
	Assembling the Formwork	Forms in Place, Columns
	Casting & Curing	Concrete-Cast-in-Place Concrete & Curing
	Removing Formwork	Removal of Formwork
...

In addition, the calculated durations' exactness was also verified. It showed that the system was able to reference the matched production rates based on the element types and their material.

4.4. Discussion

By summarizing these three models, some important points were found. First, for all models, foundation construction, reinforced concrete framing and floor construction activities take a large portion of total duration. Second, this system provides two different schedule results for each project based on sequential and optimized scheduling rules. Users are able to compare and select the more feasible schedule based to their project's conditions (e.g. applied methods and availability of resources), and then they can refine the schedule by changing sequences or durations to fit their project conditions.

This system, however, has some limitations which were observed during the validation process. First, users might have to divide a building level into smaller work zones in the projects

with large level areas. For example, floor slabs are formed and casted in two or three segments in large buildings (see Figure 35). This system, however, assumes a single work zone in each building level. But if users want to set a number of construction areas within one level, they have manually separate the tasks into different work zones.

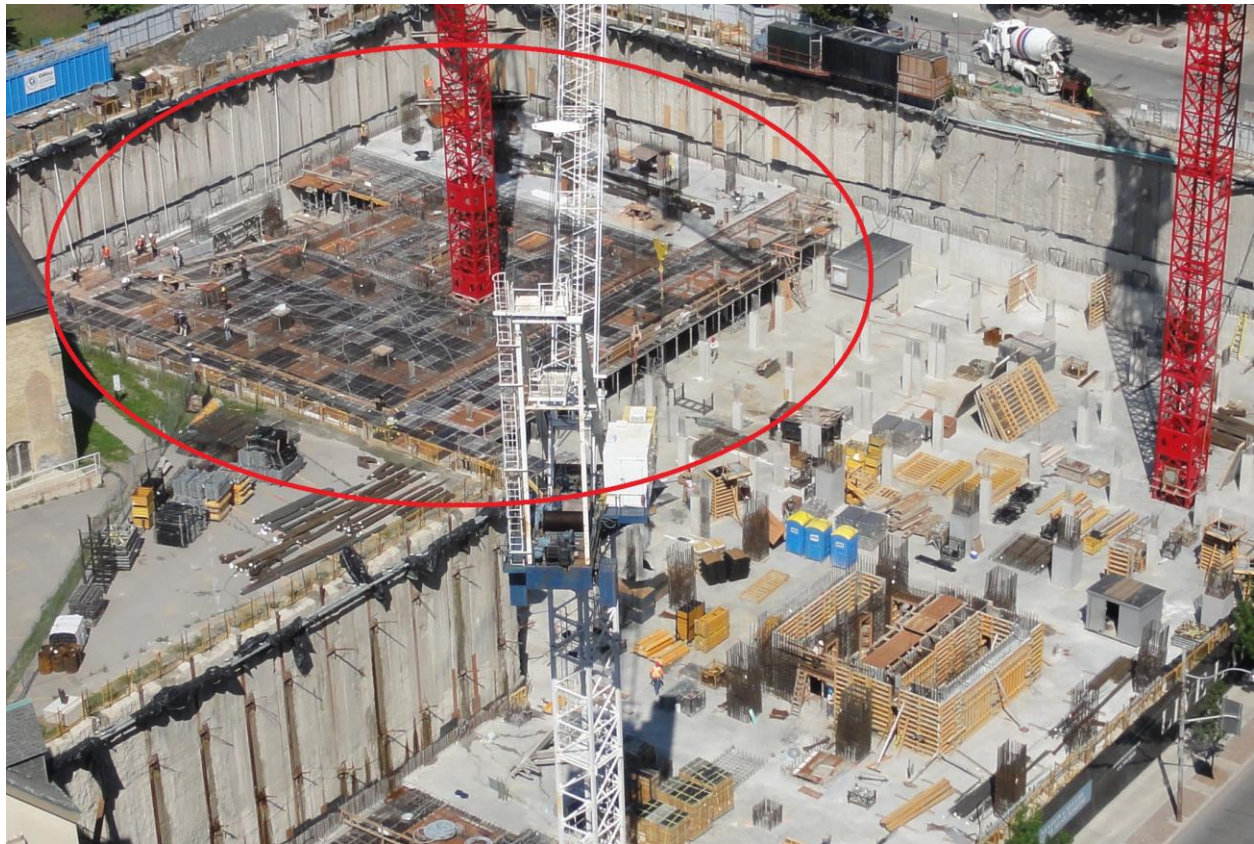


Figure 35. Form working of a floor slab in sections

Second, although this system provides two schedule results for each project, including sequential and optimized scheduling, it does not specially consider simultaneous construction (overlapping) of different activities, and the arrangement of tasks are still mainly sequential (see Figure 31). However, after a completed schedule is transferred into MS Project, users are able to change the precedence relationship of activities, as well as their durations. They can develop their own overlapping tasks schedules based on their projects' construction situation. Third, limited

types of structural materials were considered in this research, which limits its capability in scheduling various projects, and this research should be expanded to include variety of building structural systems, including steel and engineered wood.

4.5. Conclusions

The automatic scheduling generation process is tested and its result is discussed in this chapter. The main purpose of this process was to demonstrate the capability of BIM-based platforms in automated data extraction, data process, and data exchange. Comparison of the quantity takeoff reports generated from the original model and by this system revealed no lose or skips of any building data or material properties. All the information of model in Revit are consistent with the results generated by the developed system.

In addition, this system demonstrated the capacity for data access and exchange with a number of other software programs, which were the Dynamo, EXCEL's VBA and Marcos. Another objective of this process was to analyze the practicability of generated schedule. This validation process demonstrated the ability of the system in creation of the work packages based on the defined criteria, and also showed its potential in estimation of tasks' duration using a construction productivity database, as well as in determining basic relationships. But since the building models did not include all the building components, namely electrical and mechanical systems, the comparison of durations between the results of this system and a real construction project is not illustrative.

Chapter 5: Conclusion

5.1. Introduction

Scheduling is considered a fundamental tool in project management, because it can facilitate managing project time, cashflow, resource allocation, participants' working schedule, procurement and logistics timeline, and consequently it enhances the chance of project success. It is difficult to generate precise results by applying traditional manual scheduling methods, because of potential human errors. Traditional scheduling methods are also tedious and troublesome for engineers. Emergence of BIM in AEC industry has encouraged researchers to explore its potentials in project scheduling field.

The objective of this research is to develop a BIM-based automated scheduling process for reinforced concrete buildings. It extends BIM's potential in automated construction management and helps construction engineers avoid tedious and error-prone tasks in scheduling. Several types of software products are linked with BIM platform to create a bridge that can exchange, process, and export building data.

In this chapter, a summary of this research is presented, which includes the objectives, contributions, conclusion, as well as, the recommendations and future development of this research area.

5.2. Conclusion and Research Contributions

5.2.1 Conclusions

This framework is designed to automatically generate schedule of a reinforced concrete building project using its building information model. It can generate construction tasks list, each task's duration, and project's total duration by using a BIM platform, programming construction sequencing rules, and productivity rates from RSMeans.

This system extracts model information from Revit by using Dynamo programming platform, which also transfers data to Microsoft Excel. The Excel subsequently generates activity package, calculates the project durations, and saves it in Microsoft Project file for further analysis, such as generating Gantt Chart and CPM.

5.2.2 Research Contributions

1) Contributions on automated schedule generation

This framework can automatically create the tasks list, calculate their duration, and provide the schedule. It offers a way that can solve the most drawbacks of traditional scheduling method, including the difficulty of exchanging data between different project stages, and reduce human errors. This system is able to generate project plan and save the troubles for engineers in developing task list and calculation of durations.

2) Contributions on extending BIM's connecting function

In the development of this prototype, two programming tools have been linked with BIM, which are the VBA Macros and the Dynamo. It has demonstrated the possibility of associating BIM with programming tools, therefore, some extensions of BIM's functions can be discovered.

Dynamo, a graphic programming tool, is able to link BIM to Excel. By extracting building information and exporting to spreadsheet, some advanced functions, such as data mapping and processing, are executed.

The BIM has been connected with Microsoft Project as well, which is a project management software. Data exchange between the design and construction stages has formed, which is convenient for designers to communicate with construction engineers, contractors, and owners.

3) Contributions on testing several software's capabilities

Several tools' functionalities have been tested during the system development and a summary has made in the following content.

Dynamo

The Dynamo is a novel graphical programming tool, which is used to extract the data of building model from Revit. It can export building components' parameters, such as volumes, area, estimated reinforcement volumes, organize and transfer these data to Microsoft Excel. It is verified that the Dynamo is practical in the schedule's automated creating process. It can examine model's accuracy, such as checking if all the columns are placed in the right locations, in addition, make changes on the designed model, such as removing beams or columns from the model. This graphical programming tool can improve the efficiency and reduce the difficulty of programming.

Macros and VBA

The combinations of Macros and VBA is critical to the system. It enables Excel to automatically produce task lists, compute the project durations, and save the final schedule in Microsoft Project file. Moreover, it is a common software, which lowers the programming requirement and increases the applicability of this system.

In conclusion, this system is functional to project management. All the software or tools applied are able to support this system to generate the schedule automatically, which indirectly saves the time and cost for project managers.,

5.3. Limitations

Though this system is proved practicable, some additional works are observed to improve this framework. The main limitations are concluded in the following content.

1) Increase the complexity of system

In this system, only a limited number of building components have included, such as walls, columns, and beams. However, for scheduling real buildings' construction, many more complicated building elements are needed to consider. Firstly, it is possible to increase material types in the system. For example, various sizes and types of finishing works can be added in the database of this prototype. Second, the schedule generated in this system does not take the temporary building factors into account, such as scaffoldings. It also requires the consideration of materials' preparation, such as fresh concrete preparation.

2) Optimizing generated schedule

Although this system is able to generate project schedule automatically, it does not generate an optimized solution to crash tasks durations. For some projects, it is possible to build beams during the curing time of walls within the same level. However, the main aim of this system is to demonstrate a proof of concept an automated scheduling system. It only considers basic overlapping tasks based on the common construction rules, such as installing different types of windows or doors within one level. This limitation can be addressed by allowing users to edit tasks'

predecessors in the Excel or MS Project. In the future, the GA algorithm method can be used to extend this system's function in optimizing project duration.

