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A More Reliable Method for Cost Estimation of Reinforcement Steel in Early Stages of Design

Master Thesis

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Abstract

Cost analysis has always had a huge impact in the construction industry. It is one of the most important factors for owners, designers and contractors in critical decision making. Traditional methods are very laborious and susceptible to human error, and involve volumetric calculations for complex geometry and manual data input.

The process of cost estimation is tied tightly to quantities take-off. If it is well prepared, it can make cost estimation less labor-intensive, faster and less prone to omissions due to human errors. Therefore, using 2D documentation has become inefficient in contrast with advanced tools in 3D CAD environment. However, in the early stages of design, a BIM model is a prototype with many uncertain parameters and lacks many details. Reinforcement steel is one of these missing details, which makes it very difficult to get reliable quantities, while it is a very important factor in terms of cost.

The purpose of this study is to develop a method that aims to improve the accuracy of cost estimation for reinforced concrete elements in early stages of design using BIM technology. This research consists of the following two stages:

- The first stage is feeding the database; it starts with using reinforcement cross section area (A_s) from analysis calculations to find code-based proper reinforcement. Next step is generating that reinforcement in BIM models. Afterwards, load parameters are implemented and filled for reinforced concrete elements. Lastly, information is collected and exported to database.
- The second stage is calling from the database; no structural design reports are required in this stage. Firstly, loads and dimensions of reinforced concrete elements in a BIM model are gathered, and then an iterative search is carried out through the database to find elements with similar loads and dimensions. Then, reinforcement is generated based on previous experiences stored in database. Finally, quantities are extracted from the BIM model and information is collected and sent to update the database again.

This method was tested on real-life projects designed by Bollinger+Grohmann and results were compared to conventional methods. Moreover, the product of this research can generate rule-based reinforcement parametrically in advanced stages of design.

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List of Abbreviations and Symbols

AEC	Architecture, Engineering and Construction
AIA	American Institute of Architects
API	Application Programming Interface
BIM	Building Information Modeling
CAD	Computer Aided Design
CDE	Common Data Environment
FEM	Finite Element Method
HVAC	Heating, Ventilation and Air Conditioning
LOD	Level of Development/Detail
SQL	Structured Query Language
VPL	Visual Programming Language

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1 Introduction

1.1 Introduction

Construction cost estimation is a foundational principle in forecasting the cost of construction of a structure (ProEst 2020). Owners, designers and contractors need reliable cost estimation in order to determine whether the project will be successful, whether the goals and objectives will be achieved and whether the deliverables will be produced. With conventional methods, a huge effort is required in order to get precise results.

Traditional cost estimation methods are very laborious and susceptible to human error, and could involve volumetric calculations for complex geometry and manual input of information. With large complicated projects, this job gets very time consuming.

Cost Estimate							Page 2
	Description	Qty	Price	UM	Draw	Me	Total
51	SITE PREPARATION						
52	• Rough Stake	1	125.00	Lump Sum	0.00	125.00	125.00
53	• Clearing, Grading, Hauling	6	115.00	Hour	0.00	690.00	690.00
54	• Fill Dirt	5	75.00	Load	375.00		375.00
55	• Locate Corners	1	275.00	Lump Sum	275.00		275.00
56					0.00		0.00
57	TOTAL SITE PREP (LINES 52-55)				650.00	815.00	1,465.00
58							
59	FOOTINGS						
60	• Layout, Dig, and Pour	225	1.10	LF	247.50		247.50
61	• Steel	45	5.40	EA	243.00		243.00
62	• Concrete	15	115.00	CY	1,725.00		1,725.00
63	• Drains				0.00		0.00
64	TOTAL FOOTINGS (LINES 60-63)				2,215.50	0.00	2,215.50
65							
66	FOUNDATIONS						
67	• Concrete	20	115.00	CY	2,300.00		2,300.00
68	• Brick				0.00		0.00
69	• Block				0.00		0.00
70	• Mortar				0.00		0.00
71	• Sand	5	85.00	CY	425.00		425.00
72	• Steel	75	5.40	EA	405.00		405.00
73	• Vents				0.00		0.00
74	• Damp Proofing	1	375.00	Lump Sum	375.00		375.00
75	• Backfill				0.00		0.00
76	• Labor	1	1,000.00	Lump Sum	0.00	1,000.00	1,000.00
77	• Foundation Survey	1	475.00	Lump Sum	475.00		475.00
78					0.00		0.00
79	TOTAL FOUNDATIONS (LINES 67-77)				3,980.00	1,000.00	4,980.00
80							
81	PAGE TOTALS (LINES 57, 64, 79)				6,845.50	1,815.00	8,660.50
82							
83							
84							

Figure 1 - An example of traditional methods for cost estimation (Construction Cost Estimating n.d.)

Conventional cost estimations of structures in construction projects are based on the reading of 2D drawings, which is accompanied by several drawbacks like human errors. Therefore, today's modern means aim to make cost estimation more realistic, faster and more reliable using advanced tools in 3D CAD environment (Vitásek and Zak 2018).

Accurate estimates are especially critical for development projects, which have budgets and timelines closely linked to paying back lenders and generating revenue as early as possible. They are also essential for large civil projects or mega-projects because of their sizable scope and the potential involvement of public money. On a mega-project, small miscalculations become magnified. In projects constructed with public funds, cost estimates increase accountability, provide transparency, and enhance trust in the ability to manage the project properly (Ramos 2017).

A hundred percent accurate cost estimation is impossible to achieve, but the accuracy can be improved with the help of Building Information Modeling (BIM) technology. BIM is the process of creating an intelligent 3D model, which enables document management, coordination and simulation during the entire lifecycle of a project. According to the National Building Information Model Standard Project Committee, BIM is a digital representation of physical and functional characteristics of a facility. In the context of civil engineering industry, BIM means creating an interactive data set for a structure at every stage of its lifecycle, instead of creating a set of new drawings for every stage (National BIM Standard - United States n.d.).

BIM can provide more reliable methods for cost estimation by collecting up-to-date model data from all participants in a project. It also gives the possibility to generate automated lists of volumetric information and materials take-off, which simplifies the whole process and saves time. If pricing information is integrated into a BIM model, cost estimation can be carried out directly.

One indication for model's precision is the Level of Development (LOD). It has a vital effect on quantities take-off results. LOD is a concept developed by the American Institute of Architects (AIA) and it allows BIM to track design throughout all design stages (Wood, Panuwatwanich, and Doh 2014).

LOD is sometimes interpreted as Level of Detail rather than Level of Development. There are important differences between both. Level of Detail is essentially how much detail is included in the model element. Level of Development is the degree to which

the element's geometry and attached information has been thought through, or the degree of information, which project team members may rely on when using the model (BIMForum 2015). Level of Detail can be thought of as inputs to the element, while Level of Development can be thought of as reliable output.

These levels are defined as:

- LOD 100: initial concept design
- LOD 200: general modeling with schematic design
- LOD 300: accurate modeling and detailed design
- LOD 350: greater detail and construction documentation
- LOD 400: fabrication and assembly
- LOD 500: as-built models

There are many other levels, but these are the main stations.

1.2 Motivation

Cost estimation in Germany “Kostenschätzung“ is normally area-based (DIN 277) and carried out in LPh2 “Vorplanung”, while cost calculations “Kostenberechnung” is element-based (DIN 276, 3. Ebene) and happens in LPh3 “Entwurfsplanung” or later. However, reinforcement design is not finalized until LPh5 “Ausführungsplanung”. Therefore, there is usually a gap between actual and estimated quantities, which puts the client at cost risk. This research is an attempt to close this gap for reinforcement steel.

In the early stages of design, the BIM model is a prototype and lacks many details, which are essential for cost calculations. It usually would have detail level of LOD 200 or LOD 300—LOD is not defined by design phase that is just an assumption—while reinforcement steel is modeled in LOD 350 or LOD 400. Therefore, using BIM models for cost calculations for reinforcement steel in early stages of design would also be unreliable.

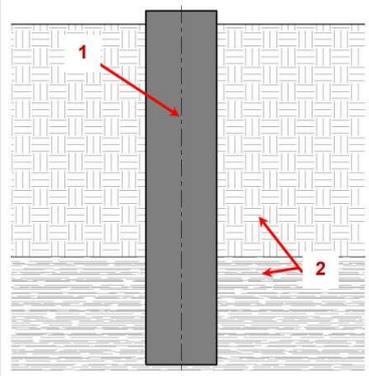


Figure 2 - Reinforced concrete element modeled in LOD 300 (BIMForum 2015)

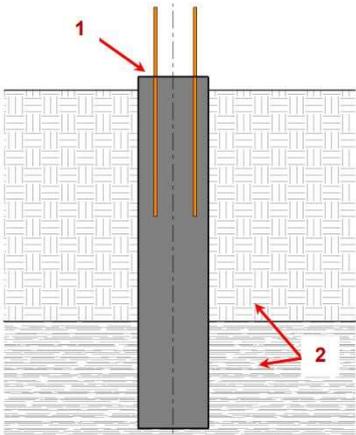


Figure 3 - Reinforced concrete element modeled in LOD 350 (BIMForum 2015)

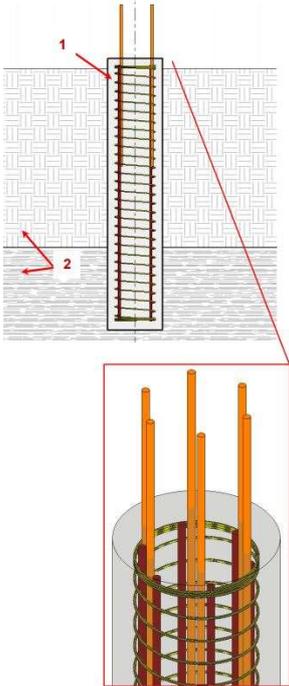


Figure 4 - Reinforced concrete element modeled in LOD 400 (BIMForum 2015)

The purpose of this study is developing a method to improve the accuracy of cost estimation for reinforced concrete elements in early stages of design using BIM technology.

This method has been applied on real-life projects designed by Bollinger+Grohmann in both of its two stages. For the first stage, seven different BIM models were used to feed the database. For the second stage, the method was applied on two other BIM models for the purpose of testing and comparing the results with conventional methods.

In addition to that, the Dynamo scripts developed in this study can be used to generate reinforcement in advanced stages of design, after the detailed design is finalized and required reinforcement for different structural elements is known.

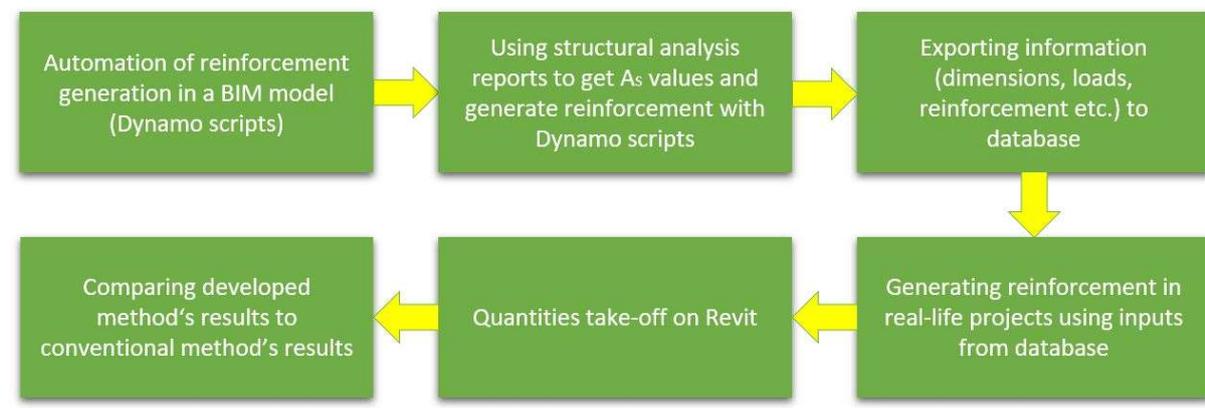


Figure 5 – Process map

1.3 Structure

In chapter 2, a brief introduction of Building Information Modeling is stated as well as an overview about BIM history and the leading countries in BIM adoption. Then, the terms Open BIM, Closed BIM, Big BIM and Little BIM are defined and the differences between them are explained.

Chapter 3 starts with discussing uncertainties and assumptions in the early stages of design. Afterwards, defining the relation between quantity take-off, cost estimation and BIM as well as the fifth dimension of BIM (5D), which is budget monitoring and cost analysis. It also shows how using BIM technology can improve and accelerate the process of cost estimation. Following this, visual programming is explained and Dynamo is

introduced. Finally, applications of reinforcement generation using visual programming and other BIM tools are reviewed.

In chapter 4, uncertain parameters and their assumptions are identified as well as the design and development of the method and workflow steps for both stages. It also illustrates how the database works and gets updated. Afterwards, quantity take-off process is explained. The last part of chapter 4 shows an example of using visual programming to carry out structural design calculations for a simply supported beam.

Chapter 5 demonstrates applications of the developed method, where seven models were used to feed the database and two other models for testing. These models are real-life projects, which were designed by Bollinger+Grohmann.

In chapter 6, a comparison between the developed method's results and conventional methods' results is reviewed.

Chapter 7 summarizes and concludes research findings and shows how this research can be a starting point for further research.

2 Overview of Building Information Modeling

Building Information Modeling (BIM) represents the consistent and continuous use of digital information across the entire lifecycle of a built facility, including its design, construction and operation (Borrmann et al. 2018). BIM is a well-established methodology for cross-disciplinary structure design based on the creation, management, and exchange of informative 3D-models. Recently, BIM has been increasingly adopted by the Architecture, Engineering, and Construction (AEC) industry, because it promotes the early exchange of 3D building models (Abualdenien and Borrmann 2019).

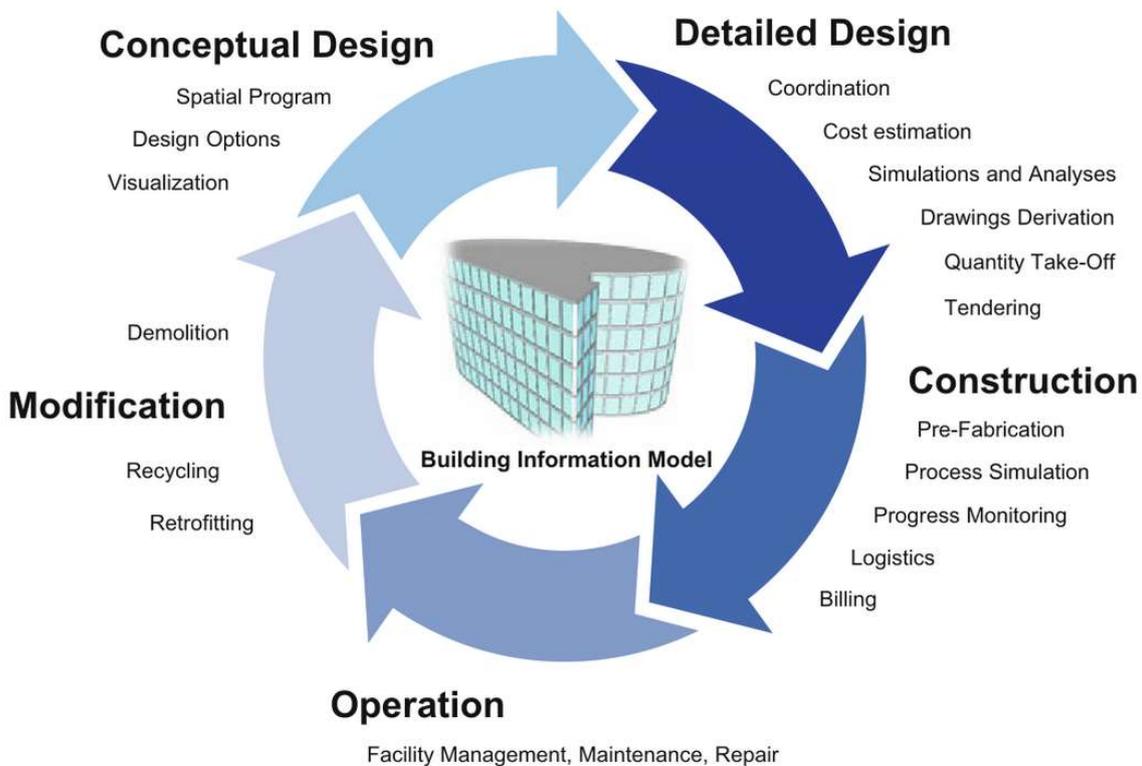


Figure 6 - Concept of Building Information Modeling (Borrmann et al. 2018)

This idea was originally proposed by researchers in the 1980s, but has only reached technical maturity in recent years and is now being adopted across the globe. If we look at the degree of BIM adoption in practice, we can see that in the USA, BIM was introduced in the mid-2000s and since then has been increasingly spread. In Asia, Singapore and South Korea are among the most advanced countries in the world in BIM working methods and governmental BIM roadmaps and guidelines (Borrmann et al. 2018).

Europe's forerunners are the Scandinavian countries: In 2007 Finland decided to make BIM mandatory for all projects. Norway and Sweden have taken similar steps and have reached a high degree of BIM adoption. The UK BIM initiative is another development that started by the British government in 2011, which has resulted in BIM becoming compulsory for all centrally procured government projects from 2016. The Netherlands, Germany, France, and Spain are among other European countries that have established governmental BIM roadmaps (Borrmann et al. 2018).

BIM significantly improves information flow between stakeholders involved at all stages, resulting in an increase in efficiency by reducing the laborious and error-prone manual re-entering of information that dominates conventional paper-based workflows. Thanks to its many advantages, BIM is already practiced in many construction projects throughout the entire world. The implementation of BIM technology profoundly changes the way architects and engineers work and drives the digital evolution of the AEC industry (Borrmann et al. 2018).

A Building Information Model is a comprehensive digital representation of a built facility with great information depth. It typically includes the three-dimensional geometry of the building components at a defined LOD. In addition, it also comprises non-physical objects, such as spaces and zones, a hierarchical project structure, schedules or analytical models. Objects are typically associated with a well-defined set of semantic information, such as the component type, materials, technical properties, or costs, as well as the relationships between the components and other physical or logical entities (Borrmann et al. 2018).

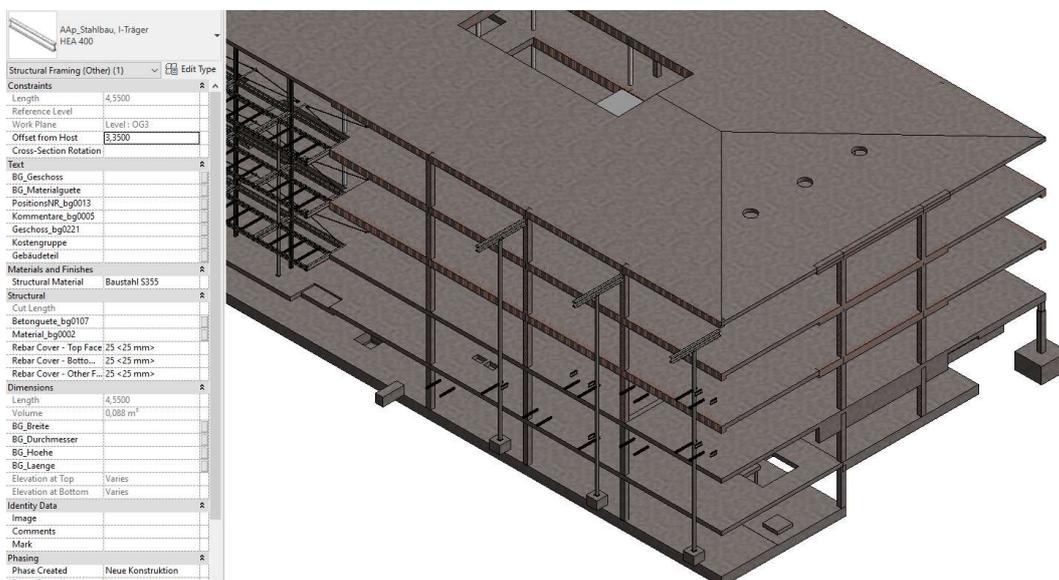


Figure 7 - An example of a BIM model showing the parameters of a structural element

BIM provides a large number of advantages for the design and engineering process. Compared to conventional 2D processes, one of the most significant advantages of using BIM is that most of the technical drawings, such as horizontal and vertical sections, are derived directly from the model and are thus automatically consistent with each other. Clash detection between the different partial models makes it possible to identify and resolve conflicts between the design disciplines at an early stage. BIM also facilitates the integration of computations and simulations in a seamless way, as a lot of input information about the building's geometry and material parameters can be taken directly from the model. A wide range of simulations, including structural analysis, building performance simulation, evacuation simulation, or lightning analysis, are then usable in the design process. In addition, the model can be checked for compliance with codes and regulations. Finally, the model data can be used to compute a very precise quantity take-off, providing the basis for reliable cost estimations and improving accuracy in the tendering and bidding process (Borrmann et al. 2018).

The shift from conventional workflows to BIM models requires significant changes in both internal company workflows as well as cross-company processes. To avoid unnecessary conflict of the basic functioning of workflows, a stepwise transition is recommended. Accordingly, different technological levels of BIM implementation are distinguished (Borrmann et al. 2018). Depending on the software solution used, the implementation of BIM can generally be divided into "Open BIM" and "Closed BIM" processes:

- Open BIM strategy makes the choice of software products free, but the project partners coordinate themselves on a planning platform. Open data formats enable data exchange between products from different manufacturers (Hengsberger n.d.).
- Closed BIM procedure requires all planning participants to work with the same software in one model. A problem with this variant can be that model requirements cannot always be mapped due to the uniform planning software (Hengsberger n.d.).