3) Cover electrical and mechanical construction processes

This system only identifies the tasks to construct architectural and structural building components. Although this prototype considers both onsite construction and the material delivery durations of these operations, there are other important tasks that have an important impact on the project schedule and budget. For example, installing heating, ventilation, air conditioning (HVAC), and electrical systems also play a significant role in the time and money spent in a building constructing a project. This can be improved by including these system in the building information model of the project. After re-customizing the Dynamo nodes for these systems, their durations can be computed in the same way as discusses before.

4) Extend the prototype to cover more types of structures

This system is only able to analyze reinforced concrete-framed buildings. There are, however, various types of structural systems, such as steel and timber-framed structures. Therefore, the system can be extended to cover more diverse types of structures.

5.4. Recommendations for Future Work

There are some recommendations for the future research projects to advance this system:

1) 4D simulation

The capability of this system should be extended to include 4D BIM simulation. By connecting this system to a 4D BIM software, such as Navisworks Manage, it is possible to achieve automated project schedule generation and simulation of construction process for users. Testing

the prospect of 4D BIM in the automated project time management field can be the next step of this research.

2) Resource allocation and leveling

Another extension can investigate resource allocation and resource leveling problems. This can be achieved by integrating a GA method with this model-based system. The GA is proficient in the optimizing resource-constrained problems, which can be used in the next study of this research.

3) On-Site spatial scheduling

After enabling the 4D BIM to simulate and visualize the construction process, on-site spatial organization task is possible to achieve. Space supervision provides an essential support to the site management. Based on the former studies, this can be achieved by integrating Global Positioning system (GPS), 4D BIM, and Programming.

4) Uncertain durations

Generating schedule for projects with uncertain work packages is also a valuable extension for this system. Because of resource availability, weather, underground conditions and other causes, duration of building projects sometimes vary from initial schedules. Therefore, it is useful to provide a schedule with probabilistic durations rather than deterministic values. Future expansion of this system could enable calculation of probabilistic durations, which will provide users with more flexible results.

References

- Azhar, S. (2011). Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadership and management in engineering*, 11(3), 241-252.
- Bryde, D., Broquetas, M., & Volm, J. M. (2013). The project benefits of building information modelling (BIM). *International journal of project management*, 31(7), 971-980.
- Candelario-Garrido, A., García-Sanz-Calcedo, J., & Rodríguez, A. M. R. (2017). A quantitative analysis on the feasibility of 4D Planning Graphic Systems versus Conventional Systems in building projects. *Sustainable Cities and Society*, 35, 378-384.
- Chapra, S. C. (2010). *Introduction to VBA for Excel*. Prentice Hall
- Chatfield, C. S., & Johnson, T. D. (2010). *Microsoft Project 2010 step by step*. Pearson Education.
- Chau, K. W., Anson, M., & Zhang, J. P. (2004). Four-dimensional visualization of construction scheduling and site utilization. *Journal of construction engineering and management*, 130(4), 598-606.
- Chen, S. M., Chen, P. H., & Chang, L. M. (2013). A framework for an automated and integrated project scheduling and management system. *Automation in Construction*, 35, 89-110.
- Cherneck, J., Logcher, R., & Sriram, D. (1991). Integrating CAD with construction-schedule generation. *Journal of computing in civil engineering*, 5(1), 64-84.
- Chevallier, N., & Russell, A. D. (1998). Automated schedule generation. *Canadian journal of civil engineering*, 25(6), 1059-1077.
- Choi, J., Kim, H., & Kim, I. (2015). Open BIM-based quantity take-off system for schematic estimation of building frame in early design stage. *Journal of Computational Design and Engineering*, 2(1), 16-25.

- Dang, T., & Bargstädt, H. J. (2015). 4D relationships: The missing link in 4D scheduling. *Journal of Construction Engineering and Management*, 142(2), 04015072.
- Data, Building Construction Cost. "RS Means Company." Inc., Kingston, MA (2017).
- De Vries, B., & Harink, J. M. (2007). Generation of a construction planning from a 3D CAD model. *Automation in Construction*, 16(1), 13-18.
- Dynamo BIM (2018). "Open source graphical programming for design", available at: <http://dynamobim.org>.
- Echeverry, D., Ibbs, C. W., & Kim, S. (1991). Sequencing knowledge for construction scheduling. *Journal of Construction Engineering and Management*, 117(1), 118-130.
- Faghihi, V., Nejat, A., Reinschmidt, K. F., & Kang, J. H. (2015). Automation in construction scheduling: a review of the literature. *The International Journal of Advanced Manufacturing Technology*, 81(9-12), 1845-1856.
- Feng, C. W., Chen, Y. J., & Huang, J. R. (2010). Using the MD CAD model to develop the time-cost integrated schedule for construction projects. *Automation in Construction*, 19(3), 347-356.
- Fischer, M., Aalami, F., & O'Brien Evans, M. (1994). Model-based constructibility analysis: the MOCA system. In CIB W78 workshop on computer integrated construction. CIB, Helsinki.
- Fischer, M. A., & Aalami, F. (1996). Scheduling with computer-interpretable construction method models. *Journal of Construction Engineering and Management*, 122(4), 337-347.
- Fu, F. (2014). Integrated scheduling and batch ordering for construction project. *Applied Mathematical Modelling*, 38(2), 784-797.

- Goedert, J. D., & Meadati, P. (2008). Integrating construction process documentation into building information modeling. *Journal of construction engineering and management*, 134(7), 509-516.
- Hartmann, V., Beucke, K., Shapir, K., & König, M. (2012). Model-based scheduling for construction planning. In 14th International Conference on Computing in Civil and Building Engineering, Moscow.
- Hyatt, C., & Weaver, P. (2006). *A Brief History of Scheduling*. Melbourne, Australia: Mosaic Project Services Pty Ltd.
- Jongeling, R., & Olofsson, T. (2007). A method for planning of work-flow by combined use of location-based scheduling and 4D CAD. *Automation in construction*, 16(2), 189-198.
- Kataoka, M. (2008). Automated generation of construction plans from primitive geometries. *Journal of Construction Engineering and Management*, 134(8), 592-600.
- Kim, H., Anderson, K., Lee, S., & Hildreth, J. (2013). Generating construction schedules through automatic data extraction using open BIM (building information modeling) technology. *Automation in Construction*, 35, 285-295.
- Klein, L., Li, N., & Becerik-Gerber, B. (2012). Imaged-based verification of as-built documentation of operational buildings. *Automation in Construction*, 21, 161-171.
- Kumar, M., Husian, M., Upreti, N., & Gupta, D. (2010). Genetic algorithm: Review and application. *International Journal of Information Technology and Knowledge Management*, 2(2), 451-454.
- Leu, S. S., & Yang, C. H. (1999). GA-based multicriteria optimal model for construction scheduling. *Journal of Construction Engineering and Management*, 125(6), 420-427.

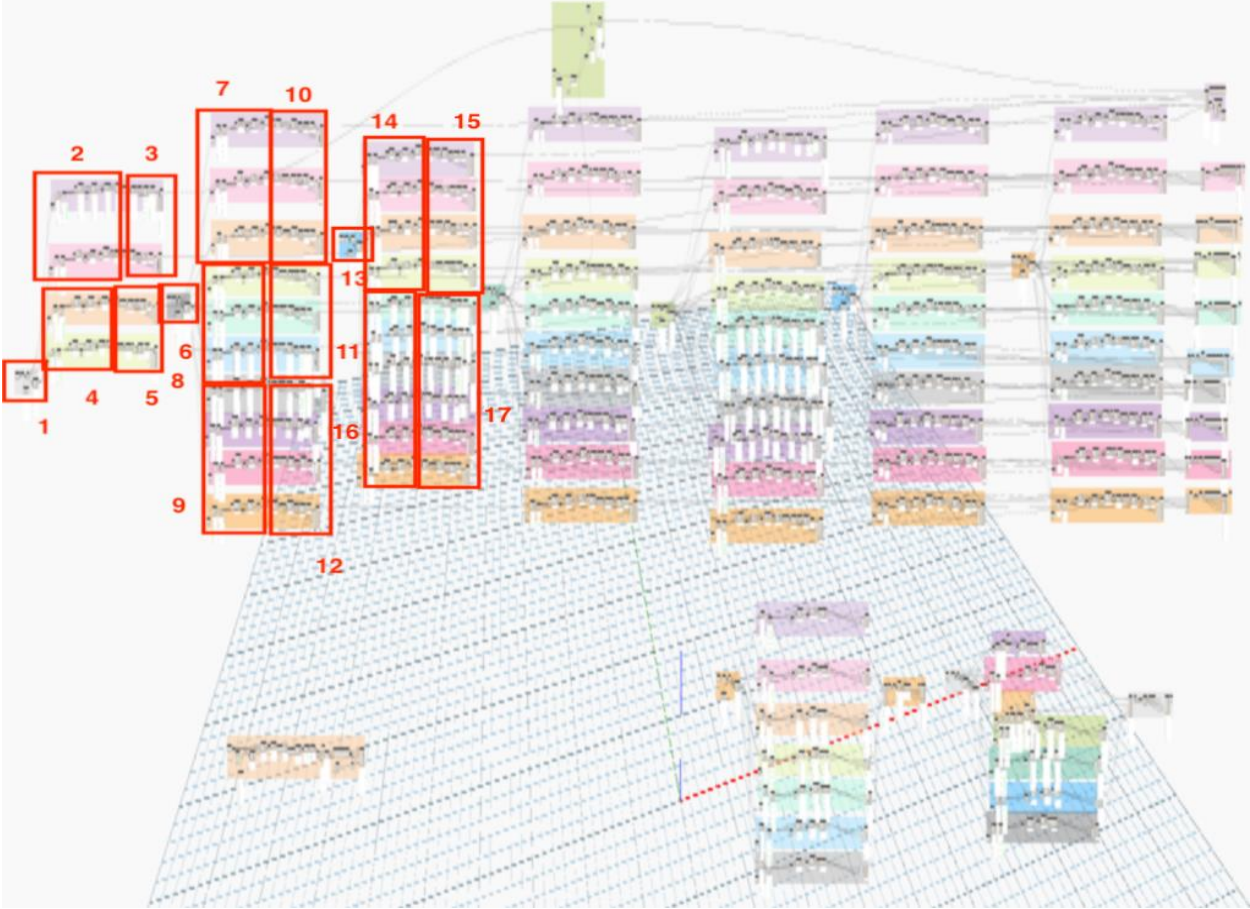
- Li, H., Xu, Z., & Demeulemeester, E. (2014). Scheduling policies for the stochastic resource leveling problem. *Journal of Construction Engineering and Management*, 141(2), 04014072.
- Liu, H., Lei, Z., Li, H. X., & Al-Hussein, M. (2014). An Automatic Scheduling Approach: Building Information Modeling-based Onsite Scheduling for Panelized Construction. In *Construction Research Congress 2014: Construction in a Global Network* (pp. 1666-1675).
- Liu, H., Al-Hussein, M., & Lu, M. (2015). BIM-based integrated approach for detailed construction scheduling under resource constraints. *Automation in Construction*, 53, 29-43.
- Lucko, G. (2009). Productivity scheduling method: Linear schedule analysis with singularity functions. *Journal of Construction Engineering and Management*, 135(4), 246-253.
- Mikulakova, E., König, M., Tauscher, E., & Beucke, K. (2010). Knowledge-based schedule generation and evaluation. *Advanced Engineering Informatics*, 24(4), 389-403.
- Moon, H., Kim, H., Kamat, V. R., & Kang, L. (2013). BIM-based construction scheduling method using optimization theory for reducing activity overlaps. *Journal of Computing in Civil Engineering*, 29(3), 04014048.
- Moon, H., Kim, H., Kim, C., & Kang, L. (2014). Development of a schedule-workspace interference management system simultaneously considering the overlap level of parallel schedules and workspaces. *Automation in Construction*, 39, 93-105.
- Nitithamyong, P., & Skibniewski, M. J. (2004). Web-based construction project management systems: how to make them successful? *Automation in construction*, 13(4), 491-506.

- Oraee, M., Hosseini, M. R., Namini, S. B., & Merschbrock, C. (2017). Where the gaps lie: ten years of research into collaboration on BIM-enabled construction projects. *Construction Economics and Building*, 17(1), 121-139.
- QUI, N. T. (2013). *AUTOMATED SCHEDULE GENERATION AND ANALYSIS FROM A CONSTRUCTION REQUIREMENT PERSPECTIVE* (Doctoral dissertation).
- Revit Architecture 2011, users' guide.
Available at: <https://www.autodesk.com/products/revit/overview>
- Rogalska, M., Bozejko, W., & Hejducki, Z. (2008). Time/cost optimization using hybrid evolutionary algorithm in construction project scheduling. *Automation in Construction*, 18(1), 24-31.
- RSMeans. (2018). "Building Construction Cost Data", Construction Publishers & Consultants, Kingston, MA, available at <https://www.rsmeans.com>.
- Ryu, H. G., Lee, H. S., & Park, M. (2007). Construction planning method using case-based reasoning (CONPLA-CBR). *Journal of computing in civil engineering*, 21(6), 410-422.
- Schwabe, K., Liedtke, S., König, M., & Teizer, J. (2016). BIM-based Construction Site Layout Planning and Scheduling. In *International Conference on Computing in Civil and Building Engineering (ICCCBE)*.
- Sigalov, K., & König, M. (2017). Recognition of process patterns for BIM-based construction schedules. *Advanced Engineering Informatics*, 33, 456-472.
- Son, H., Kim, C., & Kwon Cho, Y. (2017). Automated schedule updates using as-built data and a 4D building information model. *Journal of Management in Engineering*, 33(4), 04017012.

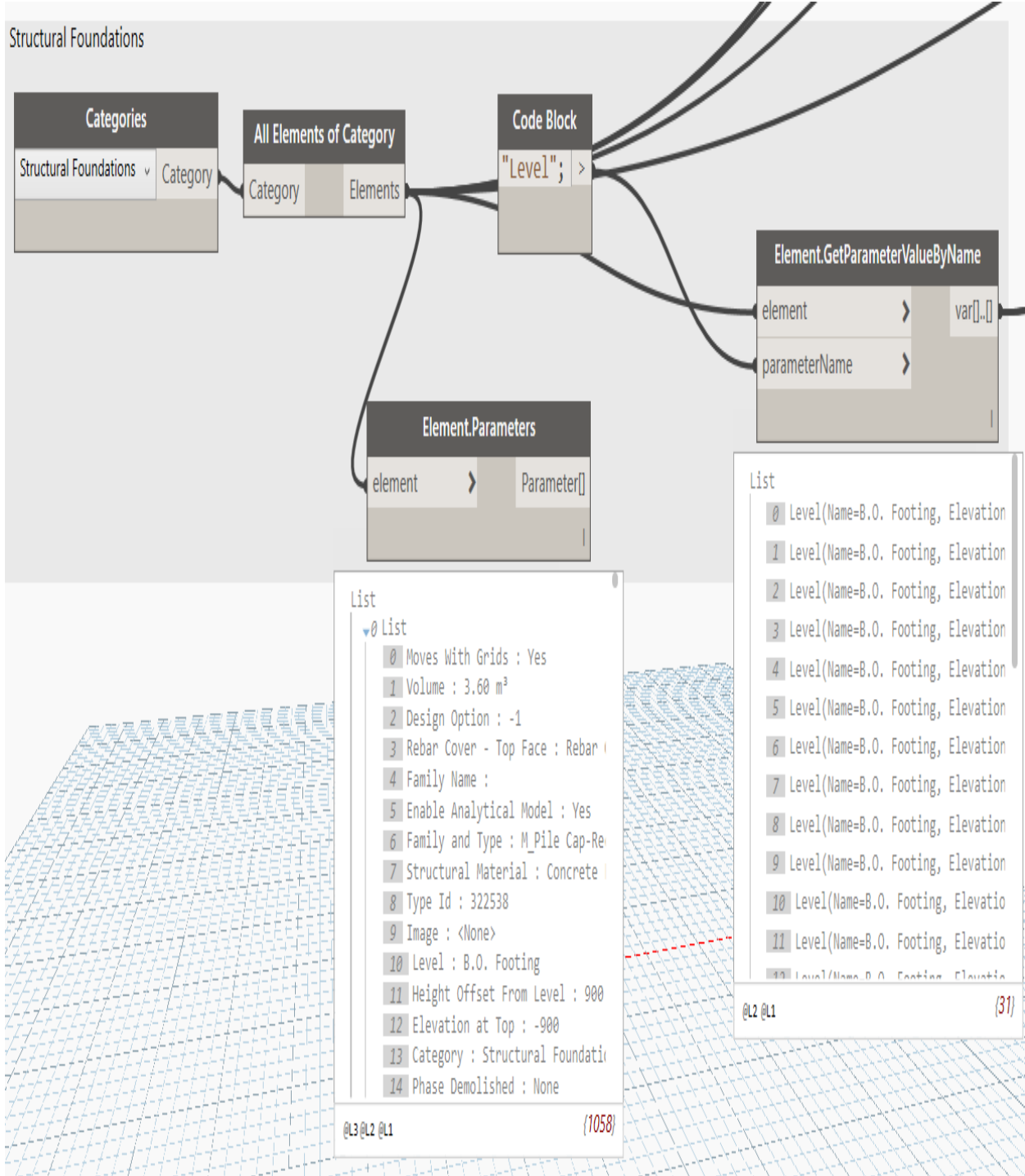
- Toklu, Y. C. (2002). Application of genetic algorithms to construction scheduling with or without resource constraints. *Canadian Journal of Civil Engineering*, 29(3), 421-429.
- Tran, D. H., Cheng, M. Y., & Pham, A. D. (2016). Using Fuzzy Clustering Chaotic-based Differential Evolution to solve multiple resources leveling in the multiple projects scheduling problem. *Alexandria Engineering Journal*, 55(2), 1541-1552.
- Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings—Literature review and future needs. *Automation in construction*, 38, 109-127.
- Wang, H., & Song, X. (2015). Research on BIM Construction Schedule Generating Algorithm. *International Journal of Simulation--Systems, Science & Technology*, 16.
- Wang, W. C., Weng, S. W., Wang, S. H., & Chen, C. Y. (2014). Integrating building information models with construction process simulations for project scheduling support. *Automation in construction*, 37, 68-80.
- Wu, I. C., Borrmann, A., Beißert, U., König, M., & Rank, E. (2010). Bridge construction schedule generation with pattern-based construction methods and constraint-based simulation. *Advanced Engineering Informatics*, 24(4), 379-388.
- Yau, N. J., & Yang, J. B. (1998). Case-based reasoning in construction management. *Computer-Aided Civil and Infrastructure Engineering*, 13(2), 143-150.
- Zhang, S., Teizer, J., Lee, J. K., Eastman, C. M., & Venugopal, M. (2013). Building information modeling (BIM) and safety: Automatic safety checking of construction models and schedules. *Automation in Construction*, 29, 183-195.