The terms "Little BIM" and "Big BIM" make a further distinction as well:

- Little BIM means that a single planner uses a BIM software for his specific planning. The BIM solution is used as an isolated solution in the specific field of

activity of a specialist planner and communication with the outside world continues to be based on drawings. Efficiency gains can be achieved with little BIM, but the potential of a consistent use of digital building information remains unused (Hengsberger n.d.).

- Big BIM allows a collaborative, multidisciplinary model-based communication to take place between all participants over all life cycle phases of a building. Data exchange and coordination take place via Internet platforms and database solutions (Hengsberger n.d.).

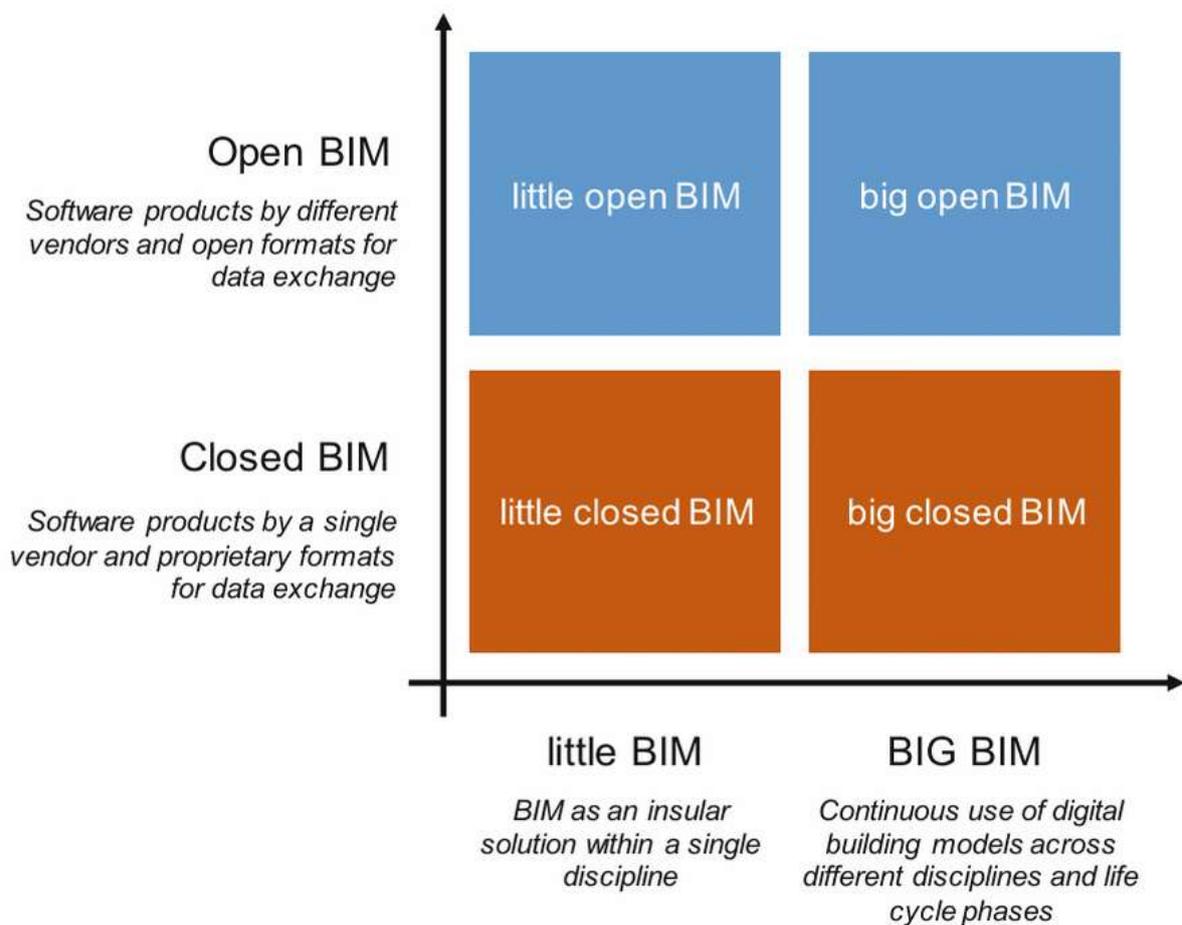


Figure 8 - The terms "Open BIM", "Closed BIM", "Big BIM" and "Little BIM" (Borrmann et al. 2018)

3 State of the Art Review

3.1 Uncertainties in Early Stage of Design

AEC industry is a collaborative environment that always requires an iterative and cooperative exchange of information. For example, developing structural design requires input from the architectural design. The design of the HVAC systems must be coordinated with the structural design to consider the required voids in the structural elements. A building design evolves through multiple design phases; each of them is characterized by a set of consecutive and calibrated actions to satisfy the different design and engineering requirements. Through the phases of design, the building model is gradually refined from a rough conceptual design to highly detailed individual components (Abualdenien and Borrmann 2019).

In general, the building design phase is divided into different stages with gradually increasing design precision and detailing. Designers face unique boundary conditions while working for clients with individual requirements. Furthermore, different planning domains are involved in the process requiring different information, each of them is carried out by an individual team. In some cases, the interests of involved teams counter each other. For instance, a structural engineer might focus on the strength of the structure in order to get high load-bearing capacity, while an architect might prefer light and more slender structures and the energy consultant recommends using renewable construction materials (Abualdenien et al. 2020).

The early stages of design have high impact on the building performance in the future. These stages are also most complex to understand, carry out and manage (Abualdenien et al. 2020). Many assumptions have to be made due to the lack of information or knowledge, which causes information uncertainty. Uncertainty is the case of incomplete information and can be further broken down into risk and ignorance, whereas risk refers to situations where possible outcomes of an event and their probabilities are known. In case of ignorance, the probabilities are unknown. The term “total ignorance” can be attributed to the umbrella-term uncertainty, describing a situation in which neither the probabilities nor the possible future environmental states are known (Hawer, Schönmann, and Reinhart 2017).

Information uncertainty is complex, multidimensional, and has many interpretations. However, the lack of information affects the decision-making process and outcomes. In early design stages, the uncertainty of how the design may evolve is high, as many decisions have not yet been made. At the same time, understanding what is precise and complete and what is not is critical. Therefore, the sources of uncertainty must be identified beforehand (Abualdenien and Borrmann 2020).

Making design decisions under uncertainty is driven by increasing the confidence that choosing a certain variable will result in a better solution. Uncertainty represents the unknown variables affecting design and their fulfillment of the project's requirements and objectives. Accordingly, defining these variables can lead to fundamental changes in the proposed design (Abualdenien and Borrmann 2020). In this study, uncertain parameters have been identified and assumed in the beginning as demonstrated in chapter 4.1.

3.2 BIM in Quantity Take-off and Cost Estimation

Traditionally, cost estimation for building projects starts with quantification. It is a time-consuming task; it takes from 50% to 80% of the cost estimator's time on a project. In order to develop quantity take-off, estimators typically begin by digitizing the drawings or carrying out manual calculations. All these methods introduce the potential for human error and propagate any inaccuracies there may be in the original drawings. By using BIM instead of 2D drawings, quantity take-off can be generated directly from the model. Therefore, the information should be consistent with the design. In addition, when a change is made in the design, it will automatically be adapted in all related construction documents and schedules, as well as take-offs, counts, and measurements that are used by the estimator (Elbeltagi et al. 2014).

The BIM technology provides many improvements, both in the process of take-off itself and in sharing information about the elements and their installation in the construction. Each element can contain its information; in addition, elements can be divided in the way they will be installed. The information can be processed automatically to create a take-off table. Most software used in BIM technology (e.g. Revit) usually has integrated options for the take-off for modeled elements (Gołaszewska and Salamak 2017).

The process of cost estimation is tightly tied to quantities take-off. A well-prepared take-off can make cost estimation less labor-intensive, faster and less prone to omissions due to human error. Without proper detailed record of the elements that need to be priced, the cost assessment will be incomplete.

In the past, BIM was mainly used as a visualization and organization tool, from the domain of AEC. Today the purpose of BIM usage has changed and it is used as a process of improving performance during the entire lifecycle of buildings. A BIM model is more than a 3D model, it is a digital description of every aspect of the built asset. Seven established dimensions exist according to BIM principles. These dimensions are:

- 3D: geometry
- 4D: time
- 5D: costs
- 6D: sustainability
- 7D: facility management (Mesároš and Mandičák 2019)

5D is used for budget monitoring and cost analysis. As a tool, BIM helps following exact needs for resources in each phase of a lifecycle and allows better planning of financial aspects of the project. The main task of 5D is to exactly specify the cost of building work. By assigning single costs to amounts, accurate and reliable cost analysis can be automatically obtained. 5D does not include only calculation and cost estimation, overall a 5D model is dependent on processing quality of its parts. It is based on 3D parametric model, from which it is possible to create and export bill of quantities, which includes all projected elements, constructions and objects (Mesároš and Mandičák 2019).

3.3 Visual Programming (Dynamo)

Visual Programming Language (VPL) allows users to create illustrations to describe different types of processes. It is a technique that was made to work with our ability to explain concepts through visual means. The inclusion of graphical elements makes it accessible to new learners. These elements can be manipulated to construct programs. It allows a person to construct a solution to a problem in a way that can be easily understood by other humans (K. R. König 2018).

Dynamo is an open source visual or graphical programming software; it is one of the most powerful tools used in BIM, since it allows the manipulation and generation of geometry and customization of building information workflow. It is compatible with most of Autodesk products and automatically installed with Revit, since Revit 2020.

Dynamo extends the power of Revit by providing access to the Revit API in a more accessible manner. Rather than typing code, with Dynamo users create programs by manipulating graphic elements called “nodes”. It’s an approach to make programming better suited for visually oriented types, like architects, designers, and engineers (Kilkelly 2018). Several nodes can be grouped into one “custom node”. Ten custom nodes were implemented in this study, in order to make the Dynamo scripts shorter and less complicated.

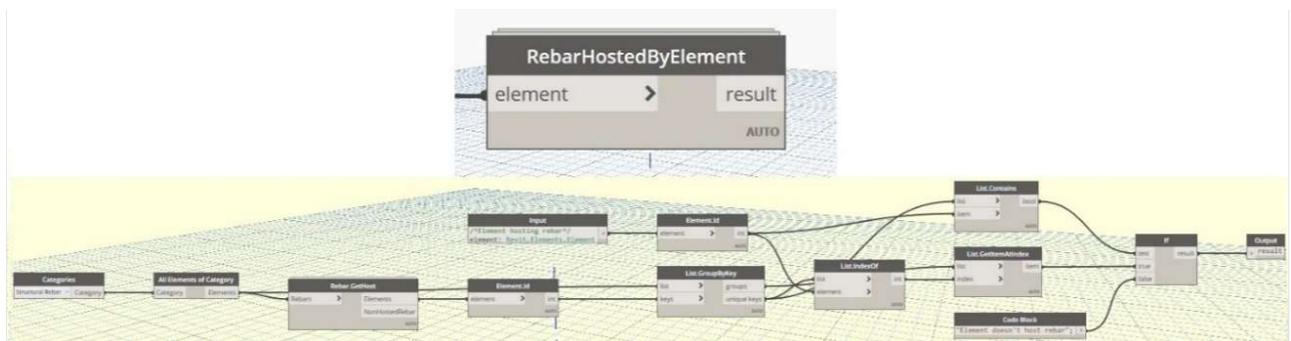


Figure 9 - An example of the custom nodes produced in this study

A collection of nodes or custom nodes can be called a “package”. Dynamo packages are developed by third parties in order to extend Dynamo's core functionality and accessibility to everyone. All Dynamo packages are free and downloadable through the “Dynamo Package Manager”. There are about 1600 packages available in different fields on the Dynamo platform, which makes Dynamo an open source. The packages used in this research are:

- Data-Shapes
- Rhythm
- Slingshot
- Structural Design
- BIM4Struc

Dynamo gives the opportunity to designers and engineers to create visual logic to explore parametric designs and automate tasks. It helps solving challenges faster by designing workflows that drive the geometry and behavior of design models. With Dynamo, designs can be extended into interoperable workflows for documentation, fabrication, coordination, simulation, and analysis (Vermeulen 2016).

3.4 Automation of Reinforcement Generation in BIM Models

In this part, a closer look into research and use cases of automation of reinforcement generation in Revit is represented. In addition to that, two commercial tools from SO-FiSTiK AG and Dlubal Software are reviewed. However, the aim of this study isn't only reinforcement generation. A new workflow is proposed by exporting to and importing from database in order to exclude any human input. Design and development of this approach are explained in chapter 4.

- **Dynam(o)ite Rebar Design**

This article was published by Dieter Vermeulen for Autodesk University in 2016. The research demonstrates a few examples of rebar generation in a Revit model with the help of Dynamo using “BIM4Struc.Rebar” and “Dynamo for Rebar v. 1.2.0” packages.

The method used in this research is based on importing the rebar and host elements properties and geometry—which already exist in a Revit model—from Revit to Dynamo, then manipulate this geometry and export it back to Revit. Here is an illustrative example in the following figure.

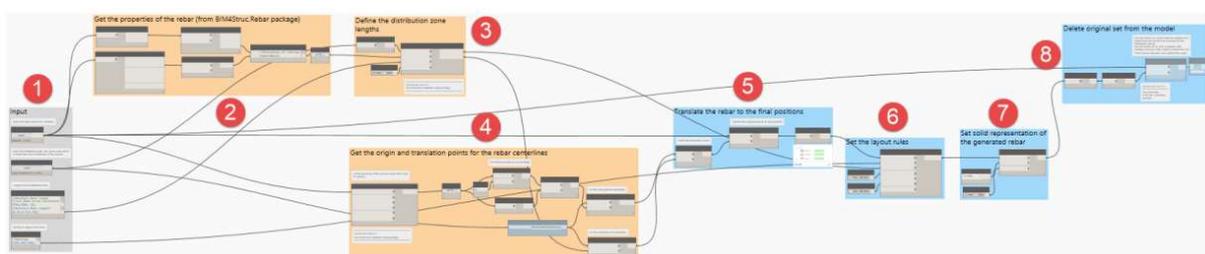


Figure 10 - Dynamo script for rebar layout (Vermeulen 2016)

The Dynamo script consists of the following parts:

1. Get the original rebar and the distribution guide curve
2. Get the geometrical properties of the rebar

3. Define the distribution zones
4. Define the source and target translation points for the different zones
5. Translate the rebar to the different zones
6. Set the layout rule for each zone
7. Set the rebar in solid representation
8. Delete the original defined stirrup in the model

In the previous example, the process is not fully automated, since the user needs to create a rebar element in Revit and read its properties in Dynamo. Moreover, the user is required to select faces and insert some dimensions manually, e.g. beam length.

- **Dynamo for Automated Reinforcement Detailing**

The visual programming interface of Dynamo gives structural engineers the tools to build optimized structures with minimal effort, and subsequently make their own design tools. Based on the Revit platform, we can use our creativity to develop optimized structural systems using computational logic in an advanced building information modeling environment (Fudala 2018).

This following illustration shows an article by Tomasz Fudala from the Autodesk blog, it explains a good example of how powerful Dynamo can be in rebar generation. The package “Structural Design” is used excessively in this Dynamo script. It is one of the most helpful packages in Dynamo, since it allows the generation of many forms of rebar, e.g. area rebar and free form rebar from curves. The script also involves some simple Python scripts.

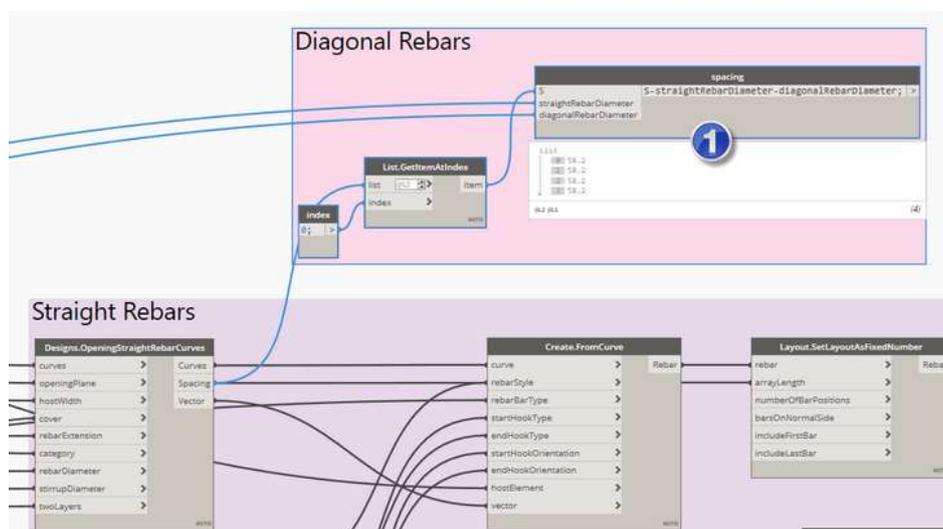
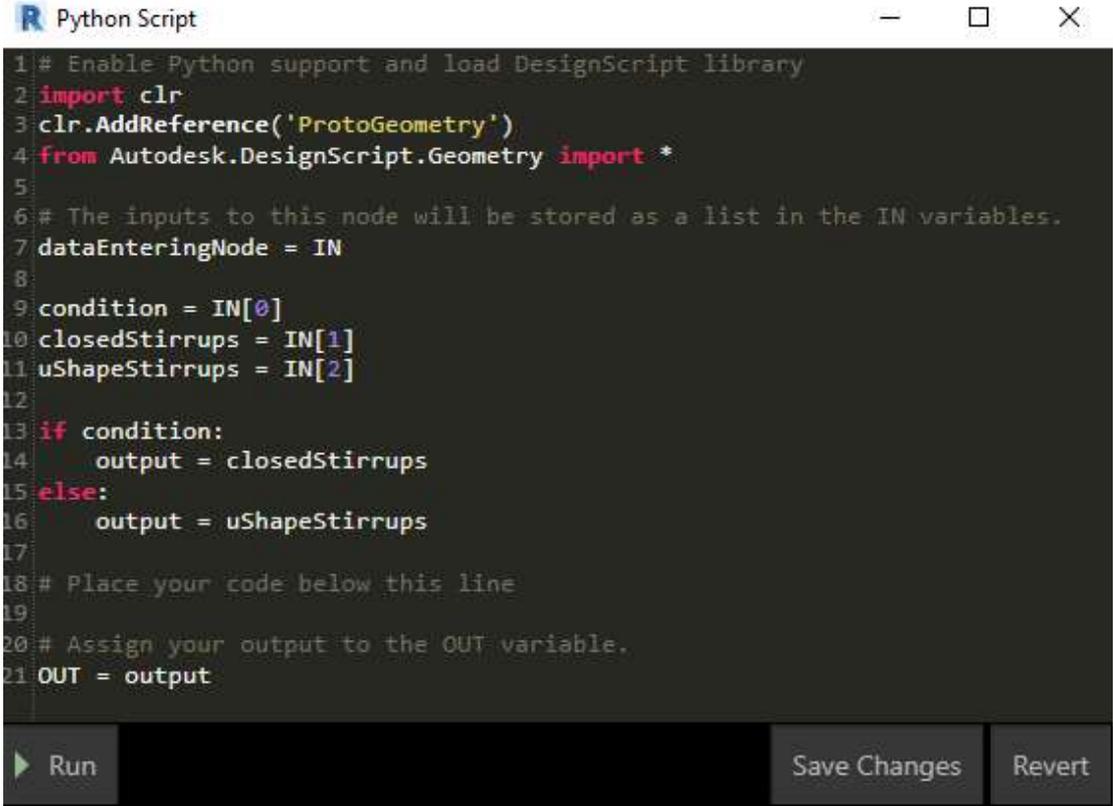


Figure 11 - Part of the Dynamo script, where "Structural Design" package is used (Fudala 2018)



```

Python Script
1 # Enable Python support and load DesignScript library
2 import clr
3 clr.AddReference('ProtoGeometry')
4 from Autodesk.DesignScript.Geometry import *
5
6 # The inputs to this node will be stored as a list in the IN variables.
7 dataEnteringMode = IN
8
9 condition = IN[0]
10 closedStirrups = IN[1]
11 uShapeStirrups = IN[2]
12
13 if condition:
14     output = closedStirrups
15 else:
16     output = uShapeStirrups
17
18 # Place your code below this line
19
20 # Assign your output to the OUT variable.
21 OUT = output

```

Run Save Changes Revert

Figure 12 – One of the Python script used in the workflow (Fudala 2018)

In this example, the process is well automated, since the user only needs to insert rebar diameter, rebar spacing, some dimensions and couple of Boolean functions. However, this example is only for reinforced concrete walls.

- **Rebar Modelling in Revit with Dynamo – Use Case by ABT**

This is a quite complicated example for using Dynamo to automate geometry creation, reinforcement generation and documentation of wind turbine foundations. This workflow was developed by ABT (multi-disciplinary consultancy firm) in 2015.