Appendix

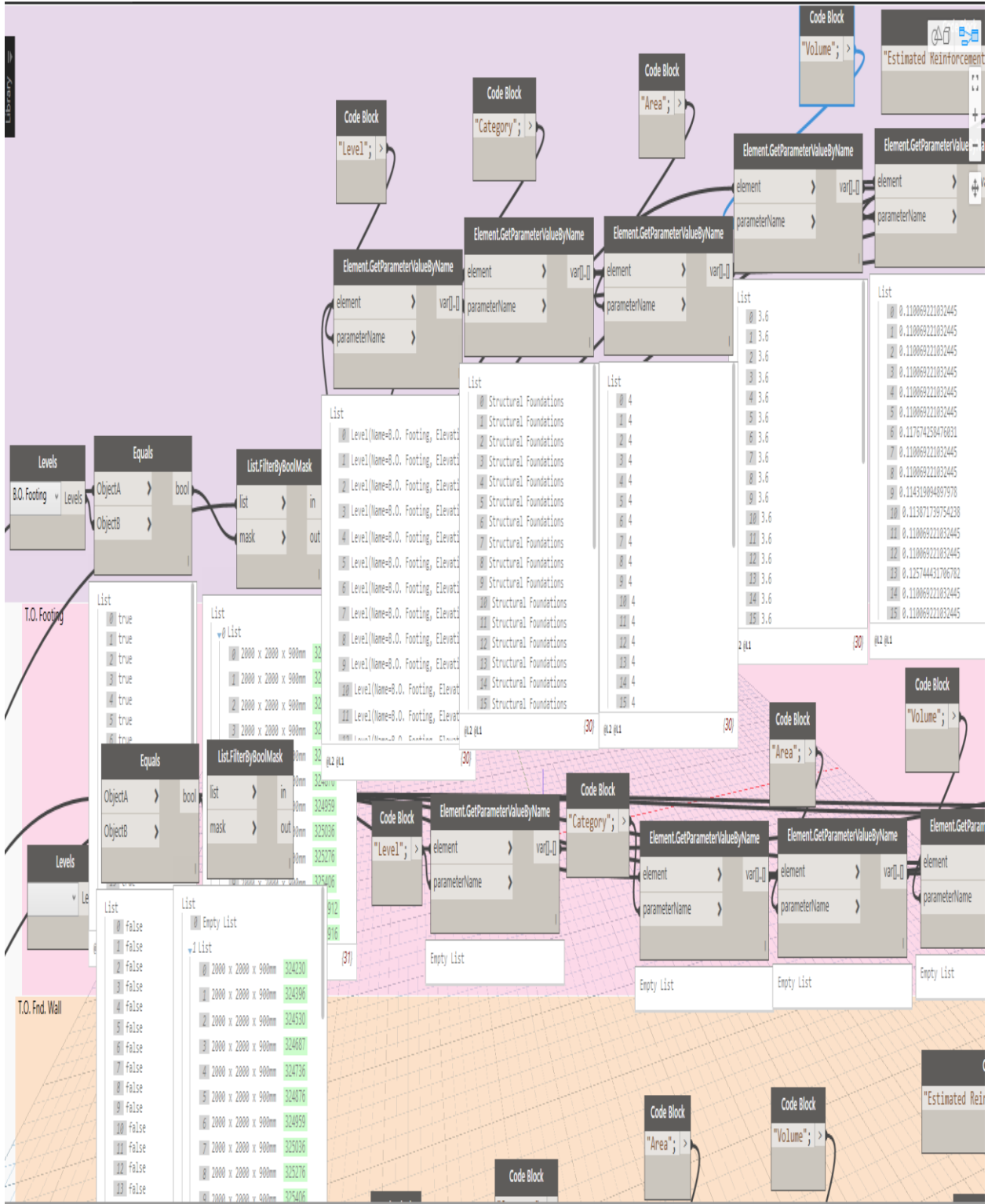
The following figures present the entire Dynamo script with high resolution. The algorithm used for extraction of all structural elements use the same logic, therefore, only a sample script for one structural element is provided.



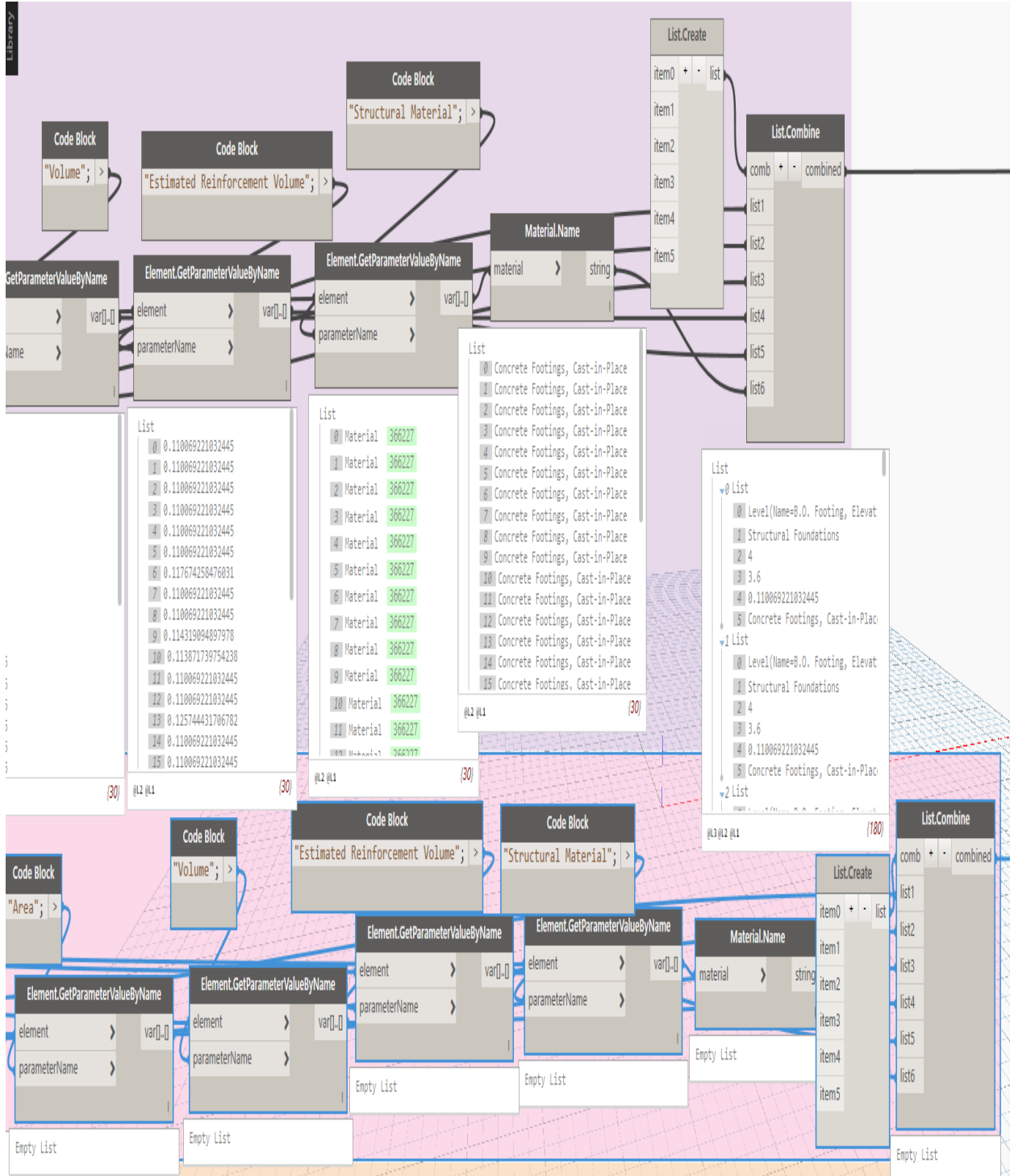
1. The picture showed the foundations' first part of Dynamo nodes (defined in the Chapter 3).



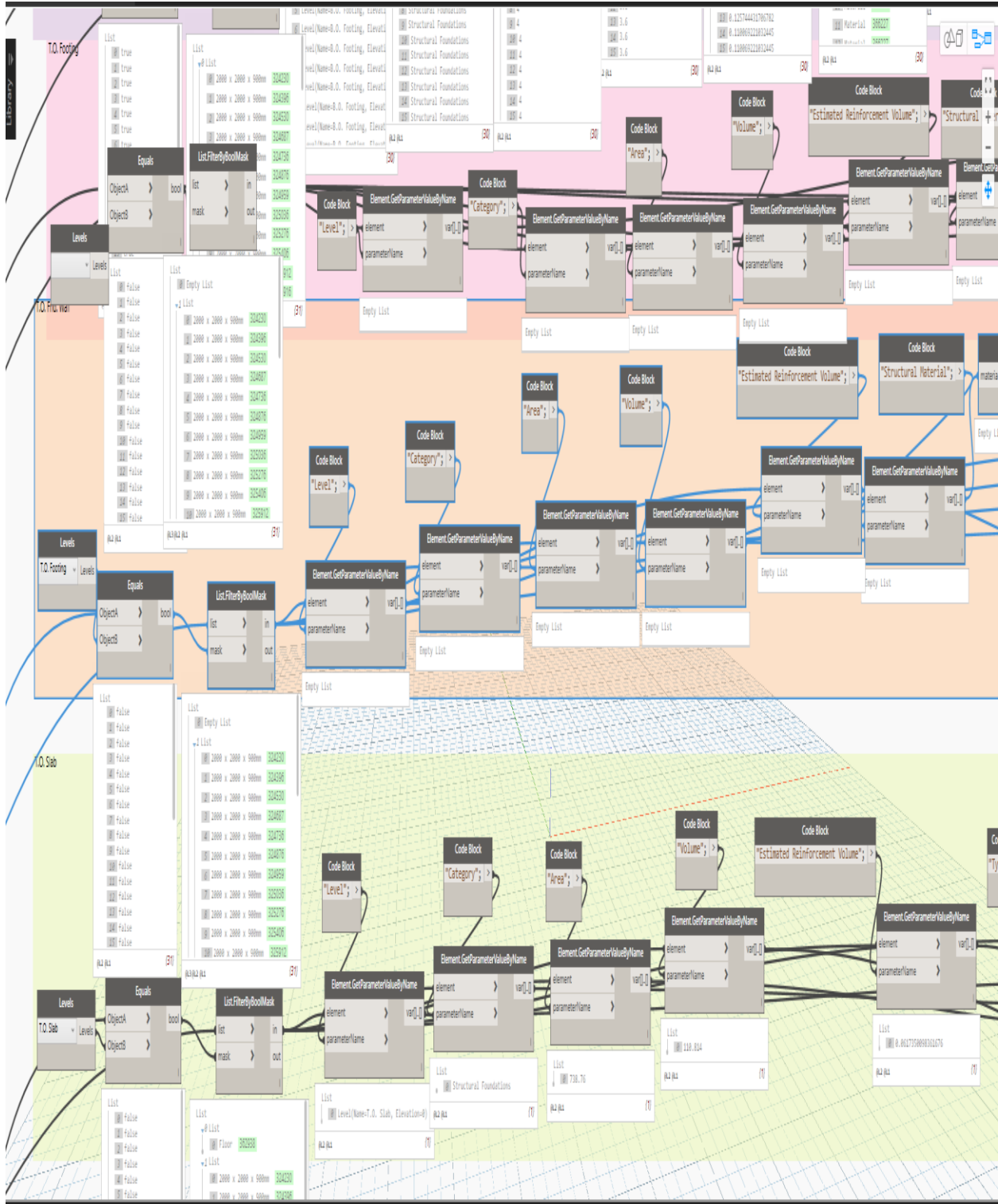
2. The picture showed foundations' second part of Dynamo nodes (defined in the Chapter 3).



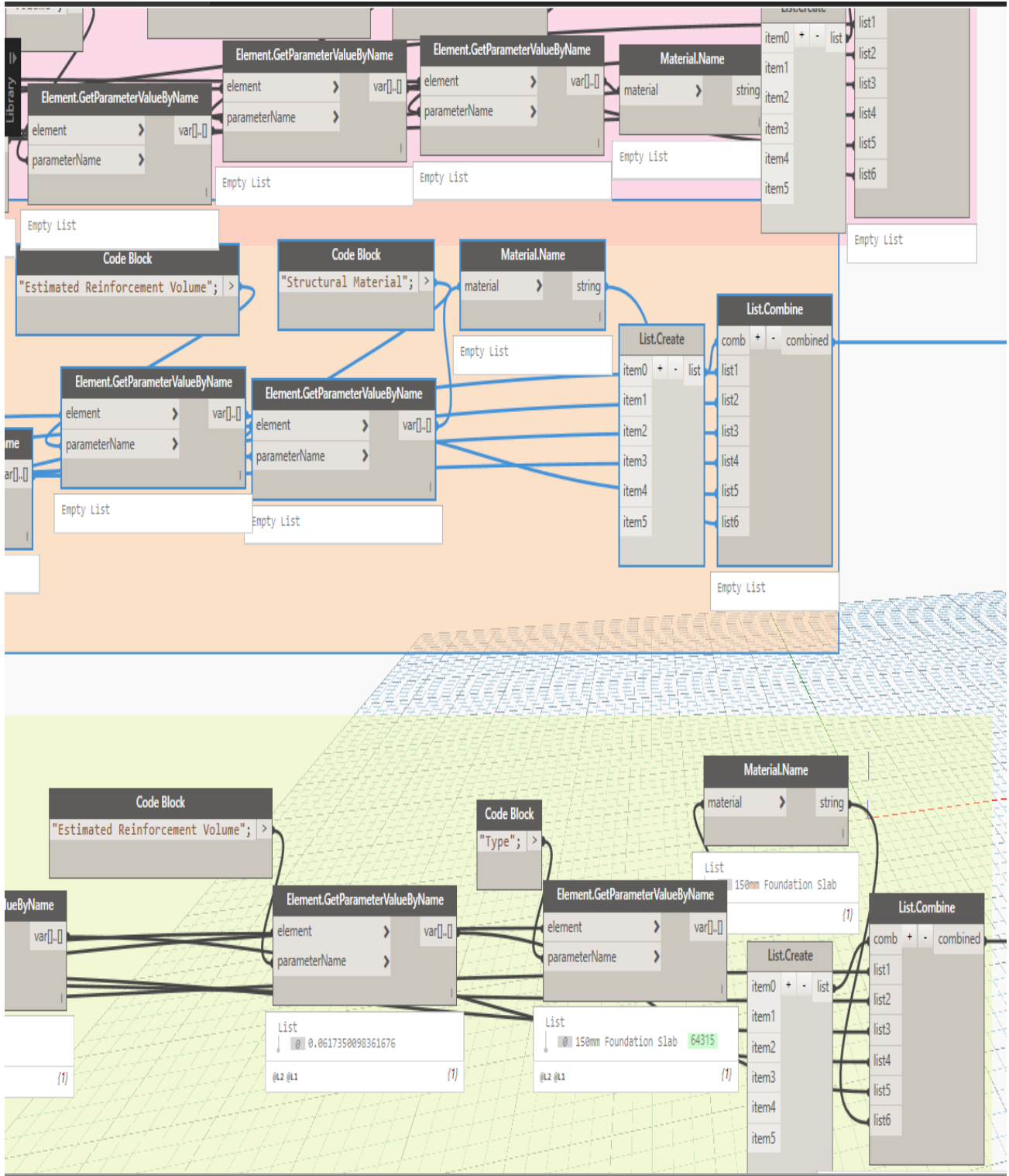
3. The picture showed the foundations' third part of Dynamo nodes (defined in the Chapter 3).



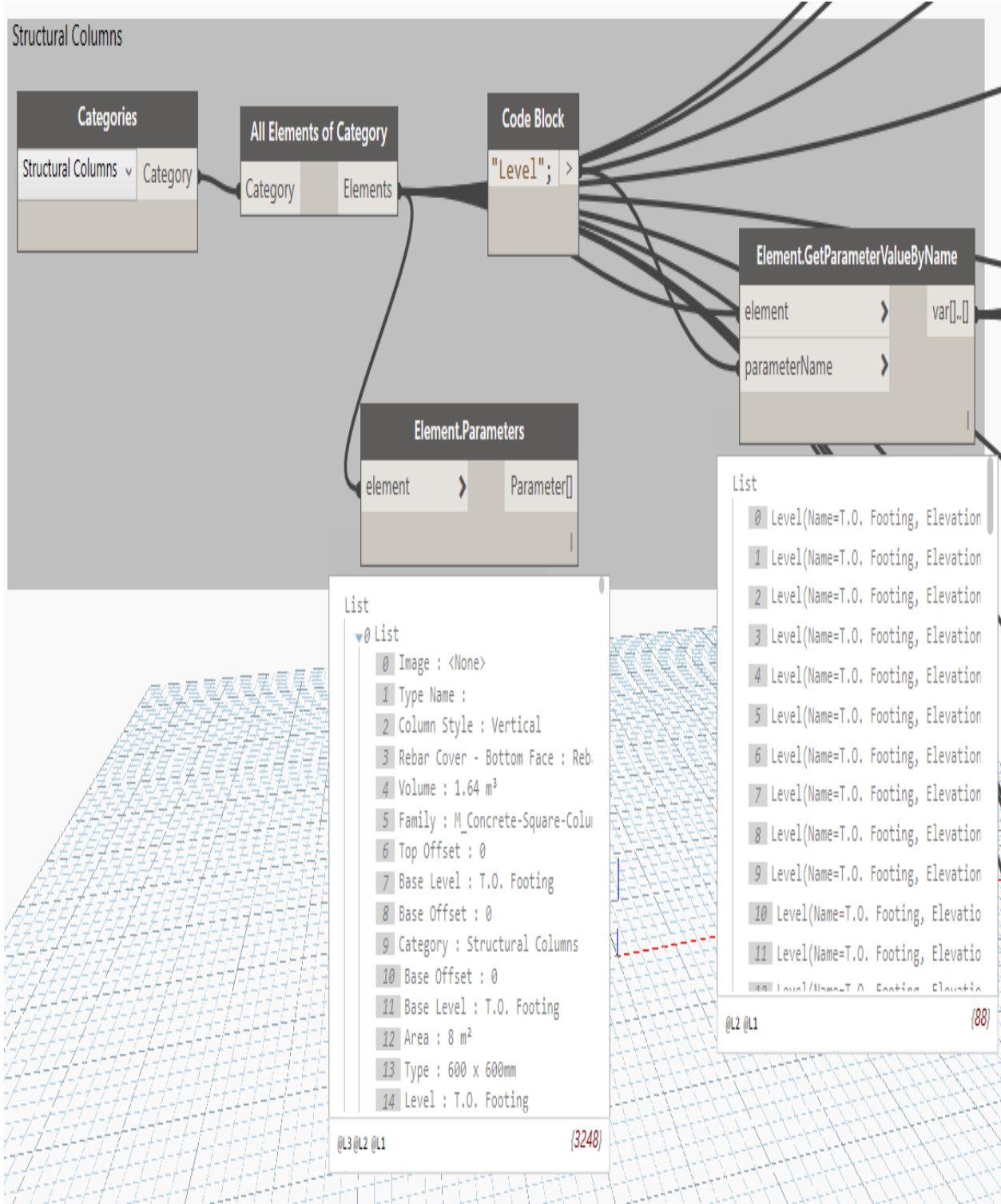
4. The picture showed the foundations' second part of Dynamo nodes (defined in the Chapter 3).