The workflow consists of four steps, as follows:

- Setting values and dimensions of geometry parameters in Excel
- Reading information from Excel into Dynamo and create geometry in Revit
- Reinforcement creation with the help of separate Dynamo scripts
- Generation of detailed drawings in Revit using SOFiSTiK Reinforcement Detailing tools

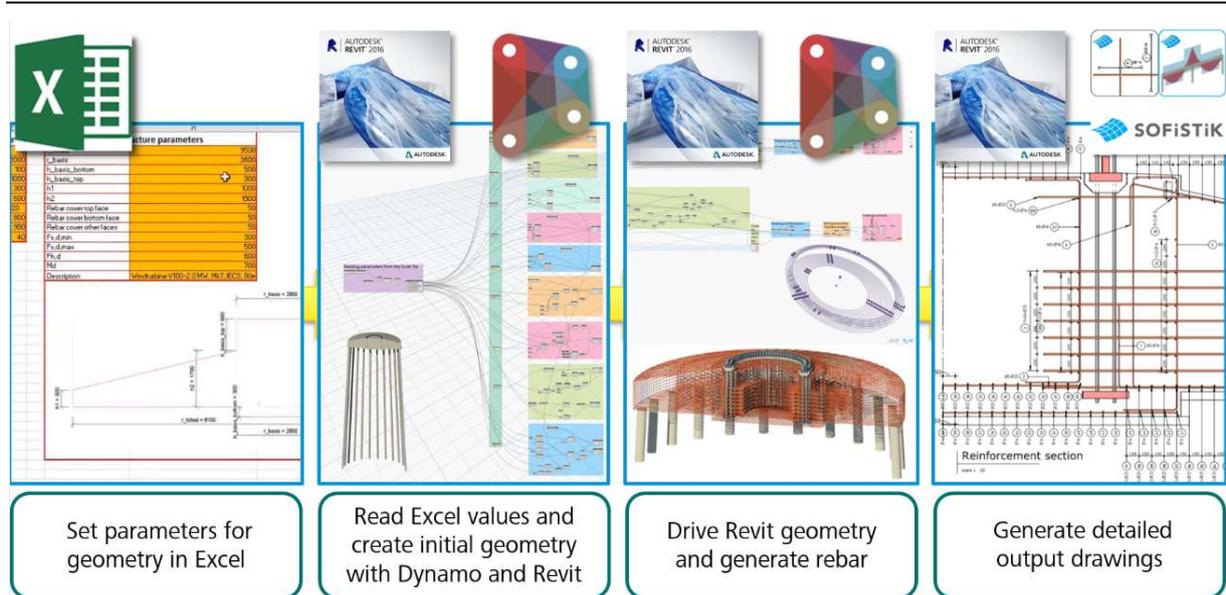


Figure 13 – Workflow of reinforcement generation for wind turbine foundations (Fudala 2015)

• SOFiSTiK Reinforcement Generation

SOFiSTiK AG developed a tool, which automatically generates a 3D rebar model inside of Revit based on computed analysis and design results from SOFiSTiK FEM. The generated rebar can be manually updated afterwards. This tool is practical when the structure design is finalized. However, usually when cost calculation is happening the structure is not yet fully designed. The cross sections are fixed, but concrete grade and reinforcement might deviate.

Tool functionalities:

- Reading of the analysis results directly from the SOFiSTiK database (CDB) as well as from the Revit Results Packages.
- Automatic generation of reinforcement bars for beams, columns, walls and slabs using results from analysis and design.
- Visualization of required (theoretical) and physically inserted reinforcement ensuring that adequate reinforcement is provided.
- Import of analysis and design results from SOFiSTiK database (CDB) and storage as Results Packages. (SOFiSTiK AG n.d.)

Disadvantages:

- No constructive rebar is generated
- Installation of a few SOFiSTiK software is required

- Model has to be calculated by SOFiSTiK FEM
- The need to load SOFiSTiK database (.cdb)

- **Reinforcement Transfer RFEM – Revit**

Dlubal Software provides an interface for data exchange with Revit as a plug-in. It is quite handy, since it can export load data, results and model objects. These objects will not get lost when exchanging data, which means an equivalent beam, column, slab or wall is created on Revit, not just a collection of lines and surfaces. As mentioned above for the tool from SOFiSTiK AG, this tool is helpful when the structure is fully designed, but not for the early stages of design.

Reinforcement can be transferred as structural rebar elements. Defined reinforcement groups from the RF-CONCRETE Surfaces add-on module can be directly imported or generated. Surface, rectangle, polygonal as well as circular reinforcement areas can be selected as an option for this (Flori 2017).

Disadvantages:

- The workflow is a long process that involves structural calculations on RFEM
- Installation of RFEM software and add-ons is required
- Add-ons from RFEM must be used for design
- Reinforcement in connections need to be adapted manually

4 Design and Development

4.1 Identification and Assumption of Uncertain Parameters

During the design and especially in early stages, important decisions that could have great impact on the building have to be made. Since this study is dealing with early stages of design, there are many uncertain parameters.

Some variables had to be assumed during the development of this method in order to reduce the number of inputs and the complexity of the scripts. In the following table, all uncertain parameters and their assumptions are listed. These assumptions are based on design regulations from “Eurocode 2: Design of Concrete Structures”.

Parameter	Assumption
Rebar Development Length for Beams	80 x Bar Diameter
Rebar Development Length for Columns with Fixed Support	80 x Bar Diameter
Rebar Development Length for Columns with Hinged Support	25 x Bar Diameter
Rebar Overlapping Length	80 x Bar Diameter
Minimum Distance between Stirrups	100 mm
Maximum Distance between Stirrups	300 mm
Minimum Distance between Longitudinal Rebar (Center to Center)	3 x Bar Diameter
Maximum Distance between Longitudinal Rebar (Center to Center)	300 mm
Ultimate Tensile Strength of Reinforcement Steel	$f_{yk} = 500 \text{ N/mm}^2$
Yield Strength of Reinforcement Steel	$f_{yd} = 500/1.15 = 435 \text{ N/mm}^2$
Minimum A_s for Beams (Bottom Reinforcement)	$A_s = M_{cr}/(Z_{ll} * f_{yk})$

Table 1 - Uncertain parameters and their assumptions

4.2 Database

This method depends mainly on data exchange between BIM models and database. Therefore, a good, fast and reliable database was needed. After going through the available database types, SQLite database was chosen. It is a C-language, in-process library that implements a small, fast, self-contained, high-reliability, full-featured, zero-configuration, transactional SQL database engine. The code for SQLite is in the public domain and is thus free for use for any purpose, commercial or private. SQLite is a widely deployed database with many applications. Unlike most other SQL databases, it does not have a separate server process. It can read and write directly to ordinary disk files. The database file format is cross-platform and can be freely copied between 32-bit and 64-bit systems.

Since the required parameters to generate reinforcement are not the same for all structural elements, the database was divided into four tables (beams, circular columns, rectangular columns, isolated foundations). Parameters saved in each table are shown in the following four figures (14, 15, 16 and 17).

Name	Type	NN	PK	AI	U	Default	Check	Collation	Foreign Key
ElementID	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
Width_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
Height_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
Span_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
BottomRebarCount	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
BottomRebarDiameter_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
TopRebarCount	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
TopRebarDiameter_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
StirrupRebarSpacing_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
StirrupRebarDiameter_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
ProjectName	TEXT	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
ProjectNumber	TEXT	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
BuildingType	TEXT	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				

Figure 14 - Parameters stored in beams table

Name	Type	NN	PK	AI	U	Default	Check	Collation	Foreign Key
ElementID	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
Diameter_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
Height_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
LongitudinalRebarCount	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
LongitudinalRebarDiameter_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
StirrupRebarSpacing_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
StirrupRebarDiameter_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
NormalForce_kN	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
ProjectName	TEXT	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
ProjectNumber	TEXT	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
BuildingType	TEXT	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				

Figure 15 - Parameters stored in circular columns table

Design and Development

Name	Type	NN	PK	AI	U	Default	Check	Collation	Foreign Key
ElementID	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
B_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
H_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
Height_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
LongitudinalRebarCount	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
LongitudinalRebarDiameter_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
StirrupRebarSpacing_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
StirrupRebarDiameter_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
NormalForce_kN	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
ProjectName	TEXT	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
ProjectNumber	TEXT	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
BuildingType	TEXT	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				

Figure 16 - Parameters stored in rectangular columns table

Name	Type	NN	PK	AI	U	Default	Check	Collation	Foreign Key
ElementID	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
Width_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
Length_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
Height_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
TransverseRebarSpacing_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
TransverseRebarDiameter_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
LongitudinalRebarSpacing_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
LongitudinalRebarDiameter_mm	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
NormalForce_kN	INTEGER	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
ProjectName	TEXT	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
ProjectNumber	TEXT	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
BuildingType	TEXT	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				

Figure 17 - Parameters stored in isolated foundations table

Table: RectangularColumns Filter in any column

ElementID	B_mm	H_mm	Height_mm	LongitudinalRebarCount	LongitudinalRebarDiameter_mm	StirrupRebarSpacing_mm	StirrupRebarDiameter_mm	NormalForce_kN *1	ProjectName	ProjectNumber	BuildingType
1	1098876	250	400	12508	6	20	150	10	84 C4	4	Industrial
2	5498649	500	500	13800	8	16	150	10	111 C2	2	Industrial
3	8006346	350	350	13555	4	25	150	10	252 C3	3	Industrial
4	1098884	400	400	12350	8	20	125	10	272 C4	4	Industrial
5	8762164	250	500	3330	4	12	125	8	278 C5	5	Commercial
6	9811041	250	500	3410	12	20	200	10	278 C5	5	Commercial
7	8006308	350	350	13855	4	25	150	10	298 C3	3	Industrial
8	1098880	400	400	7550	8	20	125	10	305 C4	4	Industrial
9	8004500	350	350	11720	12	25	150	10	330 C3	3	Industrial
10	8004502	350	350	11720	12	25	150	10	354 C3	3	Industrial
11	9811032	250	500	3410	8	14	150	8	413 C5	5	Commercial
12	8762120	250	1000	3410	8	20	125	8	413 C5	5	Commercial
13	7940938	500	500	7270	8	20	150	10	441 C3	3	Industrial
14	7940940	500	500	6950	8	20	150	10	442 C3	3	Industrial
15	8540364	250	500	3330	4	12	125	8	480 C5	5	Commercial
16	7940796	500	500	12020	8	20	150	10	483 C3	3	Industrial
17	2663265	400	400	12350	8	20	125	10	490 C4	4	Industrial
18	2663536	400	400	12570	8	20	125	10	492 C4	4	Industrial
19	6619632	400	400	3650	4	20	200	10	500 C1	1	Educational
20	6617506	400	400	3700	4	20	200	10	501 C1	1	Educational
21	6619853	400	400	3650	4	20	200	10	503 C1	1	Educational
22	6617539	400	400	3700	4	20	200	10	503 C1	1	Educational
23	7940447	500	500	12020	8	20	150	10	503 C3	3	Industrial
24	7940742	500	500	12020	8	20	150	10	522 C3	3	Industrial
25	1098534	400	400	12350	8	20	125	10	537 C4	4	Industrial
26	2743820	250	400	13020	6	20	150	10	542 C4	4	Industrial
27	8540360	250	500	3330	4	12	125	8	555 C5	5	Commercial
28	16771851	250	1000	3330	8	20	125	8	563 C5	5	Commercial
29	806508	500	800	12000	12	25	100	10	570 T1	8	Industrial
30	806506	500	800	12000	12	25	100	10	570 T1	8	Industrial

Figure 18 - A sample of rectangular columns table

Data exchange between a BIM model and the database was performed through Dynamo. This was applicable using the nodes “Command.SQLite_Command” for exporting to database and “Query.SQLite_Query” for importing from database. These nodes are part of the Dynamo package “Slingshot”.

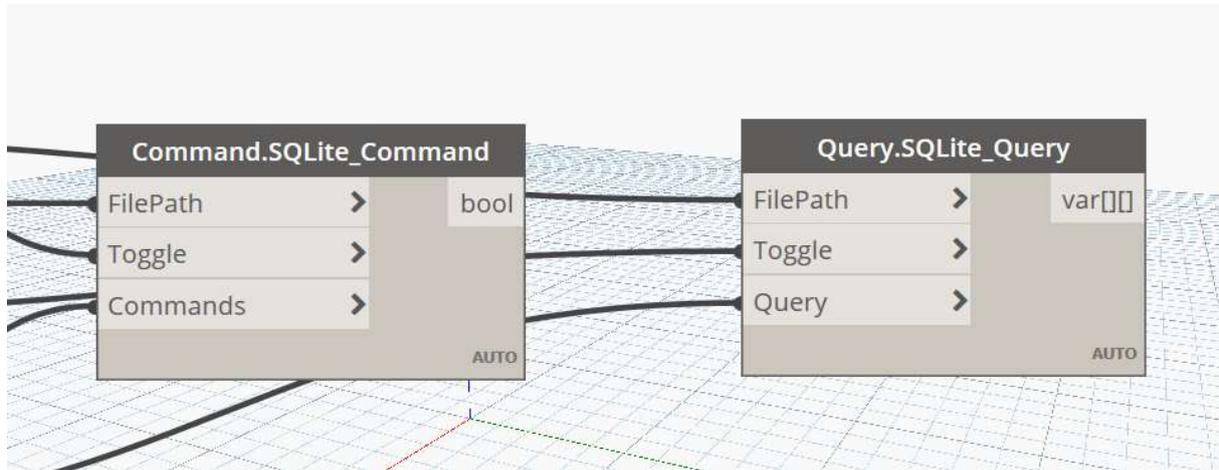


Figure 19 - Dynamo nodes used for data exchange

4.3 Dynamo Scripts

Twelve Dynamo scripts were produced in this research. Scripts 1 to 5 are used in the first stage and require manual input of quantity and diameter of bars. Script number six exports all necessary information related to rebar elements and their host elements to database. To generate reinforcement based on experiences stored in database, scripts 7 to 11 are needed. These scripts do not require any manual input, instead they run an iterative search through the database and get values of reinforcement from elements similar to the selected element. The last script, number 12, can generate reinforcement using only linear load (kN/m) acting on simply supported beams as an input parameter. This script was implemented as an attempt to push the research towards structural calculations. However, the complexity level and the number of inputs of each script would be unreliable. Therefore, the beam case was evaluated and other structural elements were not included in this study and the idea of generating reinforcement based on previous experience was adopted. The implementation of all Dynamo scripts is explained in detail in Appendix A.

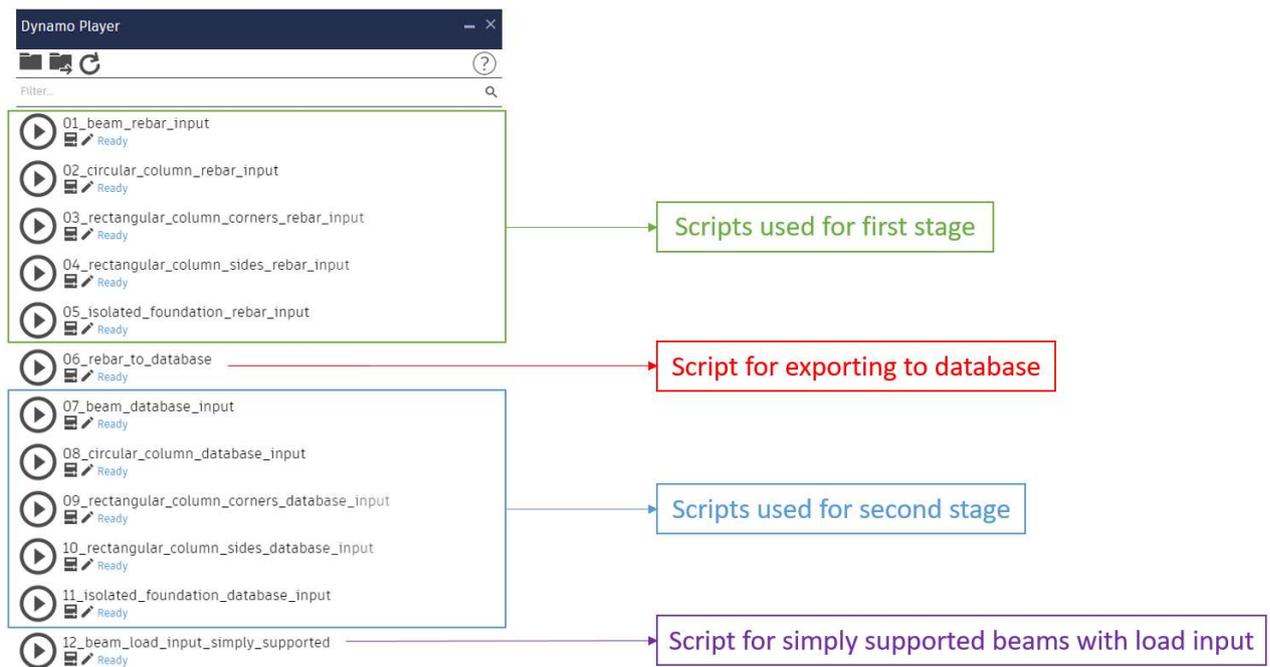


Figure 20 - Dynamo scripts produced

4.4 First Stage (Feeding Database)

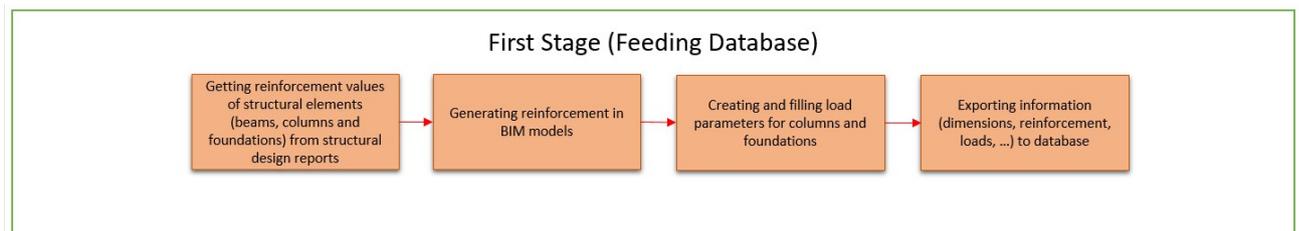


Figure 21 - Workflow diagram for first stage

The first stage can be thought of as feeding the database with certain parameters of reinforced concrete elements and their reinforcement. This stage can be divided into the following steps:

1. Getting required reinforcement from structural design reports
2. Using scripts number 1 to 5 to generate reinforcement for beams, columns and single foundations in BIM models

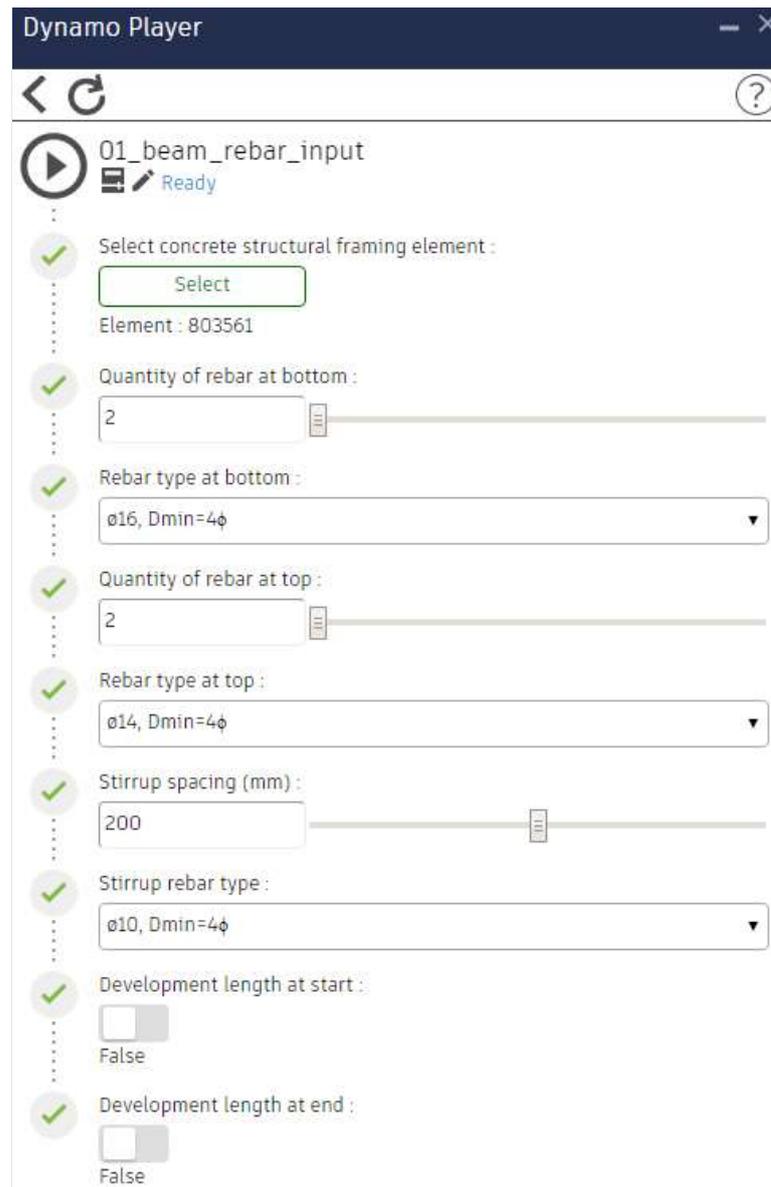


Figure 22 – Dynamo script number 1 in Dynamo Player

3. Implementing and filling load parameters for columns and foundations to use them later on as search parameters
4. Exporting information (dimensions, reinforcement, loads, etc.) to database using Dynamo script number 6

Note: the database can be filled directly by projects in LPh5 as well, even without a BIM model. Parameters, such as dimensions and rebar diameter and count can be extracted from design reports and reinforcement drawings and exported directly to the database.

In this research, the first five Dynamo scripts were applied on seven different BIM models of projects designed by Bollinger+Grohmann in order to generate reinforcement and feed it to the database.