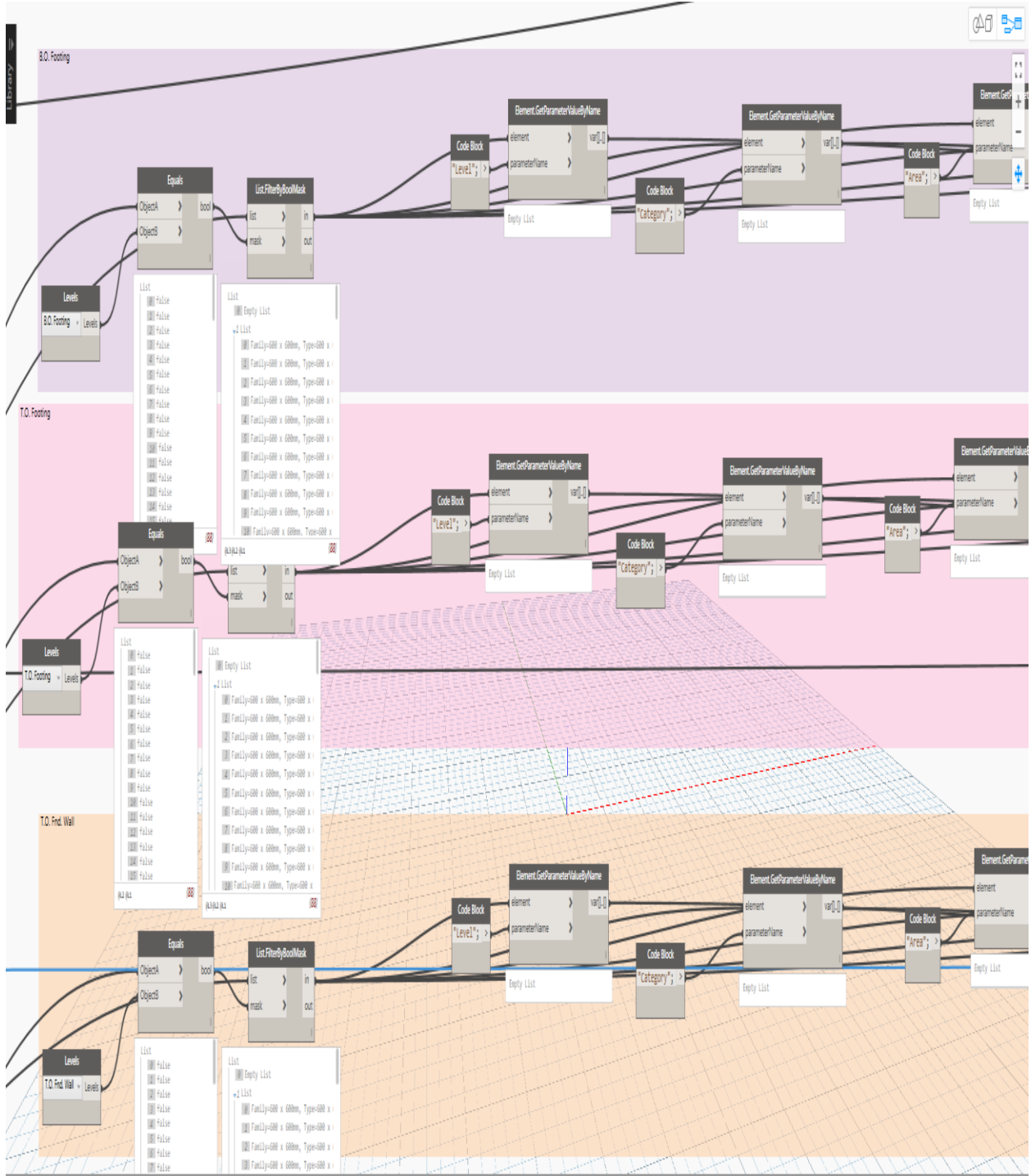
5. The picture showed the foundations' third part of Dynamo nodes (defined in the Chapter 3).



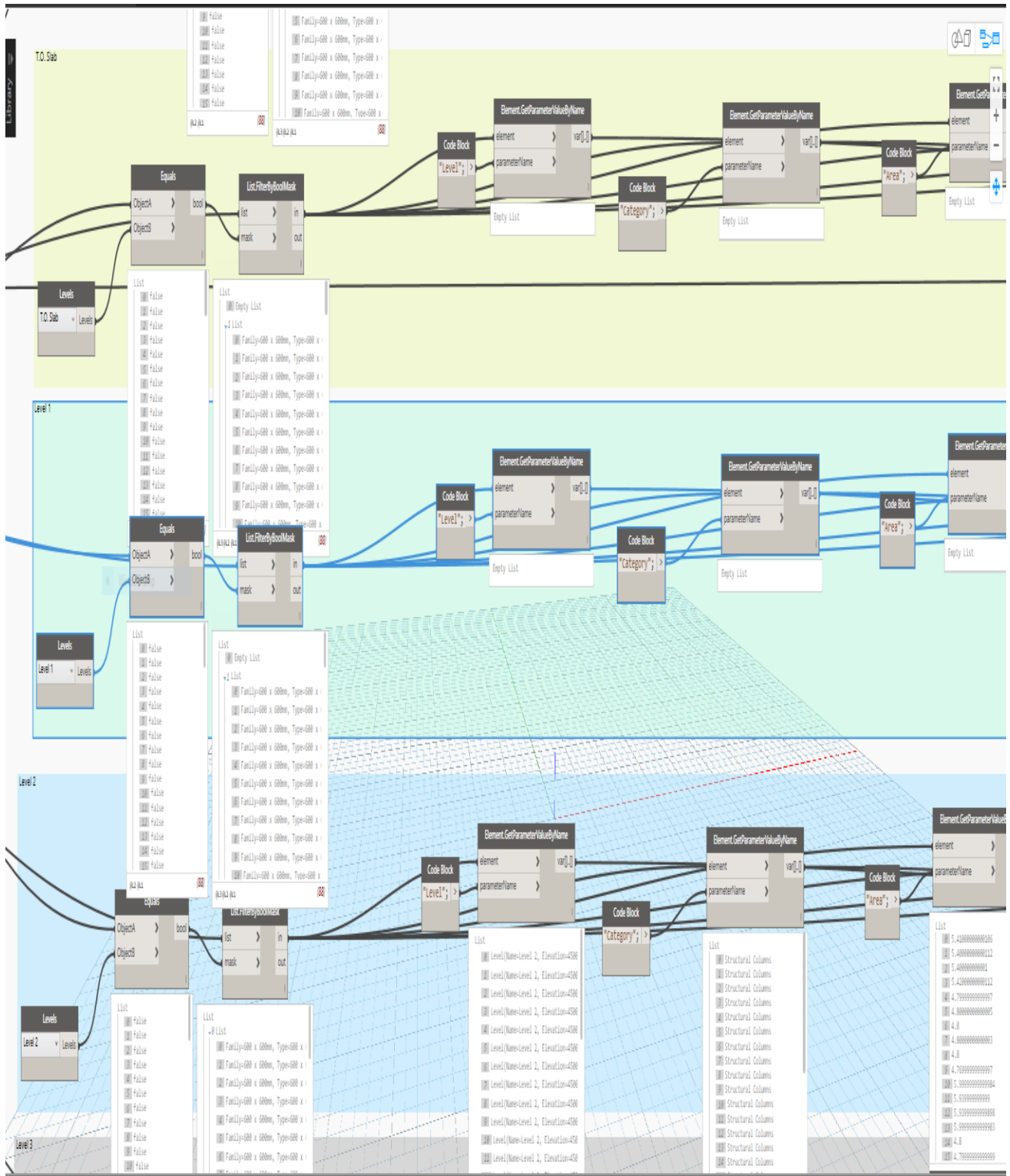
6. The picture showed the columns' first part of Dynamo nodes (defined in the Chapter 3).



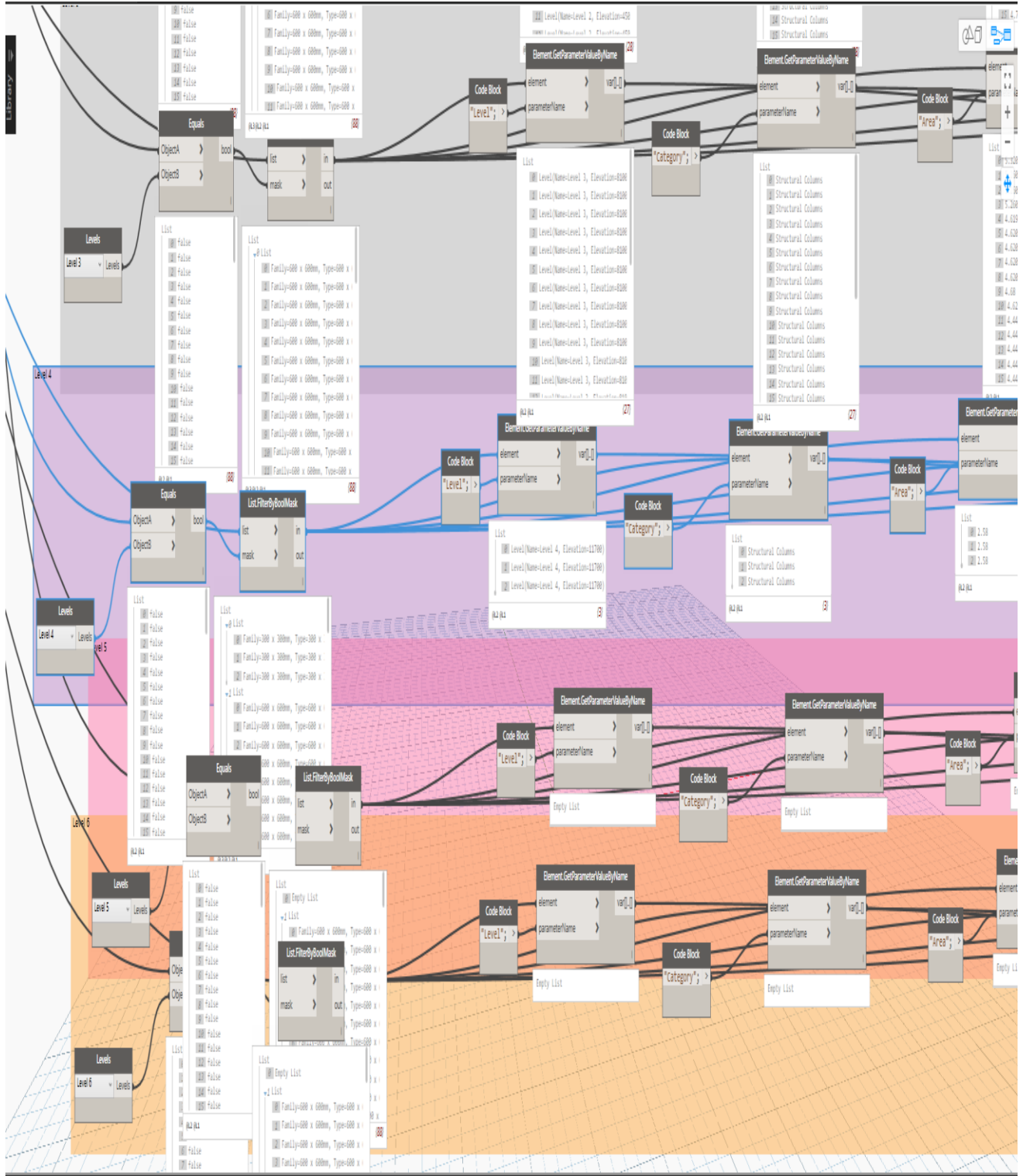
7. The picture showed the columns' second part of Dynamo nodes (defined in the Chapter 3).



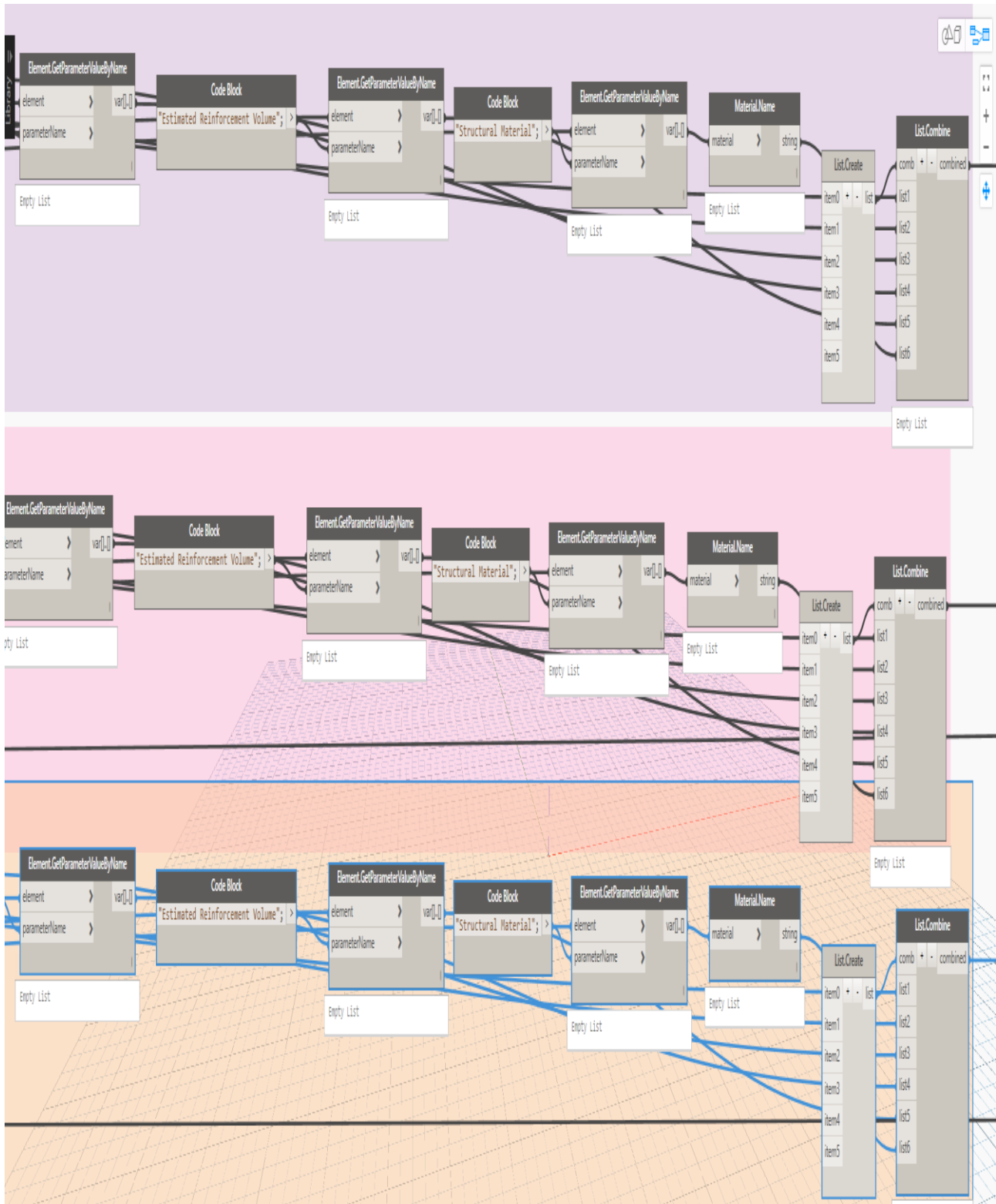
8. The picture showed the columns' second part of Dynamo nodes (defined in the Chapter 3).



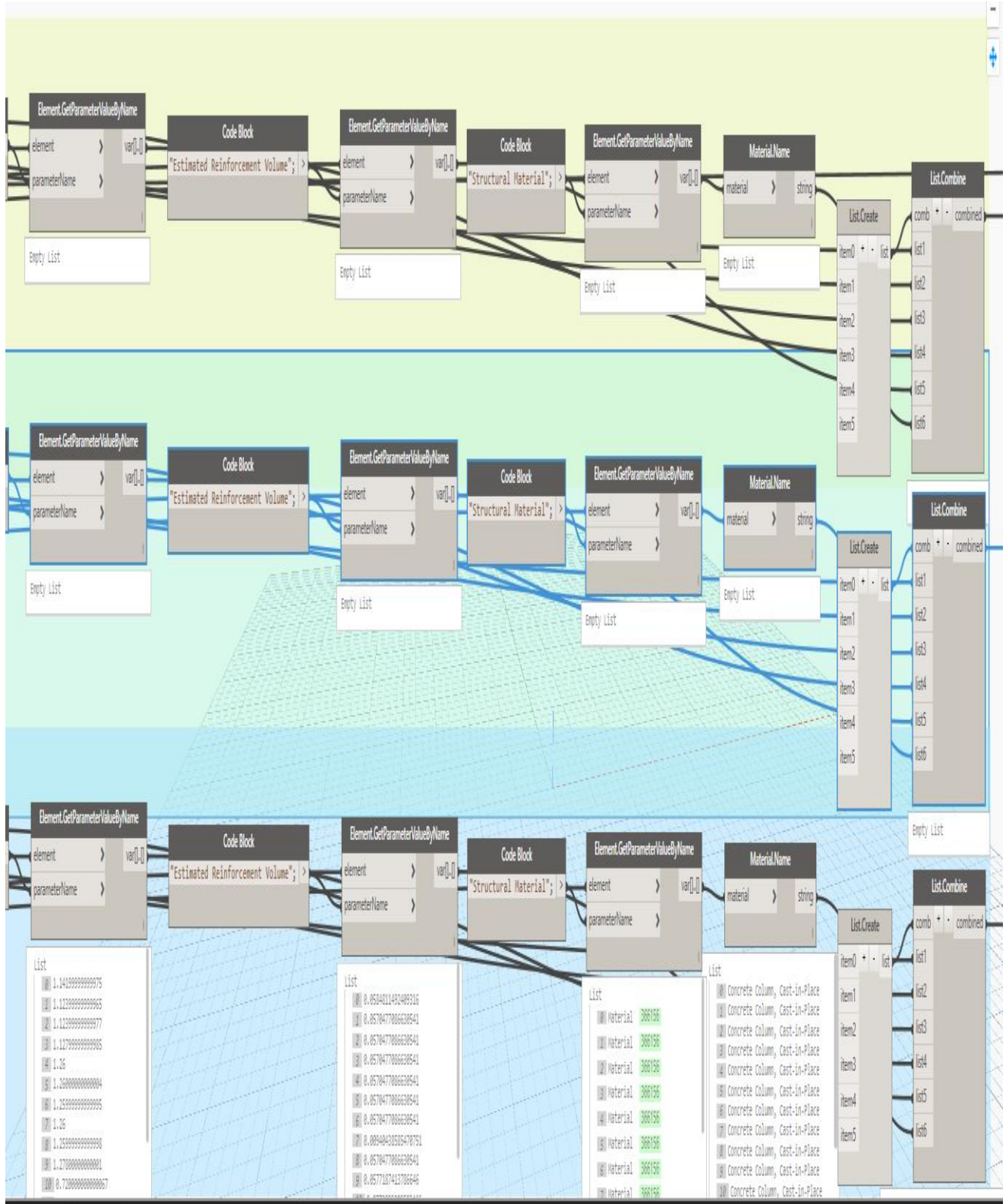
9. The picture showed the columns' second part of Dynamo nodes (defined in the Chapter 3).