4.5 Second Stage (Calling from Database)

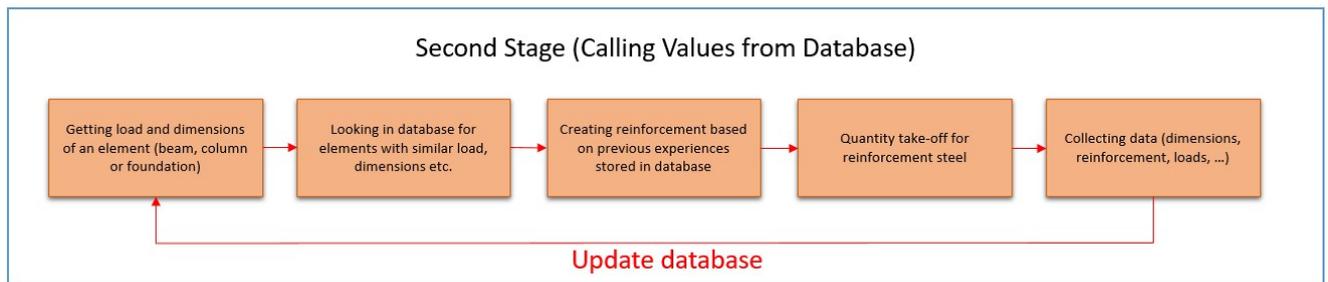


Figure 23 - Workflow diagram for second stage

This stage is basically generating reinforcement in BIM models in early stages of design without performing any structural calculations. Reinforcement parameters can be extracted from the database for elements with similar dimensions and loads. Following are the steps of this stage:

1. Getting loads and dimensions of reinforced concrete elements (beams, columns and single foundations) in a BIM model
2. Using Dynamo scripts number 7 to 11 to generate reinforcement in a BIM model. These scripts use dimensions and load parameters as search parameters to call reinforcement values for elements similar to selected element from database



Figure 24 - Dynamo script number 11 in Dynamo Player

3. Carrying out quantities take-off for reinforcement steel
4. Collecting information and updating database using Dynamo script number 6

This stage has been applied on two BIM models of projects designed by Bollinger+Grohmann and reinforcement quantities results were obtained. The results are discussed and compared to values of LPh5 in chapter 6.

4.6 Quantity Take-off

Revit can measure different categories elements and their parameters. Quantities schedules can be created at any point in the design process. As changes are made to the model that affects the schedule, it automatically updates to reflect those changes. These schedules can also be exported as spreadsheets, in case needed to be used in another software.

In this study, quantity schedules for structural rebar elements were produced. The parameter “Reinforcement Volume” in the standard structural rebar family from Revit was giving extremely false results. For example, in project T1 the given reinforcement volume was 917.69 m³, while the actual volume was 27.91 m³. However, the parameter “Total Bar Length” was accurate enough to be used in quantity schedules. Therefore, a new parameter was implemented “BG_Reinforcement Volume”. In this parameter a simple equation was used to calculate reinforcement volume from bar length and diameter.

<Rebar Schedule>					
A	B	C	D	E	F
Bar Diameter	Quantity	Total Bar Length	Reinforcement Volume	BG_Reinforcement Volume	BG_Reinforcement Weight
8 mm	2783	6536 m	0.33 m ³	0.33 m ³	2.58 t
10 mm	15694	40076 m	3.15 m ³	3.15 m ³	24.71 t
12 mm	29646	34486 m	393.41 m ³	3.90 m ³	30.62 t
14 mm	1500	1404 m	25.02 m ³	0.22 m ³	1.70 t
16 mm	23980	21842 m	479.86 m ³	4.39 m ³	34.47 t
25 mm	1212	14071 m	6.91 m ³	6.91 m ³	54.22 t
28 mm	1198	14646 m	9.02 m ³	9.02 m ³	70.79 t
Grand total: 54559	76013	133061 m	917.69 m ³	27.91 m ³	219.09 t

↑ Wrong results ↑ Correct results

Figure 25 - Reinforcement quantities schedule from project T1

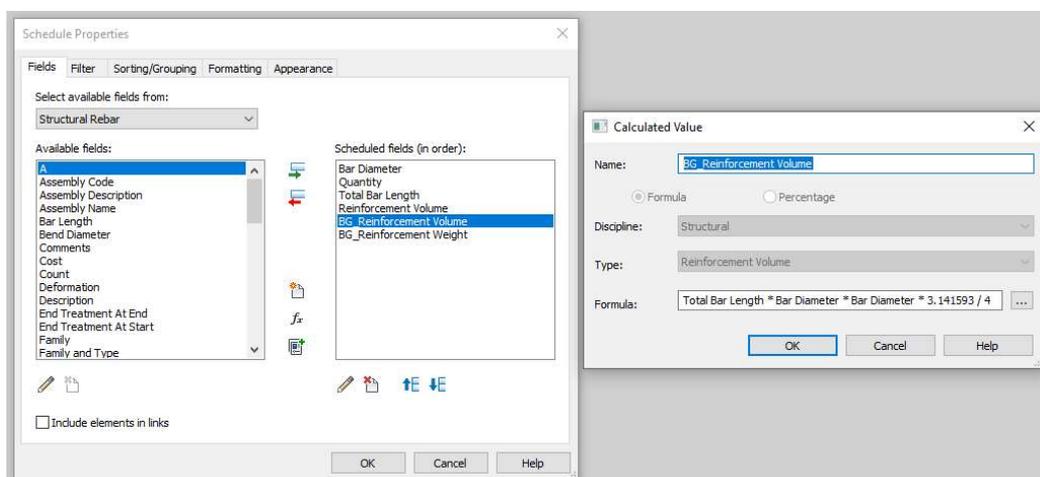


Figure 26 - Implementaion of "BG_Reinforcement Volume" parameter

4.7 Reinforcement Generation Using Load as Input

Dynamo script number 12 was designed to generate reinforcement in a simply supported beam sustaining a linear constant load. The user needs to insert the line load (kN/m) acting on the beam, concrete grade and bottom and stirrup rebar diameters. Top rebar diameter is set manually in each project, since it is considered constructive rebar.

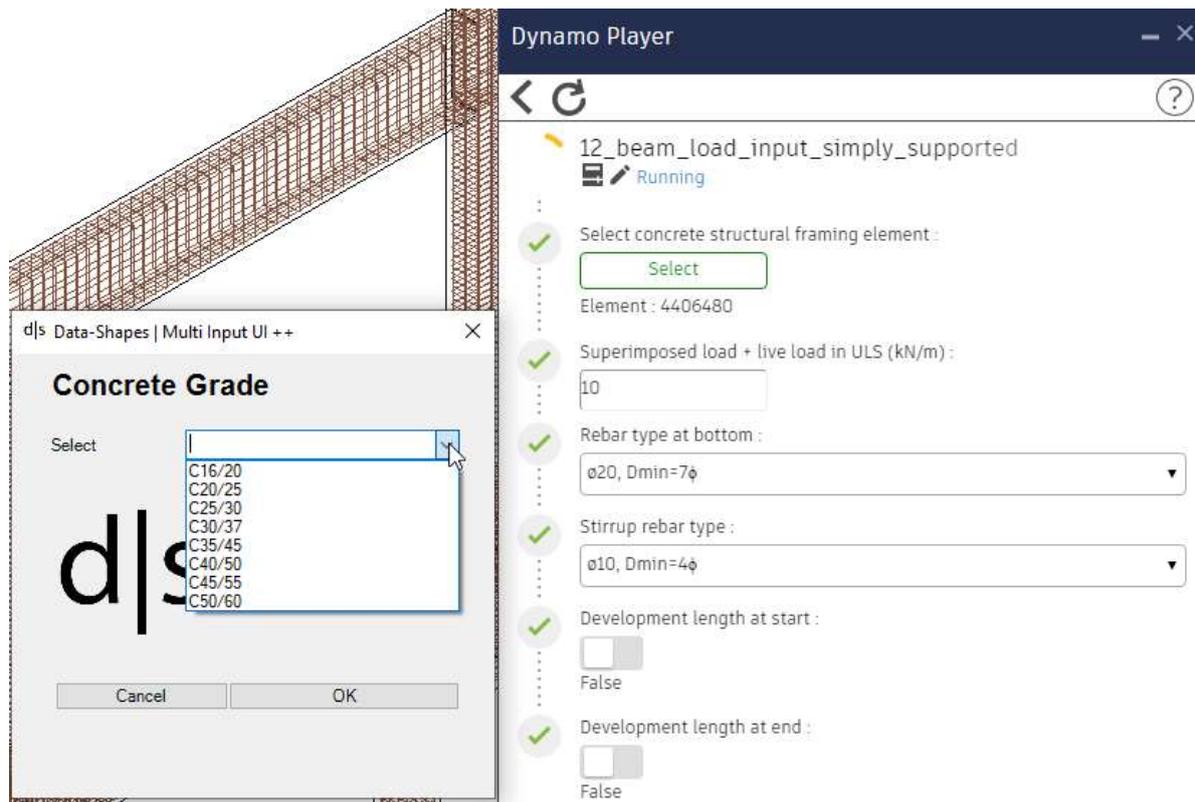


Figure 27 - Dynamo script number 12 in Dynamo Player

To achieve that, structural design equations and tables for bending moment and shear forces according to “Eurocode 2: Design of Concrete Structures” has been implemented in Dynamo, mainly using code blocks. Bottom rebar and stirrups are calculated according to the load, while top rebar is generated as constructive rebar.

```

Code Block
fck          fcd = 0.85/1.5*fck;
beamWidth    fyd = 435;
beamHeight
inputLoad    ownWeight = 1.35*beamWidth*beamHeight*25;
beamLength   q = inputLoad+ownWeight;
cover
stirrupRebarDiameter  MEd = q*beamLength*beamLength/8*1000000;
bottomRebarDiameter

d = beamHeight*1000-cover-stirrupRebarDiameter-bottomRebarDiameter/2;

muEd = MEd/(beamWidth*1000*d*d*fcd);

muEds = 0.01..0.37..0.01;

omegas = [0.0101,0.0203,0.0306,0.041,0.0515,0.0621,0.0728,0.0836,0.0946,0.1057,
0.117,0.1285,0.1401,0.1518,0.1638,0.1759,0.1882,0.2007,0.2134,0.2263,0.2395,
0.2528,0.2665,0.2804,0.2946,0.3091,0.3239,0.3391,0.3546,0.3706,0.3869,0.4038,
0.4211,0.4391,0.4576,0.4768,0.4968];

n = 0..36..1;

omegasList = muEd<=muEds[0] ? omegas[0] : (muEd>muEds[n-1] && muEd<=muEds[n] ? omegas[n] : omegas[n-1]);

omega = List.MaximumItem(omegasList);

AsRequired = (omega*beamWidth*1000*d*fcd)/fyd;

numberOfBars = Math.Ceiling(AsRequired/(Math.PI*bottomRebarDiameter*bottomRebarDiameter));

numberOfBars>=2 ? numberOfBars : 2;

```

Figure 28 – An example of structural design equations in Dynamo

5 Feeding and Testing Projects

5.1 Database Feeding Projects

As the first stage of this method is basically filling the database with reinforcement parameters of different elements, seven projects from Bollinger+Grohmann were selected for that. Following is a list of these projects and their contribution to the database.

Project	Building Type	Project Usage in Research
C1	Educational Facility	<ul style="list-style-type: none"> • Beams • Circular Columns • Rectangular Columns
C2	Industrial Building	<ul style="list-style-type: none"> • Beams • Rectangular Columns
C3	Industrial Building	<ul style="list-style-type: none"> • Rectangular Columns
C4	Industrial Building	<ul style="list-style-type: none"> • Beams • Rectangular Columns
C5	Commercial Building	<ul style="list-style-type: none"> • Circular Columns • Rectangular Columns
C6	Commercial Building	<ul style="list-style-type: none"> • Beams
C7	Commercial Building	<ul style="list-style-type: none"> • Foundations

Table 2 - Database feeding projects

The selected projects have a variety of structural elements with different dimensions and load parameters. These parameters are called “search parameters”. Normal force is an important parameter to perform an iterative search for columns and foundations, since it has the main effect on the required reinforcement. However, for beams load is not a search parameter, but span is instead. Beam’s span is an effective parameter in the structural calculations, since it affects the bending moment value by square, which is the main parameter to calculate longitudinal reinforcement in a beam. The database contains a wide range of these parameters as shown in the following table.

Parameter	Beams	Circular Columns	Rectangular Columns	Single Foundations
Diameter (mm)	-	300 ~ 450	-	-
Width (mm)	200 ~ 500	-	250 ~ 800	1500 ~ 5200
Length (mm)	-	-	350 ~ 1000	1500 ~ 5200
Height (mm)	250 ~ 1400	2250 ~ 4300	2800 ~ 17000	500 ~ 1500
Span (m)	2.25 ~ 24.25	-	-	-
Normal Force (kN)	-	81 ~ 5588	84 ~ 6862	135 ~ 4200

Table 3 – Search parameters and their range in database

5.2 Testing Projects

Two projects (T1 and T2), which have been designed by Bollinger+Grohmann, were selected to test this method. Both projects are industrial buildings. These projects were meant to have values of search parameters covered by the database range, which was not a difficult task, since the database already has a wide range of these search parameters. However, trying to get an exact match with three or four search parameters would not be efficient. Therefore, tolerance was chosen for each parameter to make the iterative search more efficient and faster in getting matches.

Parameter	Beams	Circular Columns	Rectangular Columns	Single Foundations
Diameter	-	±10 cm	-	-
Width	±10 cm	-	±10 cm	±50 cm
Length	-	-	±10 cm	±50 cm
Height	±10 cm	±1 m	±1 m	±50 cm
Span	±1 m	-	-	-
Normal Force	-	±200 kN	±200 kN	±400 kN

Table 4 - Tolerance of search parameters

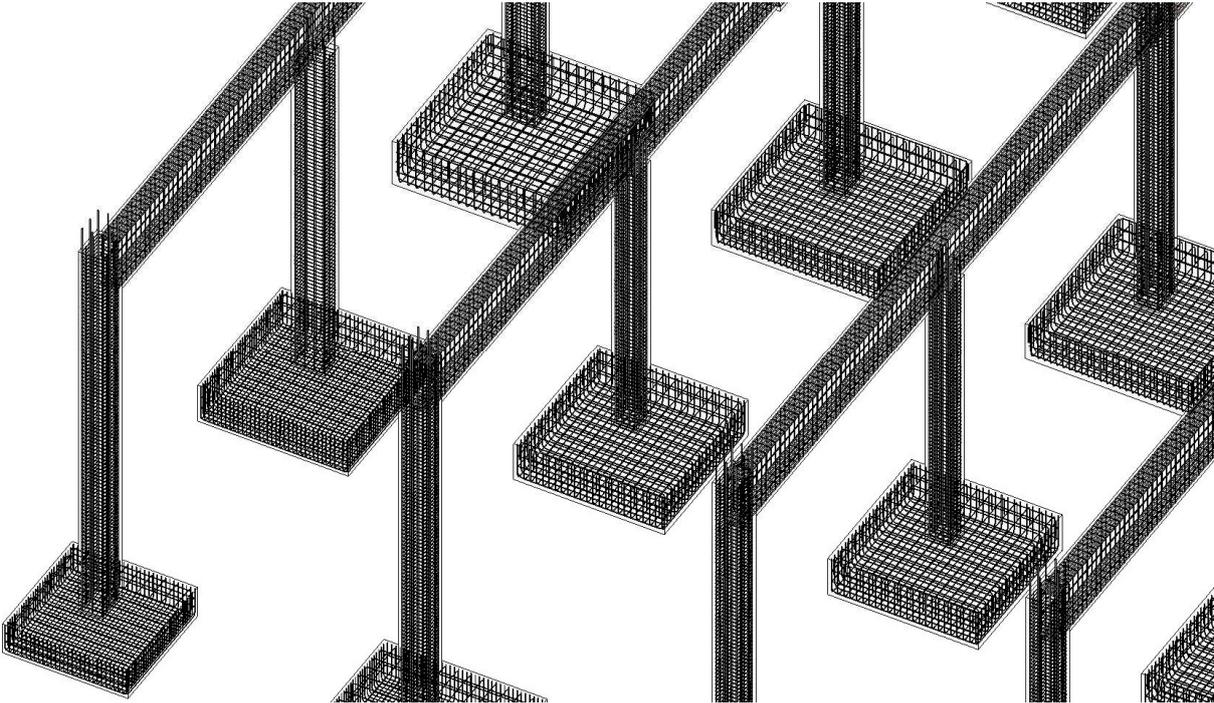


Figure 29 - An example of reinforcement generation in project T1

6 Comparing Results

Comparison of results is based on analyzing the difference between the reinforcement ratios from conventional methods and the developed method and comparing both to values from LPh5, which are called “Reality” in this study. Two BIM models were used to generate reinforcement for structural elements and get results for reinforcement ratios.

Testing was carried out for all structural elements (beams, columns and foundations) in project T1. However, to get individual results for each element, the method was tested on columns in project T1, beams in project T2 and foundations in project T2.

1. Results for all elements from project T1

- Conventional methods

Reinforcement tonnage = 432.01 t

Reinforcement ratio = 180 kg/m³

- Developed method

Reinforcement tonnage = 219.09 t

Reinforcement ratio = 92 kg/m³

- Reality

Reinforcement ratio = 103 kg/m³

Element	Anzahl	Länge	Breite	Höhe	Fläche	Beton	Bewehrungsanteil	Bewehrung	Bewehrung	Bewehrungsvolumen	Bewehrungsvolumen
	-	m	m	m	m ²	m ³	kg/m ³	kg	t	cm ³	m ³
Total	348					2378.73		432005.28	432.00528	55032519.75	55.03251975
Stützen	98	0,50 m	0,80 m	12,00 m	3057,60	470,40	300,00	141120	141,12	17977070,06	17,97707006
Stützen	12	0,60 m	0,60 m	7,20 m	207,36	31,10	300,00	9331,2	9,3312	1188687,898	1,188687898
Stützen	5	0,60 m	0,80 m	7,50 m	105,00	18,00	300,00	5400	5,4	687898,0892	0,687898089
Stützen	2	0,60 m	0,80 m	8,80 m	49,28	8,45	300,00	2534,4	2,5344	322853,5032	0,322853503
Stützen	17	0,60 m	0,80 m	8,90 m	423,64	72,62	300,00	21787,2	21,7872	2775439,49	2,77543949
Stützen	4	0,60 m	0,80 m	10,05 m	112,56	19,30	300,00	5788,8	5,7888	737426,7516	0,737426752
Stützen	1	0,60 m	0,80 m	10,20 m	28,56	4,90	300,00	1468,8	1,4688	187108,2803	0,18710828
Stützen	1	0,60 m	0,80 m	10,50 m	29,40	5,04	300,00	1512	1,512	192611,465	0,192611465
Stützen	8	0,60 m	0,80 m	12,00 m	268,80	46,08	300,00	13824	13,824	1761019,108	1,761019108
Stützen	8	0,70 m	0,80 m	14,00 m	336,00	62,72	300,00	18816	18,816	2396942,675	2,396942675
Unterzüge	36	9,00 m	0,50 m	1,40 m	957,60	226,80	180,00	40824	40,824	5200509,554	5,200509554
Fundamente	50	2,70 m	2,70 m	0,50 m	270,00	182,25	120,00	21870	21,87	2785987,261	2,785987261
Fundamente	1	2,80 m	2,80 m	0,50 m	5,60	3,92	120,00	470,4	0,4704	59923,56688	0,059923567
Fundamente	6	2,90 m	2,90 m	0,50 m	34,80	25,23	120,00	3027,6	3,0276	385681,5287	0,385681529
Fundamente	1	3,00 m	3,00 m	0,50 m	6,00	4,50	120,00	540	0,54	68789,80892	0,068789809
Fundamente	1	3,00 m	3,00 m	0,80 m	9,60	7,20	120,00	864	0,864	110063,6943	0,110063694
Fundamente	1	3,20 m	3,20 m	0,80 m	10,24	8,19	120,00	983,04	0,98304	125228,0255	0,125228025
Fundamente	28	3,50 m	3,50 m	0,50 m	196,00	171,50	120,00	20580	20,58	2621656,051	2,621656051
Fundamente	17	3,50 m	3,50 m	0,80 m	190,40	166,60	120,00	19992	19,992	2546751,592	2,546751592
Fundamente	16	3,60 m	3,60 m	1,00 m	230,40	207,36	120,00	24883,2	24,8832	3169834,395	3,169834395
Fundamente	5	3,70 m	3,70 m	0,80 m	59,20	54,76	120,00	6571,2	6,5712	837095,5414	0,837095541
Fundamente	2	3,70 m	3,70 m	1,00 m	29,60	27,38	120,00	3285,6	3,2856	418547,7707	0,418547771
Fundamente	2	3,90 m	3,90 m	1,00 m	31,20	30,42	120,00	3650,4	3,6504	465019,1083	0,465019108
Fundamente	1	4,00 m	4,00 m	0,80 m	12,80	12,80	120,00	1536	1,536	195668,7898	0,19566879
Fundamente	10	4,00 m	4,00 m	1,00 m	160,00	160,00	120,00	19200	19,2	2445859,873	2,445859873
Fundamente	1	4,10 m	4,10 m	0,80 m	13,12	13,15	120,00	1613,76	1,61376	205574,5223	0,205574522
Fundamente	1	4,10 m	4,10 m	1,20 m	19,68	20,47	120,00	2420,64	2,42064	308361,7834	0,308361783
Fundamente	1	4,20 m	4,20 m	1,00 m	16,80	17,64	120,00	2116,8	2,1168	269656,051	0,269656051
Fundamente	1	4,30 m	4,30 m	0,80 m	13,76	14,79	120,00	1775,04	1,77504	226119,7452	0,226119745
Fundamente	3	4,60 m	4,60 m	1,20 m	66,24	76,18	120,00	9141,12	9,14112	1164473,885	1,164473885
Fundamente	1	4,60 m	5,10 m	1,00 m	19,40	23,46	120,00	2815,2	2,8152	358624,2038	0,358624204
Fundamente	1	4,70 m	4,70 m	1,20 m	22,56	26,51	120,00	3180,96	3,18096	405217,8344	0,405217834
Fundamente	3	4,80 m	4,80 m	1,00 m	57,60	69,12	120,00	8294,4	8,2944	1056611,465	1,056611465
Fundamente	1	5,00 m	5,00 m	1,00 m	20,00	25,00	120,00	3000	3	382165,6051	0,382165605
Fundamente	2	5,20 m	5,20 m	1,20 m	49,92	64,90	120,00	7787,52	7,78752	992040,7643	0,992040764

Figure 30 - Conventional methods results for project T1 (all elements)

Comparing Results

<Rebar Schedule>					
A	B	C	D	E	F
Bar Diameter	Quantity	Total Bar Length	Reinforcement Volume	BG_Reinforcement Volume	BG_Reinforcement Weight
8 mm	2783	6536 m	0.33 m ³	0.33 m ³	2.58 t
10 mm	15694	40076 m	3.15 m ³	3.15 m ³	24.71 t
12 mm	29646	34486 m	393.41 m ³	3.90 m ³	30.62 t
14 mm	1500	1404 m	25.02 m ³	0.22 m ³	1.70 t
16 mm	23980	21842 m	479.86 m ³	4.39 m ³	34.47 t
25 mm	1212	14071 m	6.91 m ³	6.91 m ³	54.22 t
28 mm	1198	14646 m	9.02 m ³	9.02 m ³	70.79 t
Grand total: 54559	76013	133061 m	917.69 m ³	27.91 m ³	219.09 t

Figure 31 - Developed method results for project T1 (all elements)

2. Results for columns from project T1

- Conventional methods

Reinforcement tonnage = 221.58 t

Reinforcement ratio = 300 kg/m³

- Developed method

Reinforcement tonnage = 126.15 t

Reinforcement ratio = 170 kg/m³

- Reality

Reinforcement ratio = 120 kg/m³

Element	Anzahl	Länge m	Breite m	Höhe m	Fläche m ²	Beton m ³	Bewehrungsanteil kg/m ³	Bewehrung kg	Bewehrung t	Bewehrungsvolumen cm ³	Bewehrungsvolumen m ³
Total	156					738,61		221582,4	221,5824	28227057,32	28,22705732
Stützen	98	0,50 m	0,80 m	12,00 m	3057,60	470,40	300,00	141120	141,12	17977070,06	17,97707006
Stützen	12	0,60 m	0,60 m	7,20 m	207,36	31,10	300,00	9331,2	9,3312	1188687,898	1,188687898
Stützen	5	0,60 m	0,80 m	7,50 m	105,00	18,00	300,00	5400	5,4	687898,0892	0,687898089
Stützen	2	0,60 m	0,80 m	8,80 m	49,28	8,45	300,00	2534,4	2,5344	322853,5032	0,322853503
Stützen	17	0,60 m	0,80 m	8,90 m	423,64	72,62	300,00	21787,2	21,7872	2775439,49	2,77543949
Stützen	4	0,60 m	0,80 m	10,05 m	112,56	19,30	300,00	5788,8	5,7888	737426,7516	0,737426752
Stützen	1	0,60 m	0,80 m	10,20 m	28,56	4,90	300,00	1468,8	1,4688	187108,2803	0,18710828
Stützen	1	0,60 m	0,80 m	10,50 m	29,40	5,04	300,00	1512	1,512	192611,465	0,192611465
Stützen	8	0,60 m	0,80 m	12,00 m	268,80	46,08	300,00	13824	13,824	1761019,108	1,761019108
Stützen	8	0,70 m	0,80 m	14,00 m	336,00	62,72	300,00	18816	18,816	2396942,675	2,396942675

Figure 32 - Conventional methods results for project T1 (columns)

<Rebar Schedule>					
A	B	C	D	E	F
Bar Diameter	Quantity	Bar Length	Total Bar Length	BG_Reinforcement Volume	BG_Reinforcement Weight
8 mm	2783	54 m	6536 m	0.33 m ³	2.58 t
10 mm	14124	312 m	34194 m	2.69 m ³	21.08 t
12 mm	816	890 m	4121 m	0.47 m ³	3.66 t
25 mm	1212	1276 m	14071 m	6.91 m ³	54.22 t
28 mm	694	562 m	9230 m	5.68 m ³	44.61 t
Grand total: 393	19629	3095 m	68152 m	16.07 m ³	126.15 t

Figure 33 - Developed method results for project T1 (columns)

Comparing Results

3. Results for beams from project T2

- Conventional methods

Reinforcement tonnage = 90.48 t

Reinforcement ratio = 180 kg/m³

- Developed method

Reinforcement tonnage = 115.28 t

Reinforcement ratio = 230 kg/m³

- Reality

Reinforcement ratio = 340 kg/m³

Element	Anzahl	Länge	Breite	Höhe	Fläche	Beton	Bewehrungsanteil	Bewehrung	Bewehrung	Bewehrungsvolumen	Bewehrungsvolumen
	-	m	m	m	m ²	m ³	kg/m ³	kg	t	cm ³	m ³
Total	185					502,65		90477	90,477	11525732,48	11,52573248
Unterzüge	1	0,25 m	0,60 m	2,50 m	4,25	0,38	180,00	67,5	0,0675	8598,726115	0,008598726
Unterzüge	2	0,25 m	0,60 m	5,00 m	17,00	1,50	180,00	270	0,27	34394,90446	0,034394904
Unterzüge	1	0,25 m	0,60 m	7,50 m	12,75	1,13	180,00	202,5	0,2025	25796,17834	0,025796178
Unterzüge	40	0,25 m	0,60 m	10,00 m	680,00	60,00	180,00	10800	10,8	1375796,178	1,375796178
Unterzüge	84	0,25 m	0,80 m	10,00 m	1764,00	168,00	180,00	30240	30,24	3852229,299	3,852229299
Unterzüge	8	0,40 m	0,50 m	6,50 m	93,60	10,40	180,00	1872	1,872	238471,3376	0,238471338
Unterzüge	19	0,50 m	0,60 m	9,50 m	397,10	54,15	180,00	9747	9,747	1241656,051	1,241656051
Unterzüge	16	0,50 m	0,95 m	6,25 m	290,00	47,50	180,00	8550	8,55	1089171,975	1,089171975
Unterzüge	14	0,50 m	0,95 m	24,00 m	974,40	159,60	180,00	28728	28,728	3659617,834	3,659617834

Figure 34 - Conventional methods results for project T2 (beams)

<Rebar Schedule>					
A	B	C	D	E	F
Bar Diameter	Quantity	Bar Length	Total Bar Length	BG_Reinforcement Volume	BG_Reinforcement Weight
10 mm	6731	290132 mm	13528 m	1.06 m ³	8.34 t
12 mm	5326	3150522 mm	17910 m	2.03 m ³	15.90 t
20 mm	32	68115 mm	197 m	0.06 m ³	0.48 t
25 mm	910	3268130 mm	10112 m	4.96 m ³	38.97 t
28 mm	1046	7212001 mm	10672 m	6.57 m ³	51.58 t
Grand total: 1548	14045	13988900 mm	52419 m	14.69 m ³	115.28 t

Figure 35 - Developed method results for project T2 (beams)

4. Results for foundations from project T2

- Conventional methods

Reinforcement tonnage = 148.94 t

Reinforcement ratio = 120 kg/m³

- Developed method

Reinforcement tonnage = 37.74 t

Reinforcement ratio = 30 kg/m³

- Reality

Reinforcement ratio = 56 kg/m³

Comparing Results

Element	Anzahl	Länge m	Breite m	Höhe m	Fläche m ²	Beton m ³	Bewehrungsanteil kg/m ³	Bewehrung kg	Bewehrung t	Bewehrungsvolumen cm ³	Bewehrungsvolumen m ³
Total	175					1241,11		148933,725	148,933725	18972449,04	18,97244904
Fundamente	22	3,50 m	3,50 m	0,60 m	184,80	161,70	120,00	19404	19,404	2471847,134	2,471847134
Fundamente	15	3,00 m	3,00 m	0,50 m	90,00	67,50	120,00	8100	8,1	1031847,134	1,031847134
Fundamente	7	3,50 m	3,50 m	1,55 m	151,90	132,91	120,00	15949,5	15,9495	2031783,439	2,031783439
Fundamente	19	1,60 m	1,60 m	1,25 m	152,00	60,80	120,00	7296	7,296	929426,7516	0,929426752
Fundamente	19	1,50 m	2,00 m	1,25 m	166,25	71,25	120,00	8550	8,55	1089171,975	1,089171975
Fundamente	4	1,80 m	2,10 m	1,25 m	39,00	18,90	120,00	2268	2,268	288917,1975	0,288917197
Fundamente	4	2,55 m	2,55 m	1,35 m	55,08	35,11	120,00	4213,62	4,21362	536766,879	0,536766879
Fundamente	5	2,00 m	2,00 m	1,35 m	54,00	27,00	120,00	3240	3,24	412738,8535	0,412738854
Fundamente	5	2,30 m	2,80 m	1,35 m	68,85	43,47	120,00	5216,4	5,2164	664509,5541	0,664509554
Fundamente	8	2,30 m	2,30 m	0,50 m	36,80	21,16	120,00	2539,2	2,5392	323464,9682	0,323464968
Fundamente	1	2,05 m	2,05 m	1,35 m	11,07	5,67	120,00	680,805	0,680805	86726,75159	0,086726752
Fundamente	14	2,00 m	3,70 m	1,00 m	159,60	103,60	120,00	12432	12,432	1583694,268	1,583694268
Fundamente	16	2,50 m	4,20 m	1,00 m	214,40	168,00	120,00	20160	20,16	2568152,866	2,568152866
Fundamente	14	2,50 m	3,40 m	1,00 m	165,20	119,00	120,00	14280	14,28	1819108,28	1,81910828
Fundamente	7	3,00 m	4,60 m	1,00 m	106,40	96,60	120,00	11592	11,592	1476687,898	1,476687898
Fundamente	2	3,00 m	4,30 m	1,00 m	29,20	25,80	120,00	3096	3,096	394394,9045	0,394394904
Fundamente	2	2,50 m	3,00 m	1,00 m	22,00	15,00	120,00	1800	1,8	229299,3631	0,229299363
Fundamente	2	2,40 m	2,40 m	1,35 m	25,92	15,55	120,00	1866,24	1,86624	237737,5796	0,23773758
Fundamente	2	2,30 m	2,30 m	1,35 m	24,84	14,28	120,00	1713,96	1,71396	218338,8535	0,218338854
Fundamente	7	1,80 m	2,40 m	1,25 m	73,50	37,80	120,00	4536	4,536	577834,3949	0,577834395

Figure 36 - Conventional methods results for project T2 (foundations)

<Rebar Schedule>					
A	B	C	D	E	F
Bar Diameter	Quantity	Bar Length	Total Bar Length	BG_Reinforcement Volume	BG_Reinforcement Weight
12 mm	27138	23711660 mm	23712 m	2,68 m ³	21,05 t
14 mm	4650	4650445 mm	4650 m	0,72 m ³	5,62 t
16 mm	8670	7011318 mm	7011 m	1,41 m ³	11,07 t
Grand total:	40458	35373424 mm	35373 m	4,81 m³	37,74 t

Figure 37 - Developed method results for project T2 (foundations)

The following table summarizes the comparison of developed method and conventional method results (kg/m³) and their percentage of reality.

Structural Element	All Elements	Columns	Beams	Foundations
Reality	103	120	340	56
Conventional Methods Results	180	300	180	120
Conventional Method Results as a Percentage of Reality	175%	250%	53%	214%
Developed Method Results	92	170	230	30
Developed Method Results as a Percentage of Reality	89%	142%	68%	54%

Table 5 - Summary of results comparison

7 Conclusion

To conclude, the method developed in this research could get an early estimation of 89% of the actual required reinforcement, rather than 175% by conventional methods. Of course, it is very difficult to get 100% accurate results, since the method depends on generating reinforcement based on previous experiences.

In early stages of design, 100% accuracy is not required. However, the results can definitely be improved by feeding the database more projects or using more search parameters e.g. building type. Structures from the same category tend to have closer reinforcement ratios. For instance, an industrial building would have cross sections and reinforcement profiles more similar to another industrial building rather than a residential building.

Another aspect that could improve the results is reducing the tolerance of search parameters. However, this is difficult in the current stage, since the database has information from only nine projects (seven feeding projects and two testing projects). For further research, the database can be loaded with more projects, reduce tolerances and test the approach again.

There is no doubt that uncertain parameters have influenced the results as well. The amount of constructive reinforcement depends mainly on the assumed parameters of maximum and minimum distance between bars. Overlapping and development bar lengths are also factors that affect the reinforcement quantity. Therefore, the assumption of uncertain parameters in the beginning of the research is a very important step.

This method is recommended to be used on BIM models in early stages of design, where LOD is equal to or less than 300. However, in LOD 400 or higher reinforcement should be calculated and modeled more precisely. These models with higher LOD would be perfect for feeding the database though.

For future development of this research, the scripts can be adapted to run through a whole model with one click. However, this could crash the model or take very long time to process due to the huge amount of data. This could be a problem, which can be solved in further research.

Conclusion

Another improvement to the study is using an online database in a Common Data Environment (CDE), where more than one user can export to and import from the database at the same time. This will accelerate the database feeding process, but in this case, information sent to the database has to be reviewed and approved by the developer.

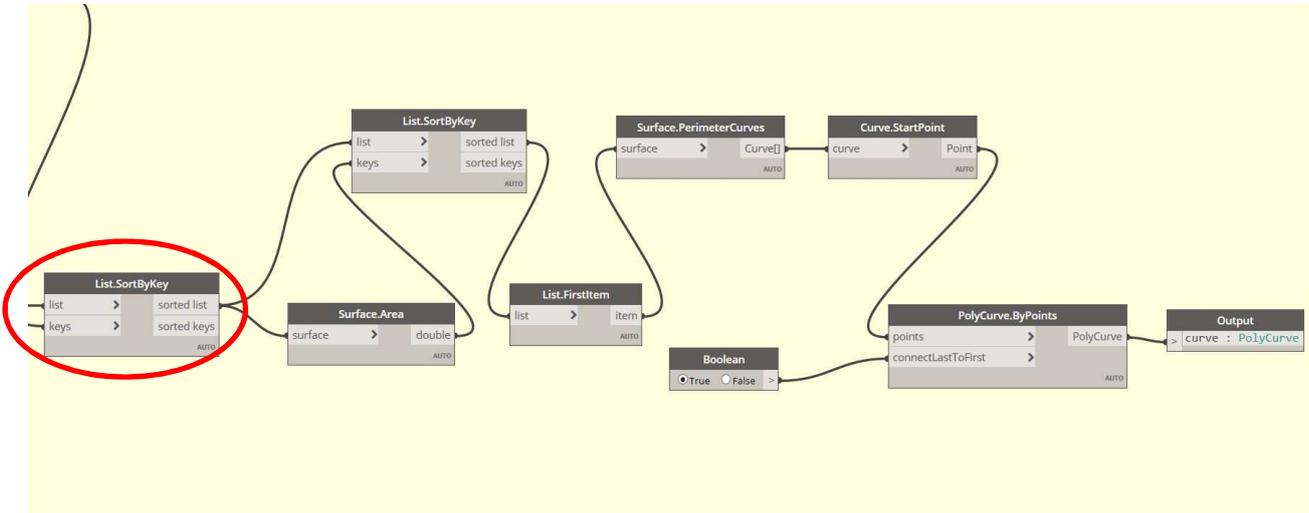
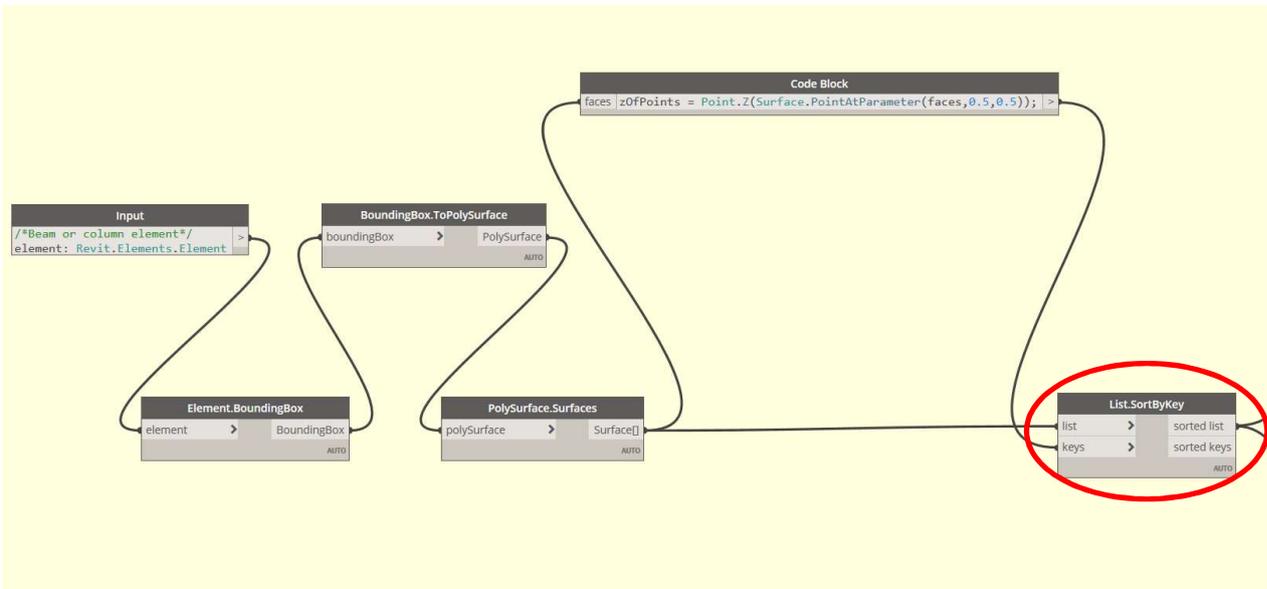
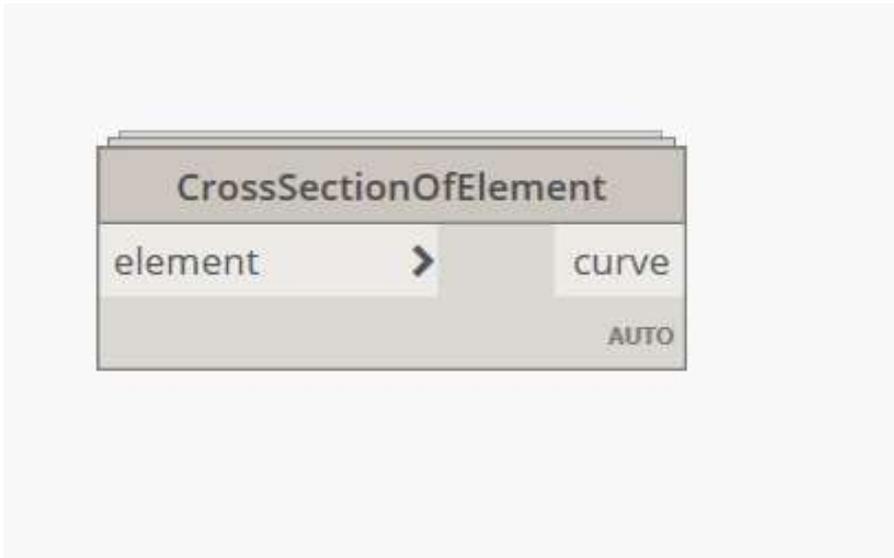
Appendix A