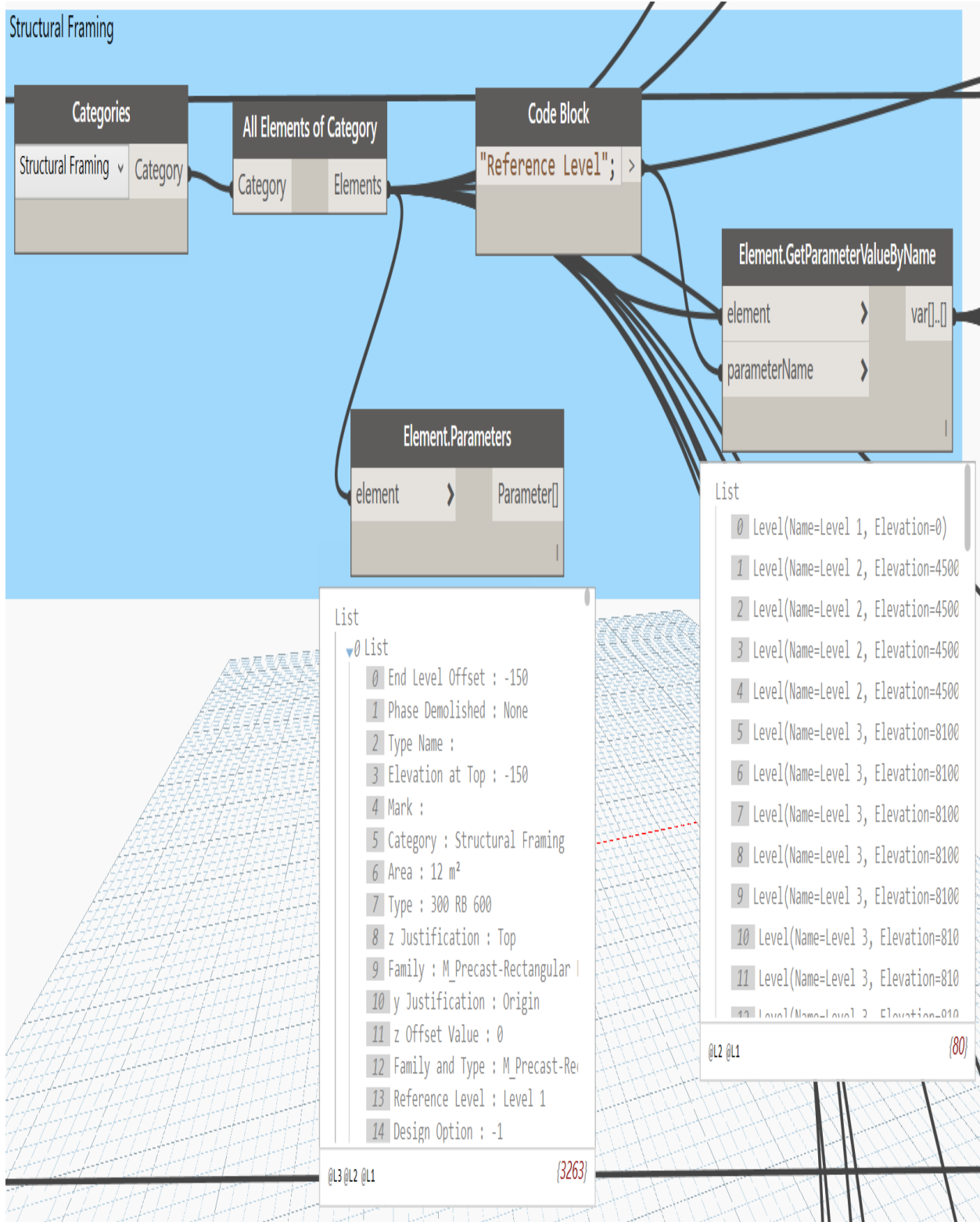
10. The picture showed the columns' third part of Dynamo nodes (defined in the Chapter 3).



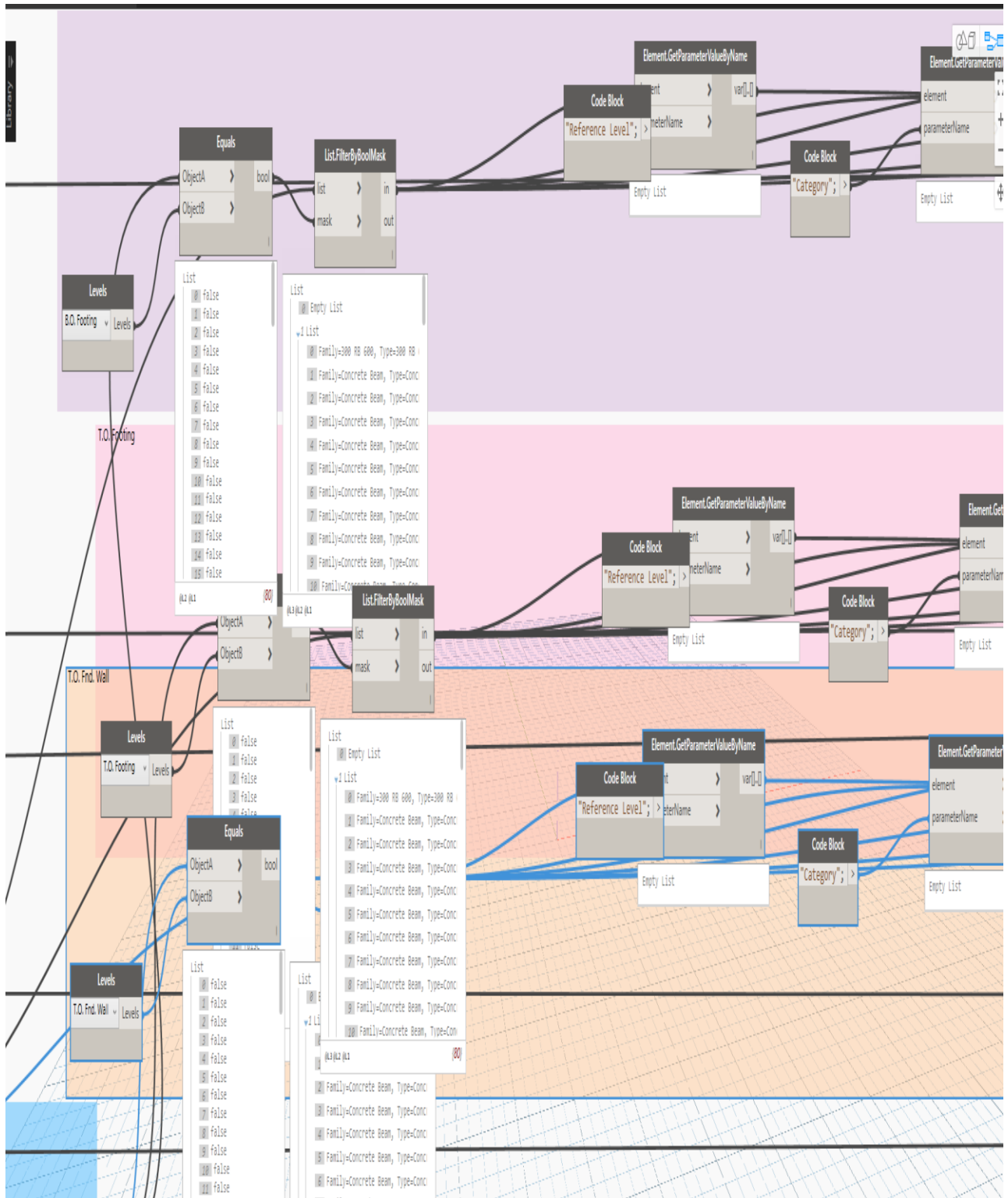
11. The picture showed the columns' third part of Dynamo nodes (defined in the Chapter 3).



13. The picture showed the framings' first part of Dynamo nodes (defined in the Chapter 3).



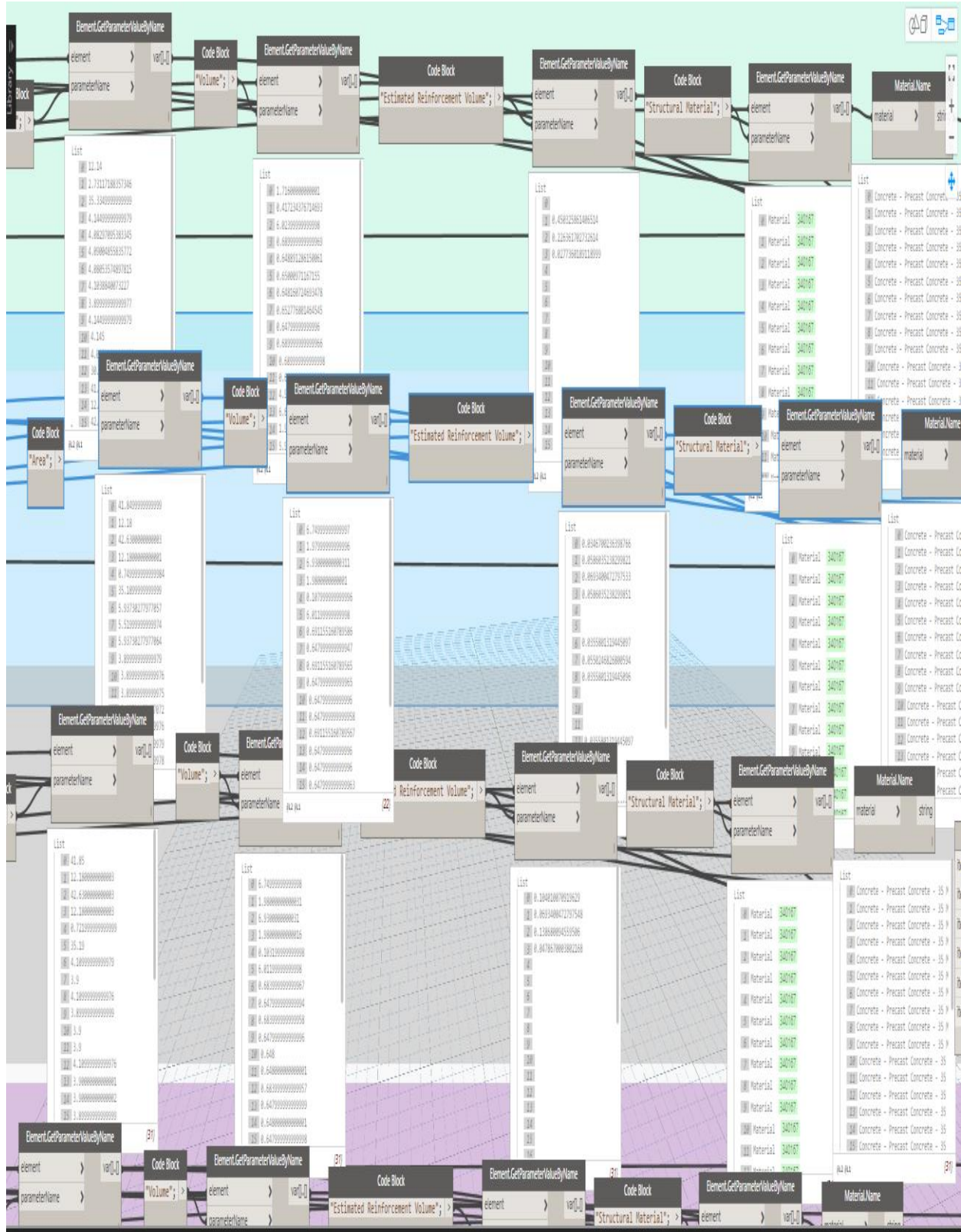
14. The picture showed the framings' second part of Dynamo nodes (defined in the Chapter 3).



15. The picture showed the framings' second part of Dynamo nodes (defined in the Chapter 3).



16. The picture showed the framings' second part of Dynamo nodes (defined in the Chapter 3).



17. The picture showed the framings' third part of Dynamo nodes (defined in the Chapter 3).