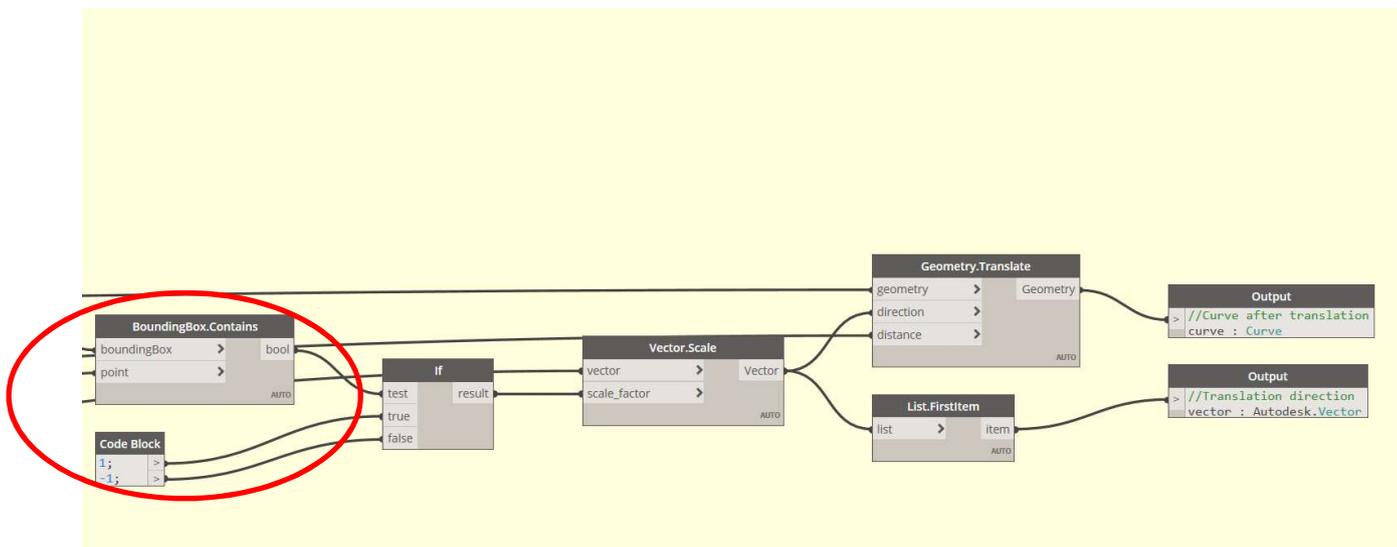
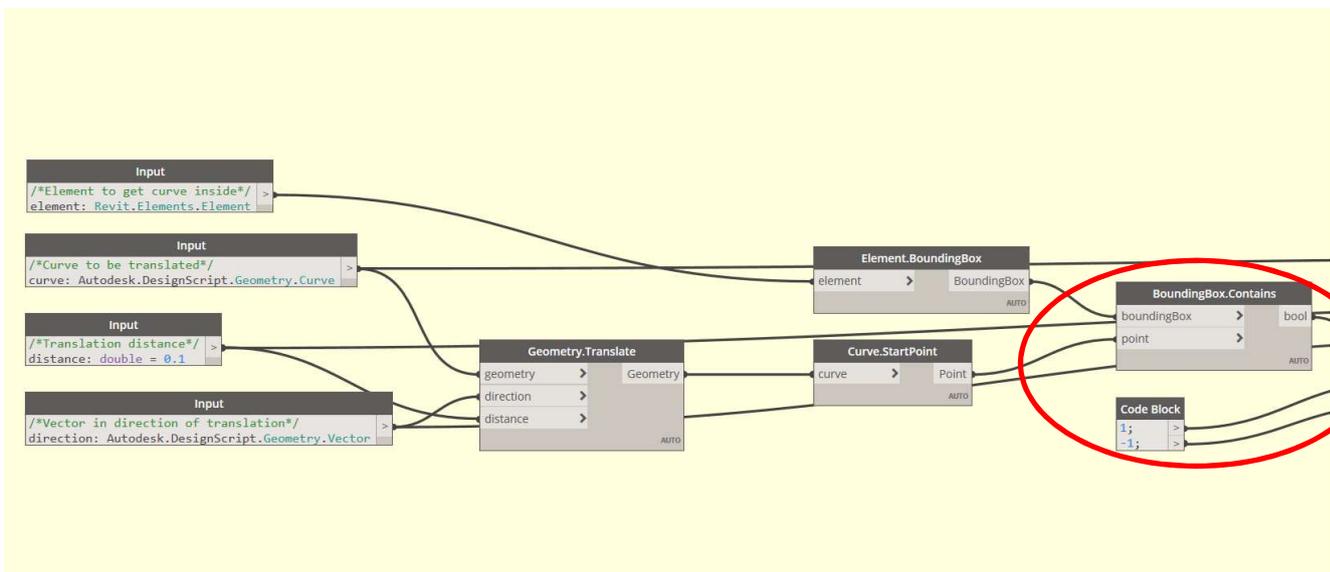
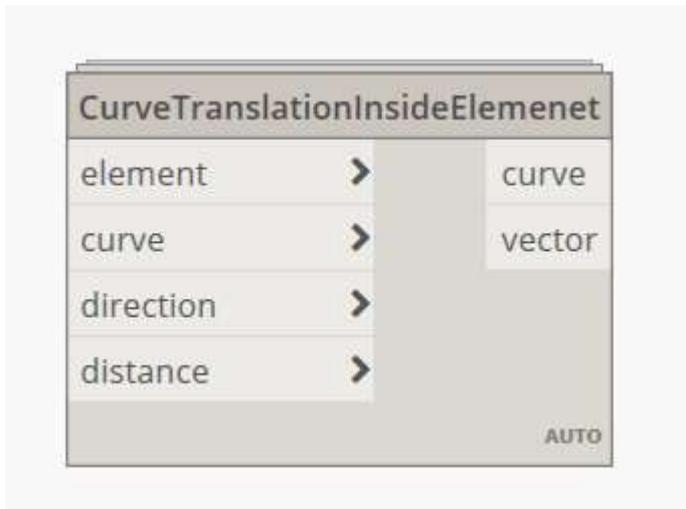
A.1 Custom Nodes

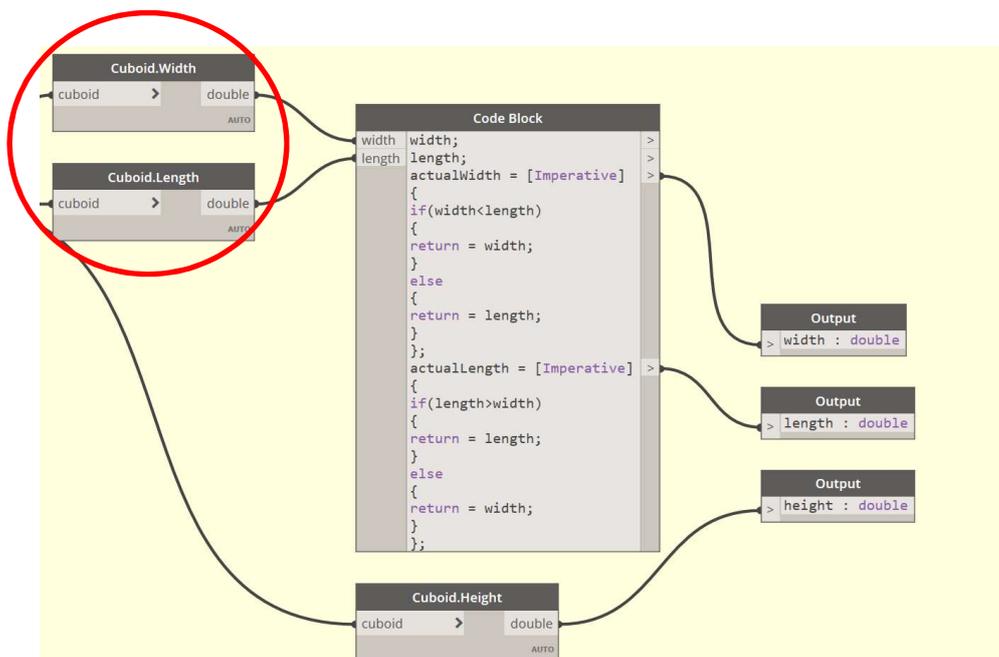
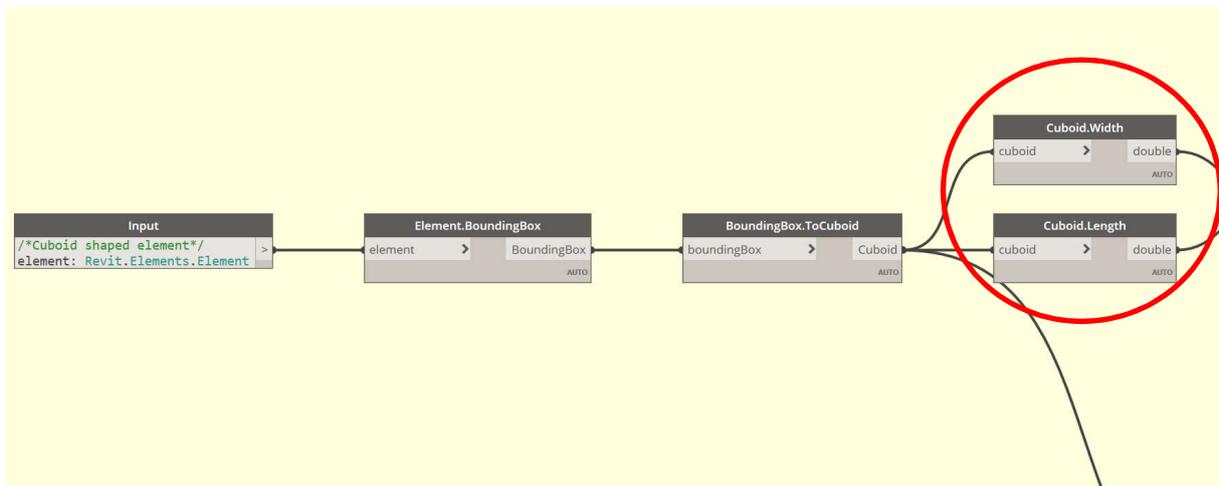
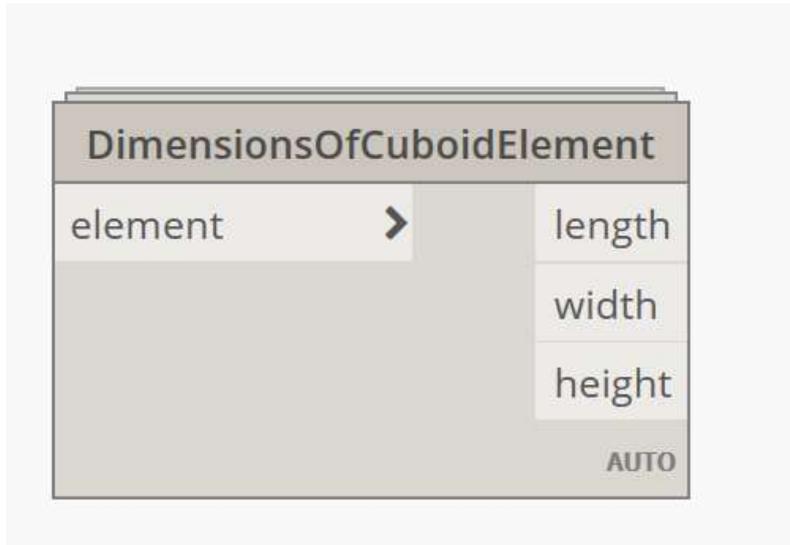
There have been some difficulties faced in order to manipulate the geometry of structural elements and get the reinforcement path curves. To solve these difficulties and to make Dynamo scripts shorter and less complicated, ten custom nodes were implemented. These custom nodes are:

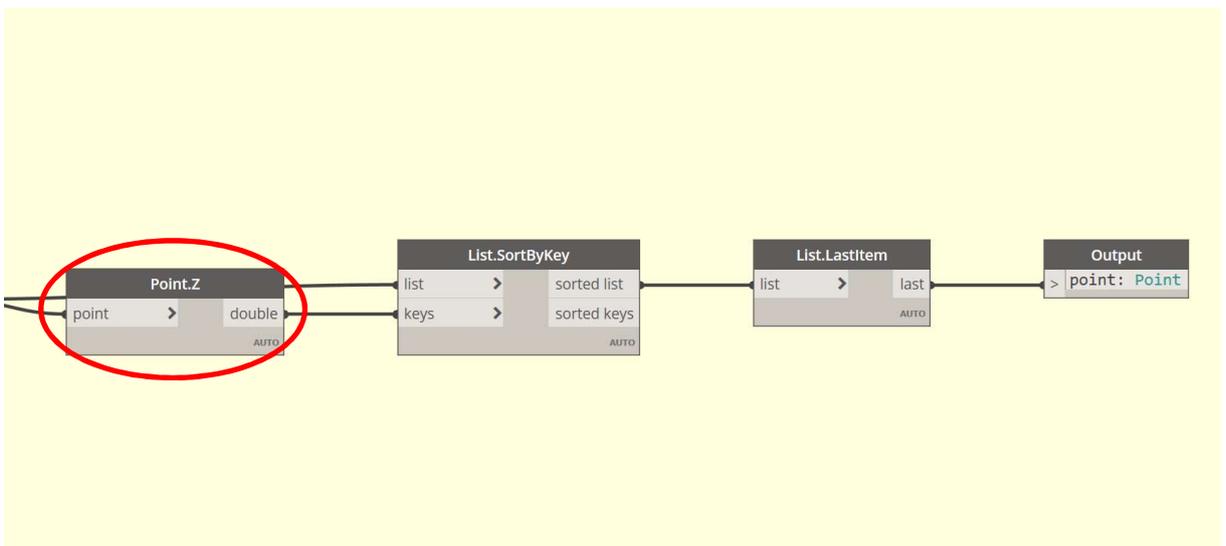
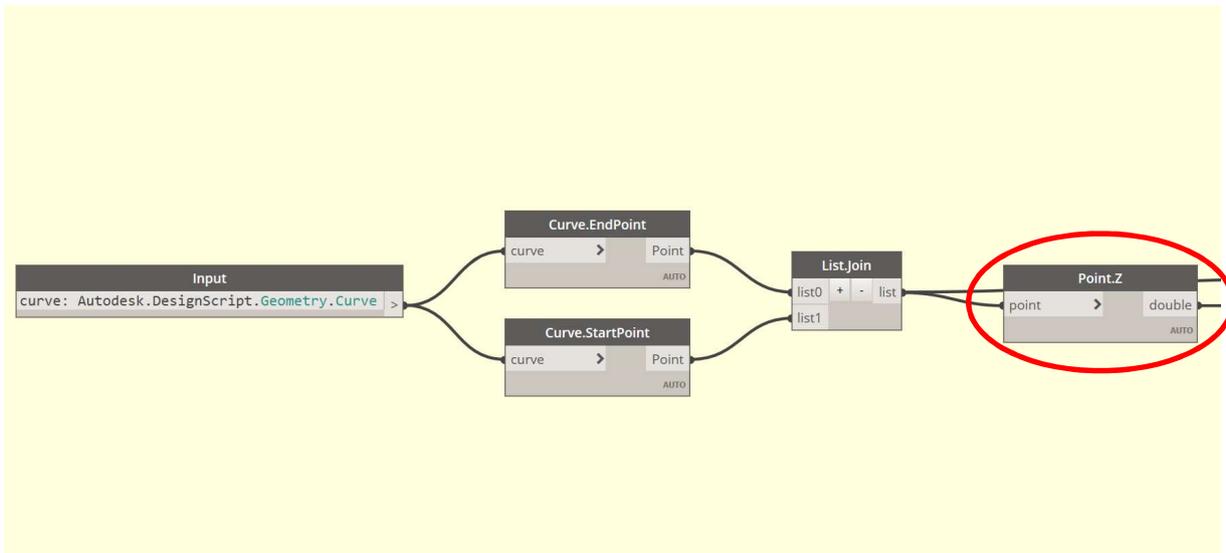
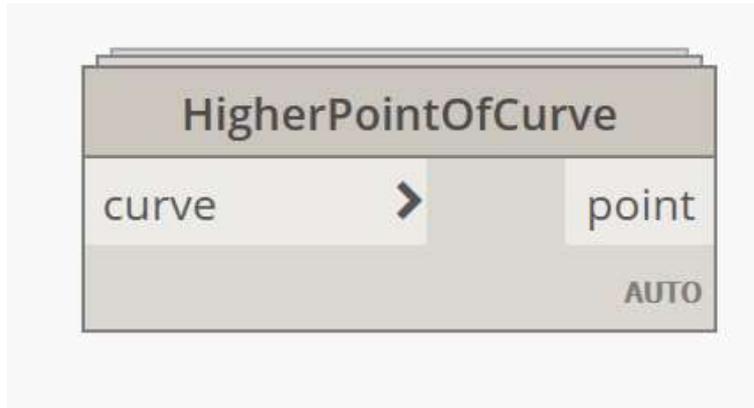
1. CrossSectionOfElement
2. CurveTranslationInsideElement
3. DimensionsOfCupoidElement
4. HigherPointOfCurve
5. HigherSurfaceOfCupoidElement
6. LowerSurfaceOfCupoidElement
7. LongitudinalEdgeOfColumn
8. LongLowerEdgeOfCupoidElement
9. ShortLowerEdgeOfCupoidElement
10. RebarHostedByElement

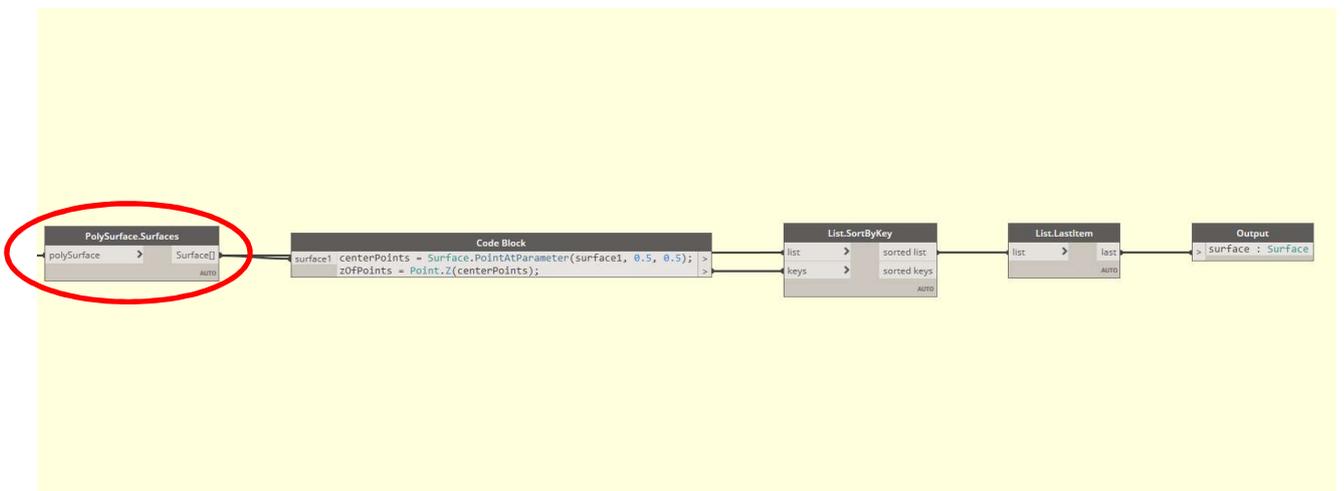
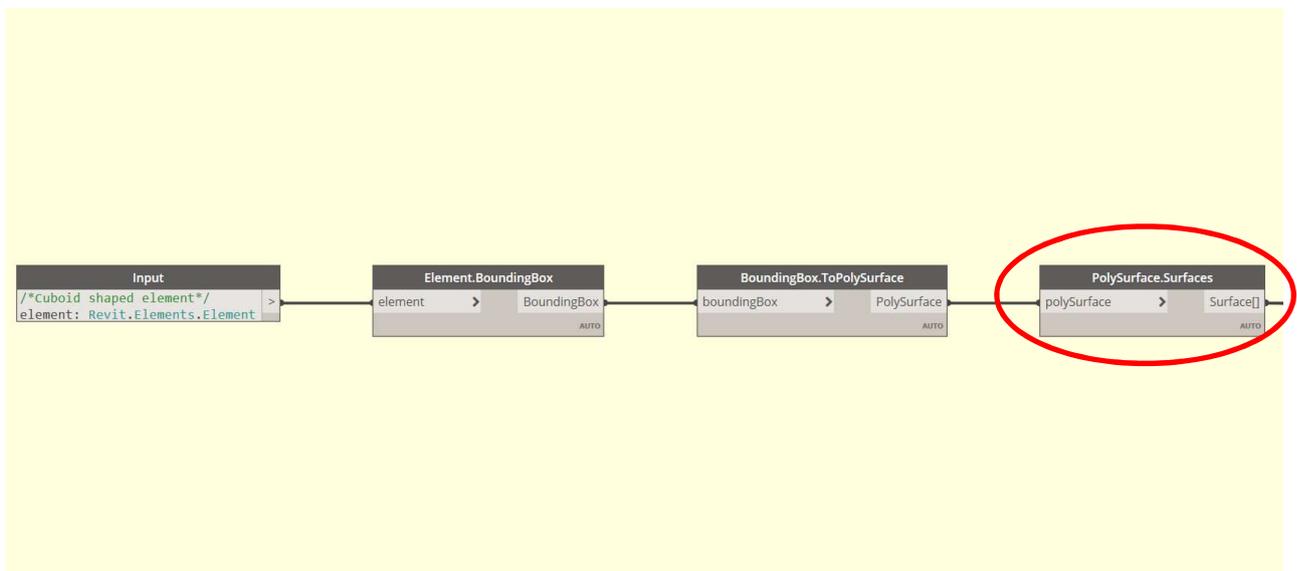
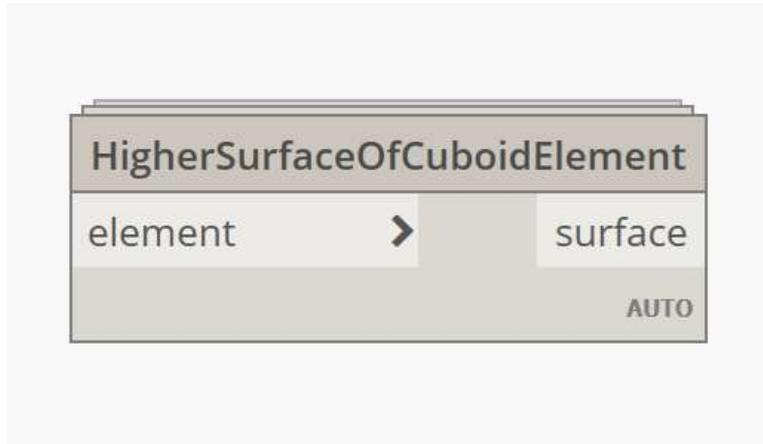
The following figures represent the implementation of these custom nodes in the same order.

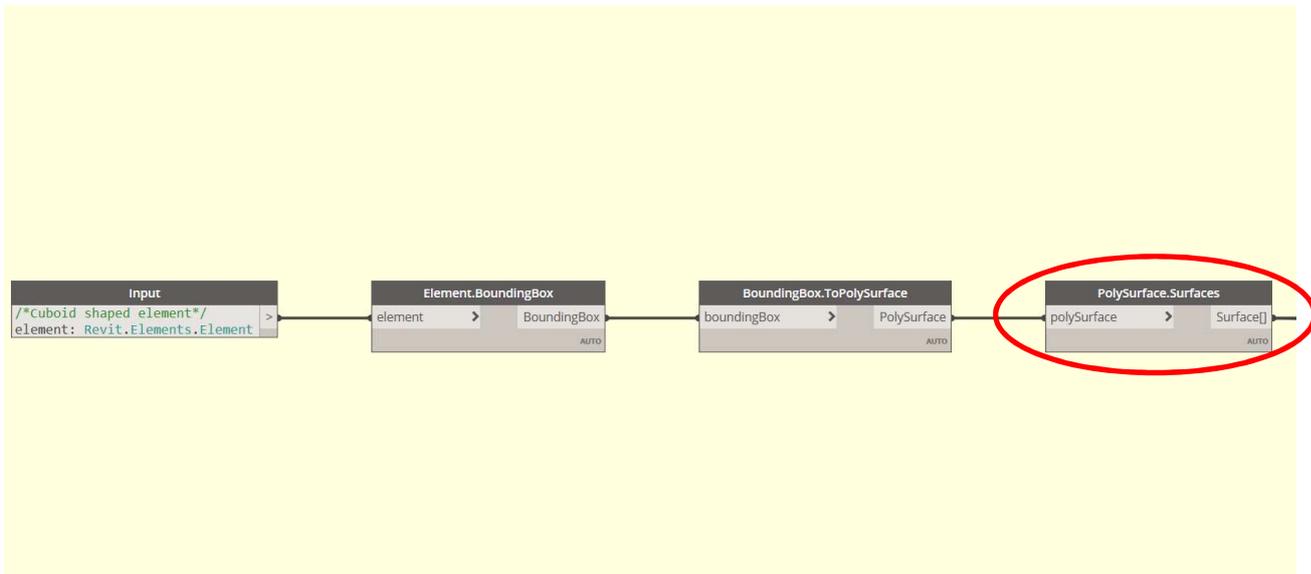
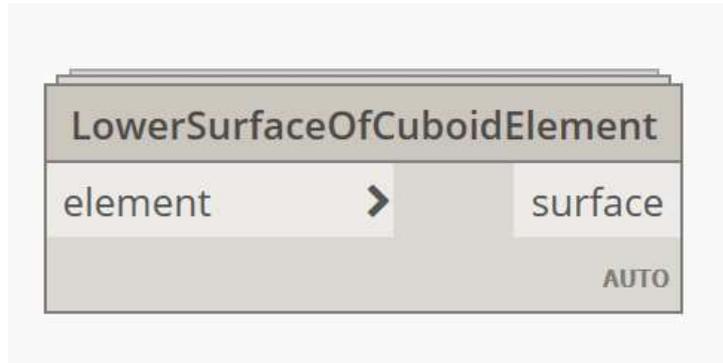


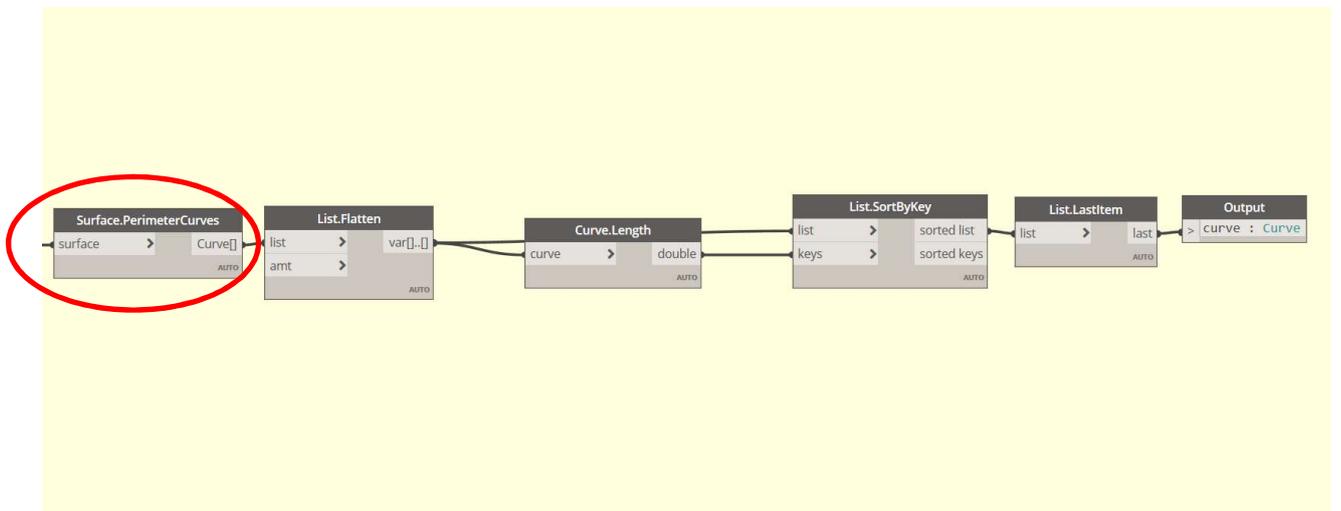
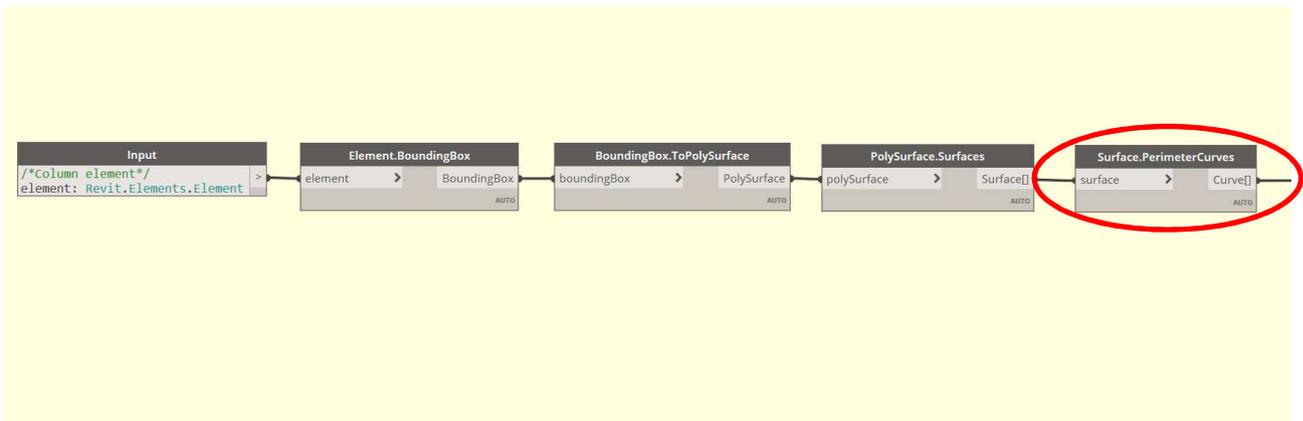
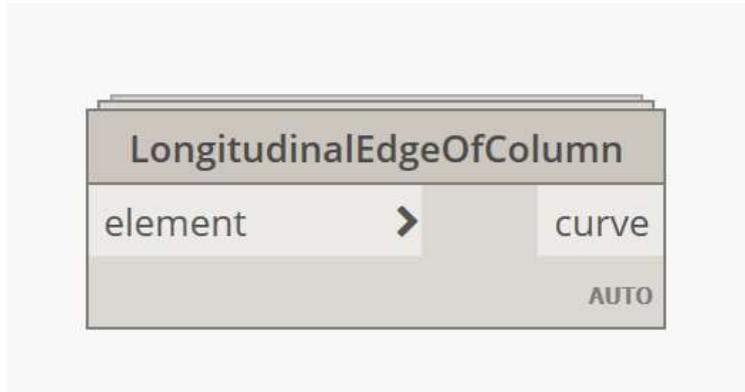


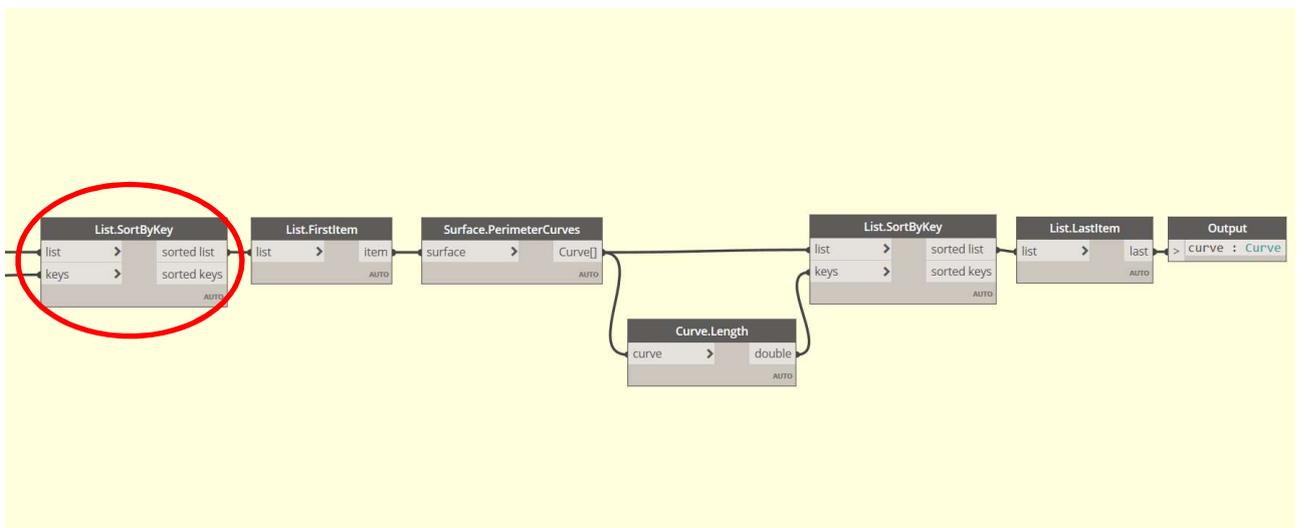
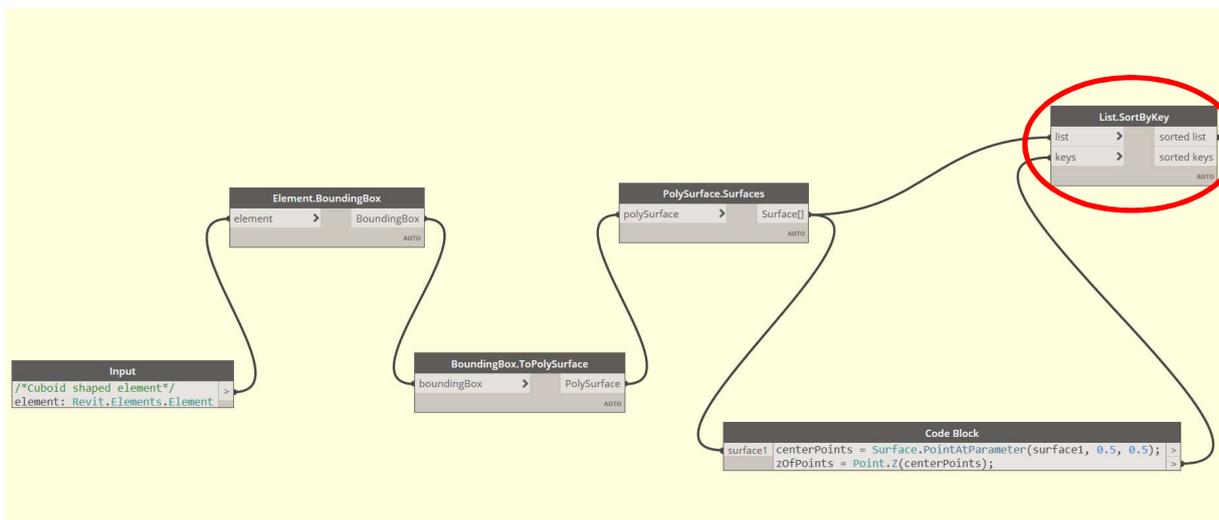
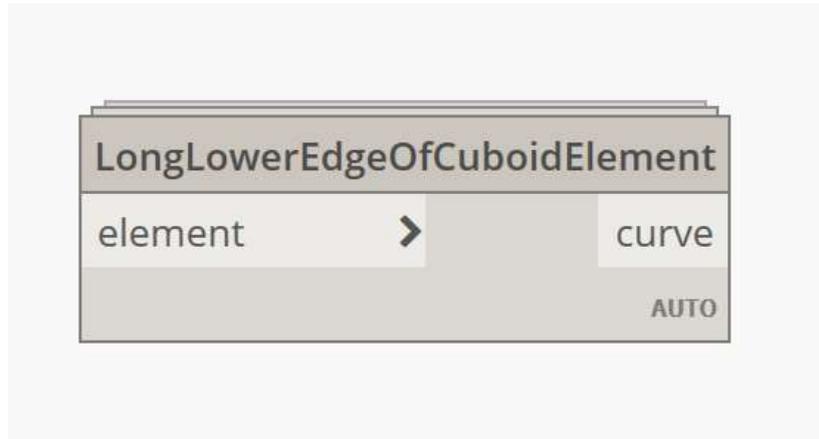


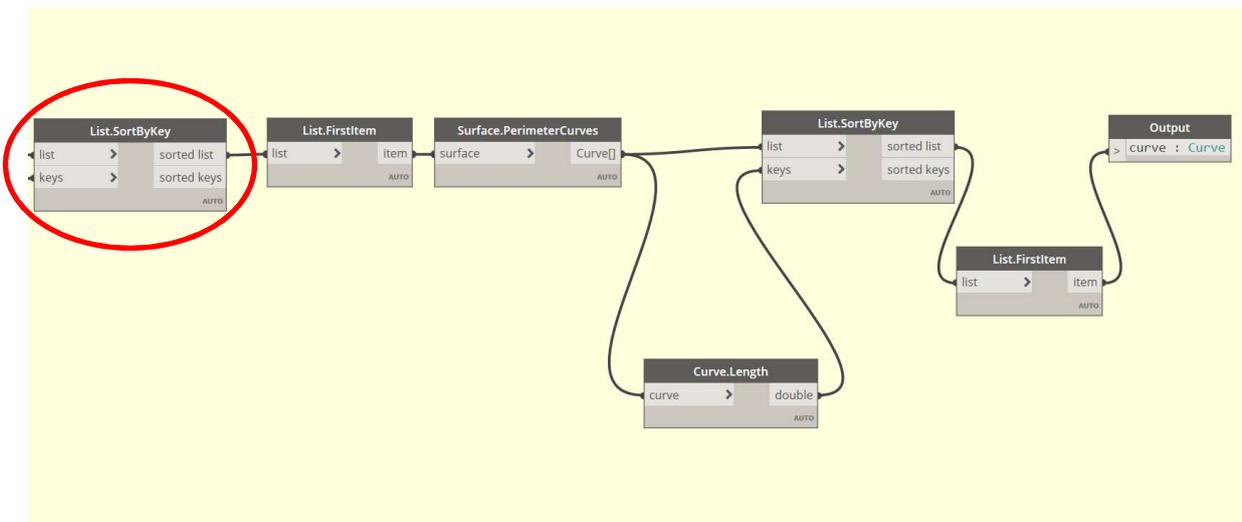
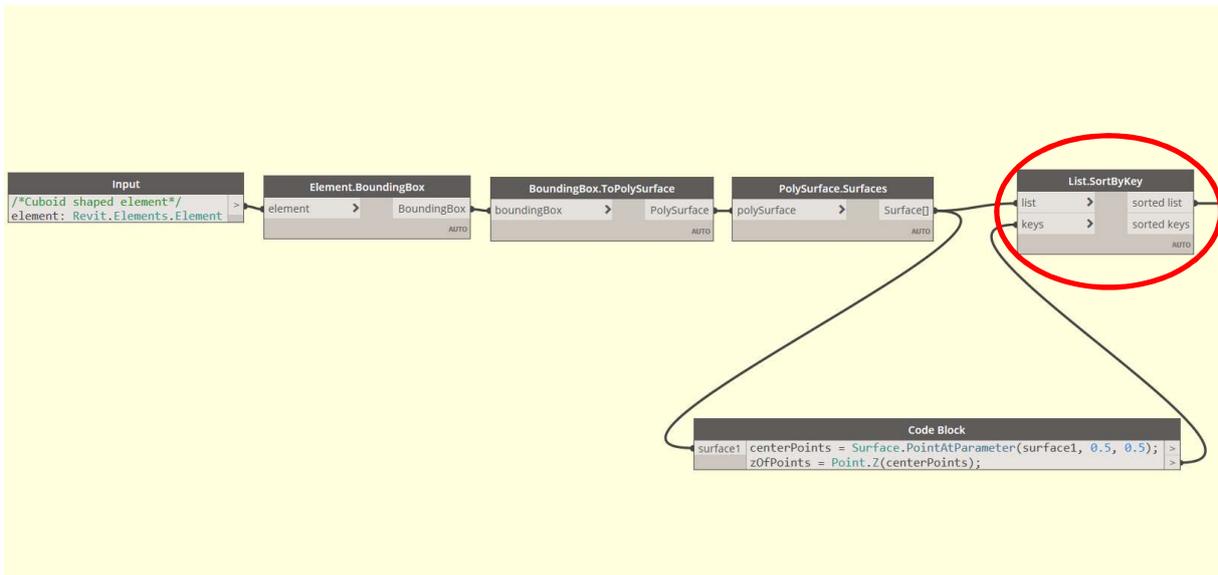
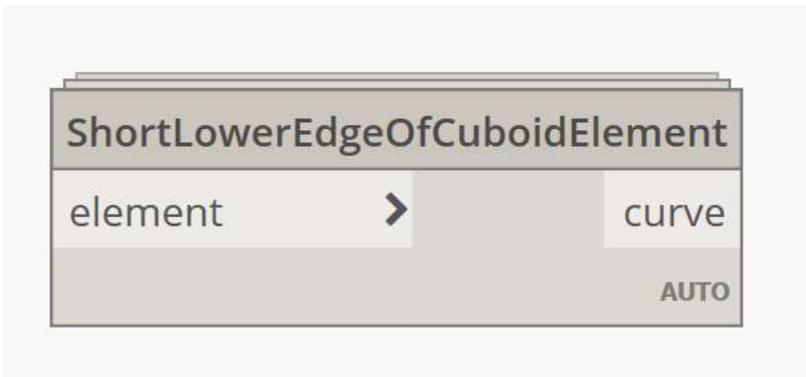


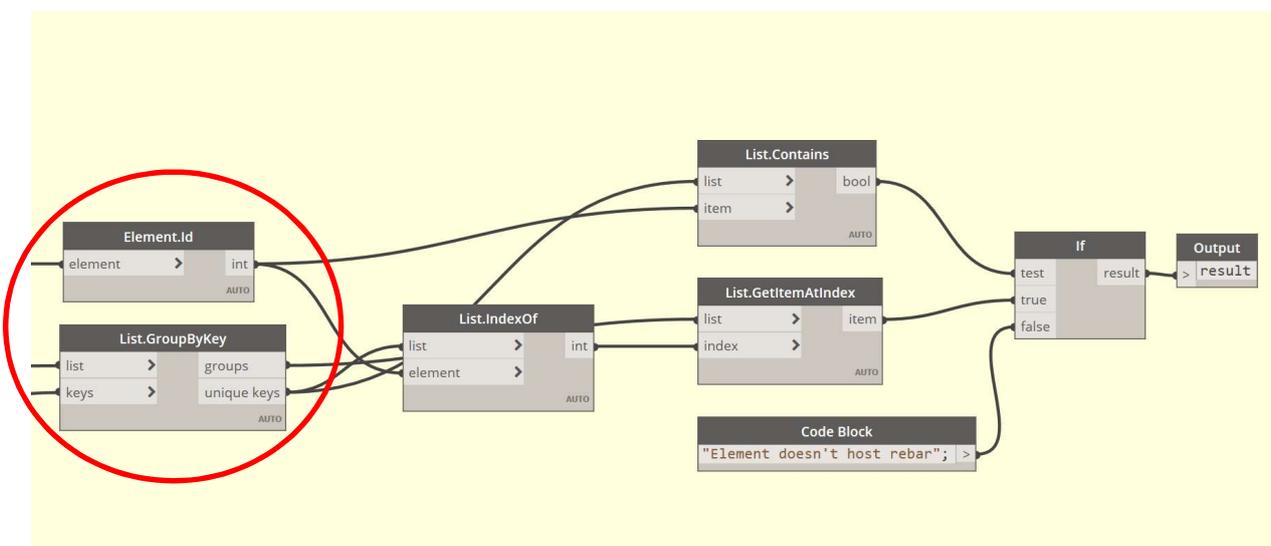
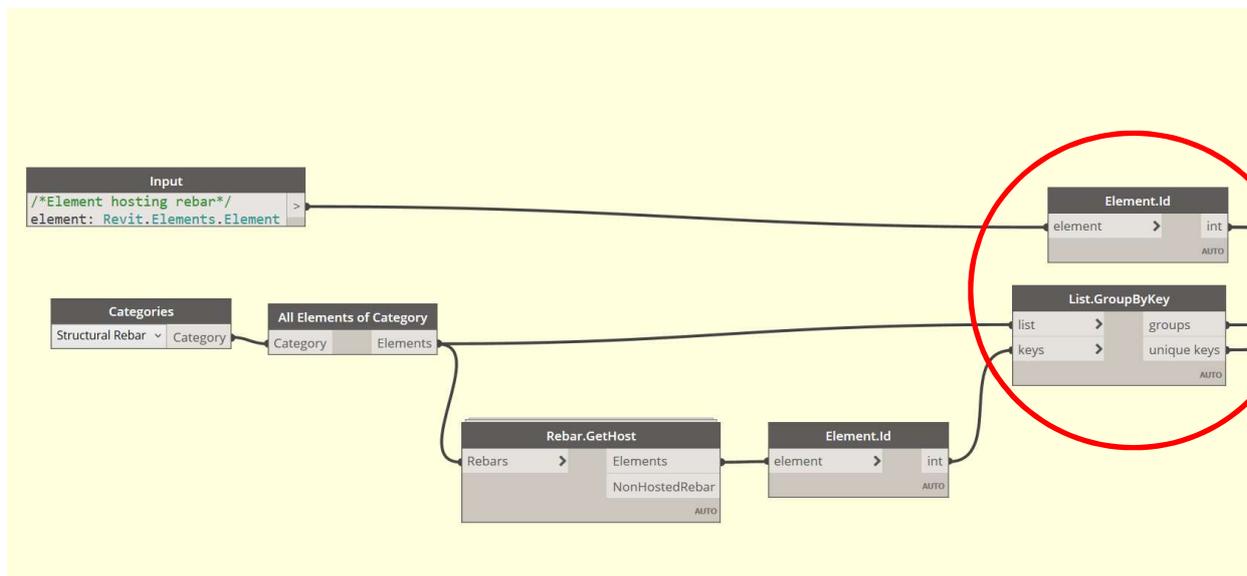
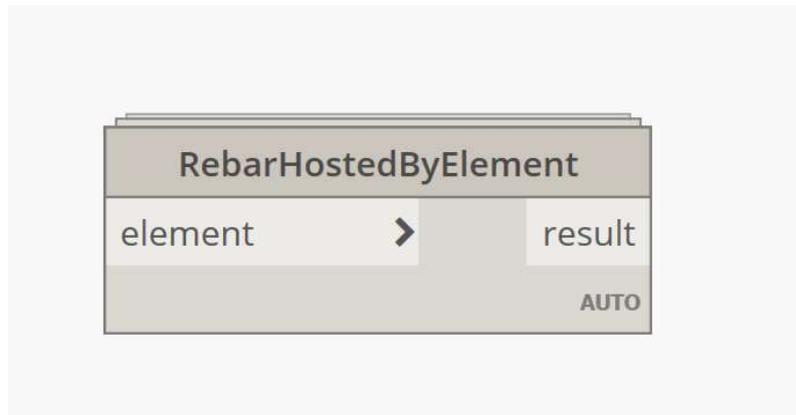












Note: another custom is used inside of the previous custom node (RebarHostedByElement). This custom node is from the package BIM4Struc.

A.2 First Stage Scripts

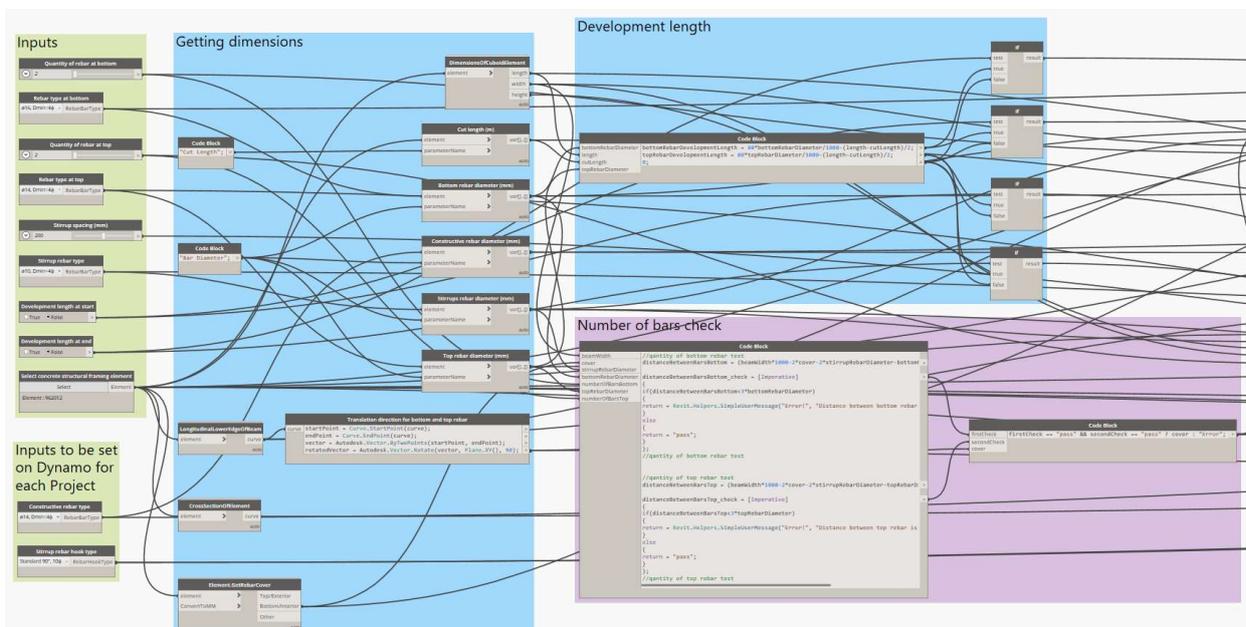
For the first stage five Dynamo scripts were developed. These scripts require input of rebar quantity and diameter. Each script is grouped into groups of nodes, these groups are:

1. Input (green)
2. Getting dimensions and curves of element (blue)
3. Structural checks (purple)
4. Rebar generation (orange)
5. Output (red)

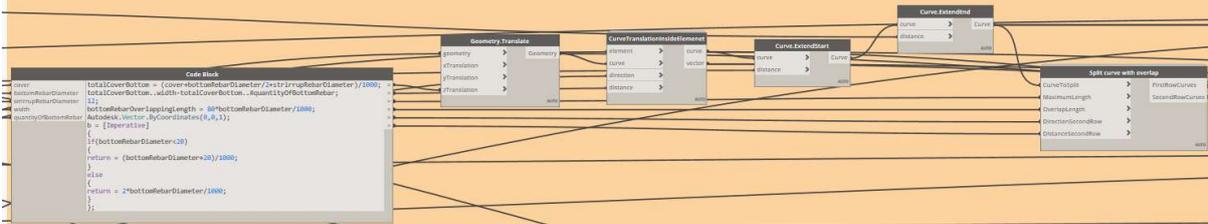
Following is an explanation of each script.

- **01_beam_rebar_input**

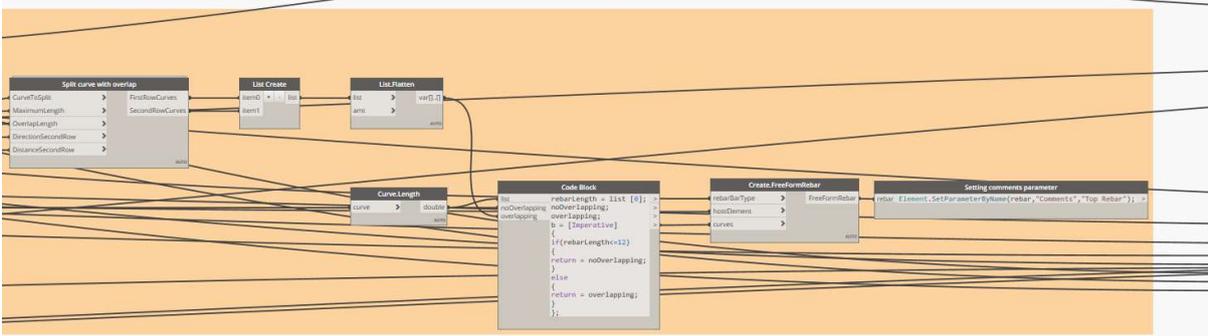
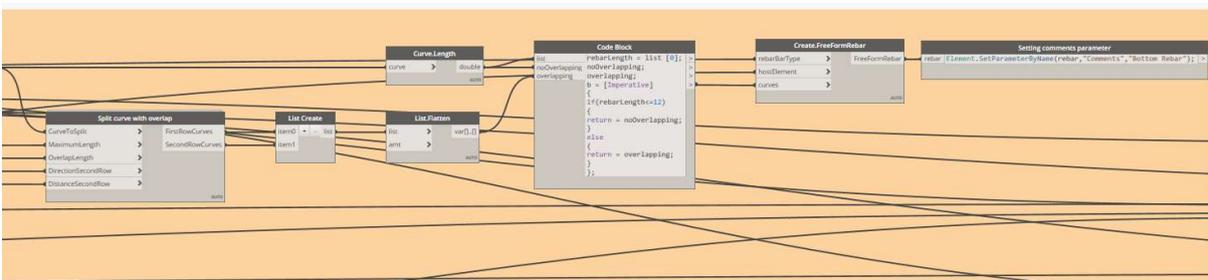
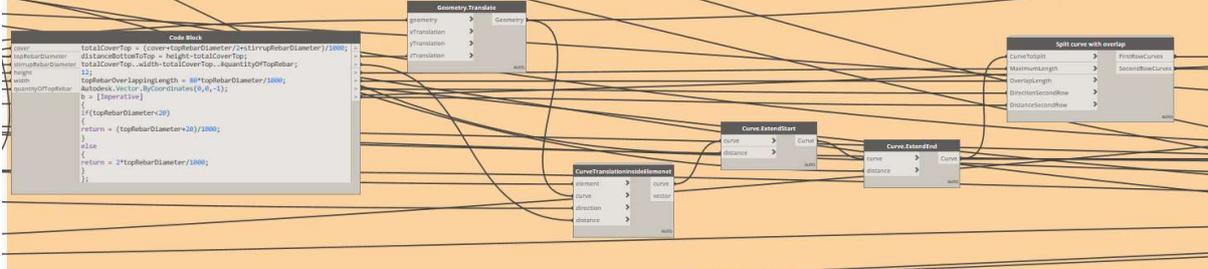
This script generates rebar in rectangular beams, taking into consideration overlapping between steel bars for bars longer than 12 m. The user can also control whether development length is needed or not at the beginning and the end of the selected beam. The script also generates constructive rebar automatically, when distance between main bars is more than 30 cm; the diameter of the constructive rebar can be set manually.



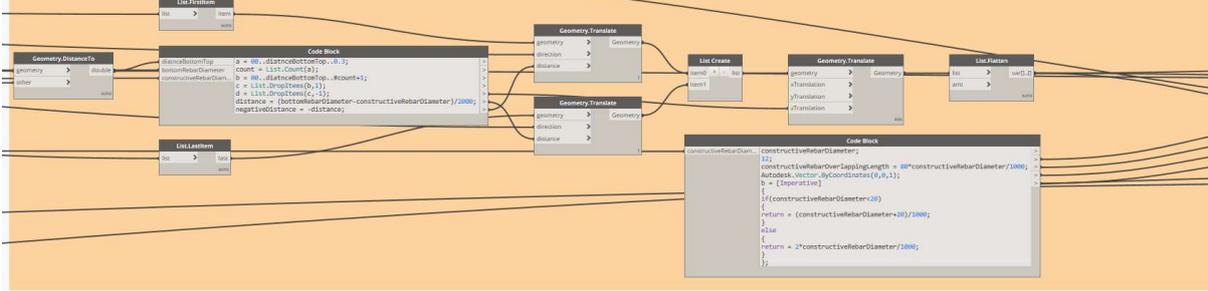
Bottom rebar



Top rebar

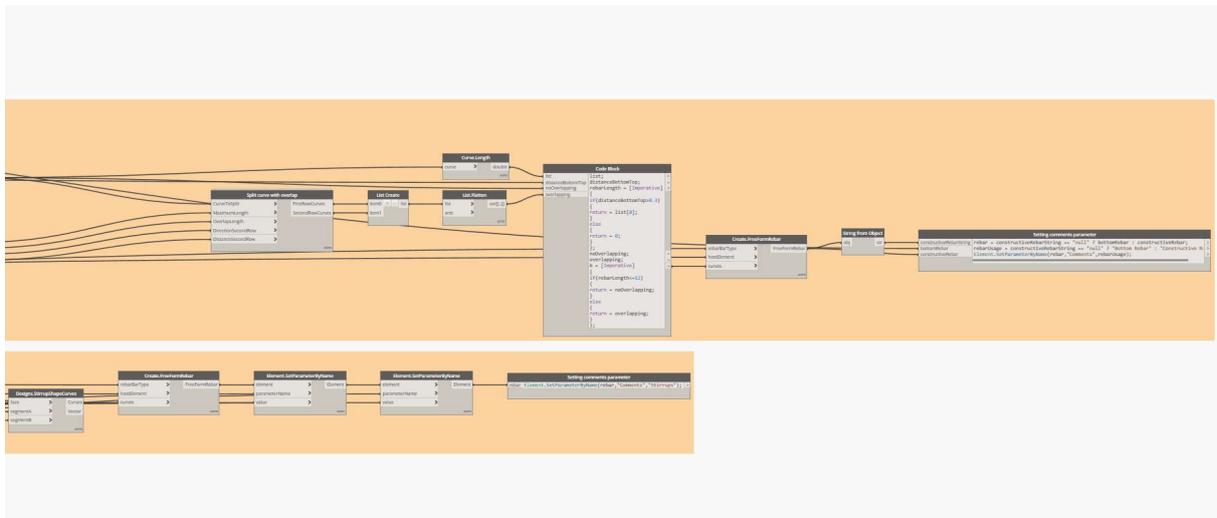


Constructive rebar



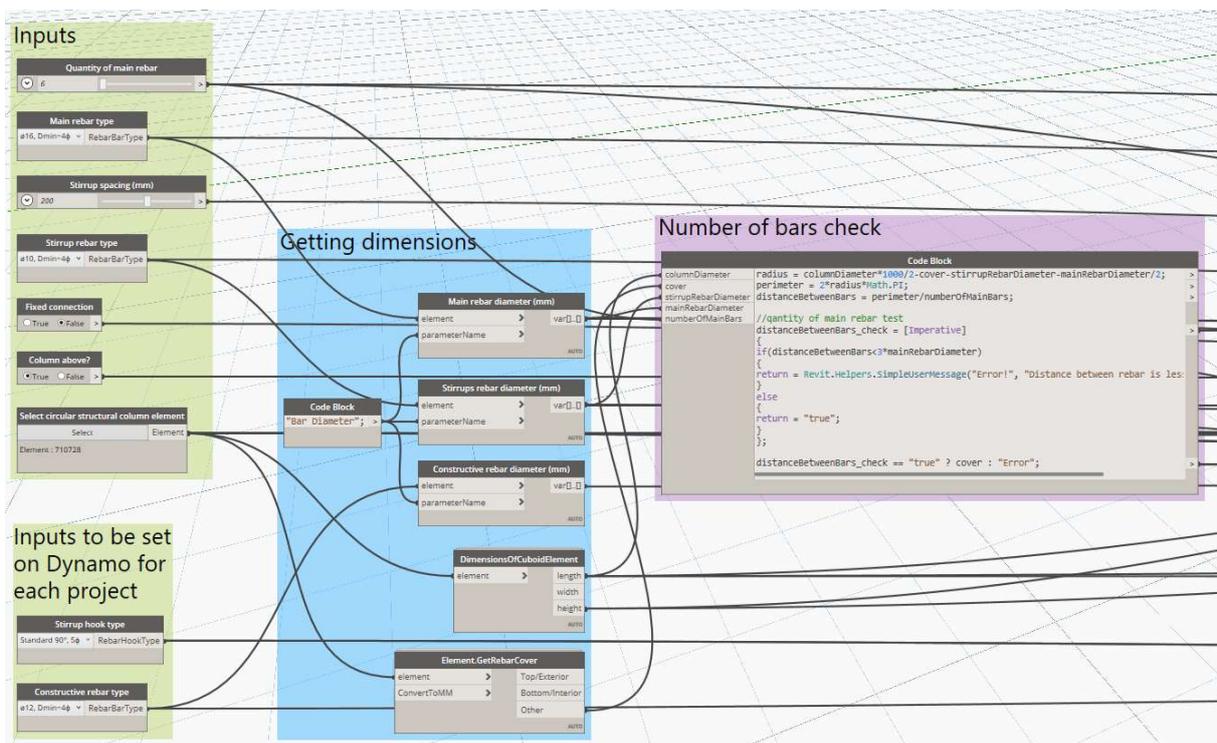
Stirrups

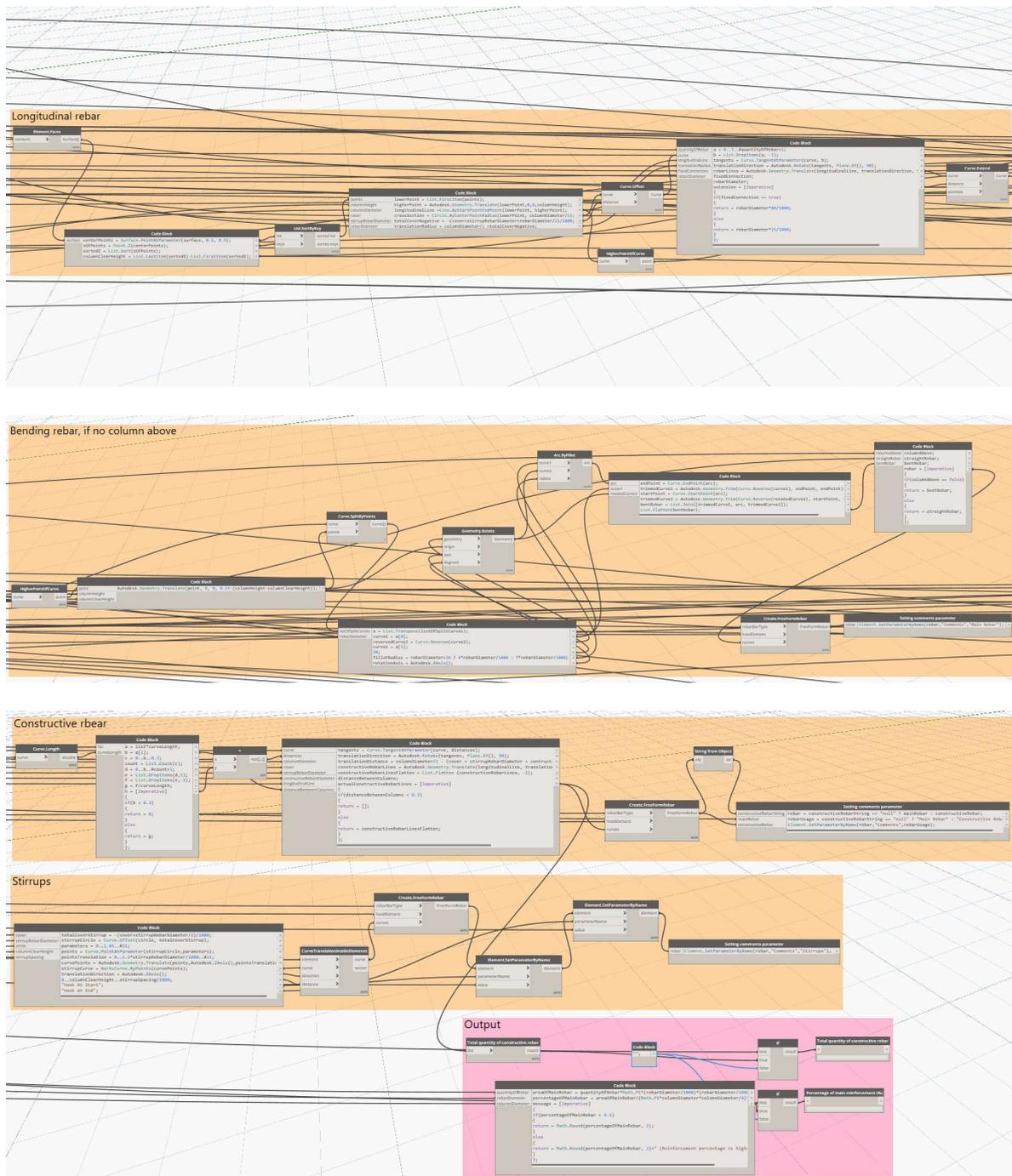




- **02_circular_column_rebar_input**

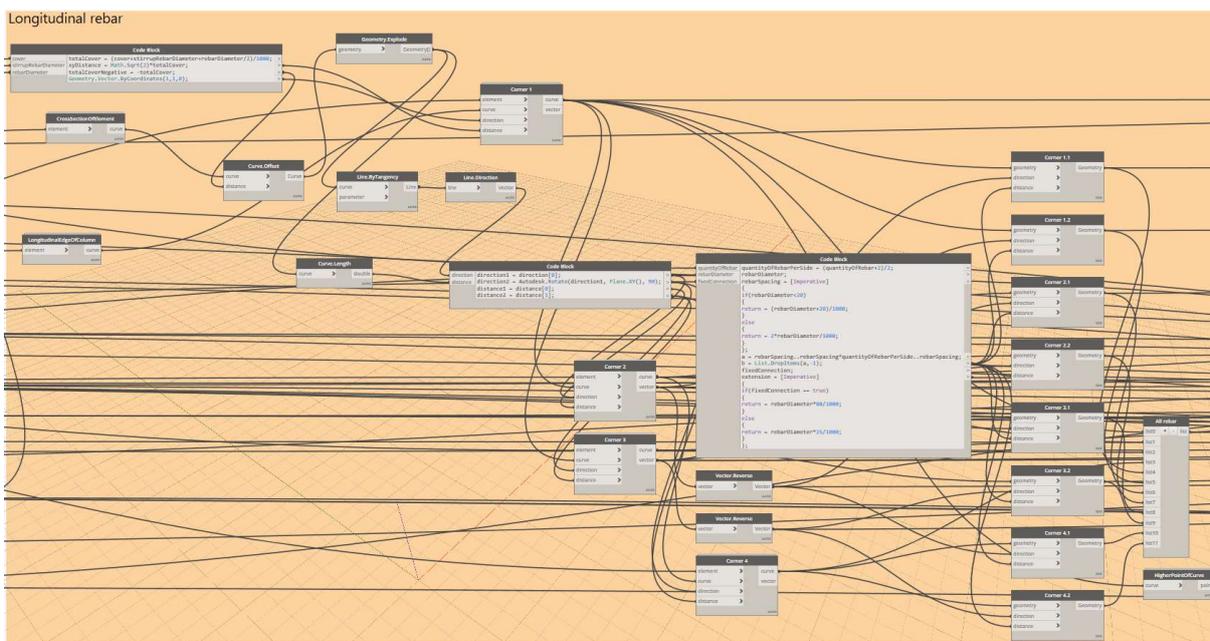
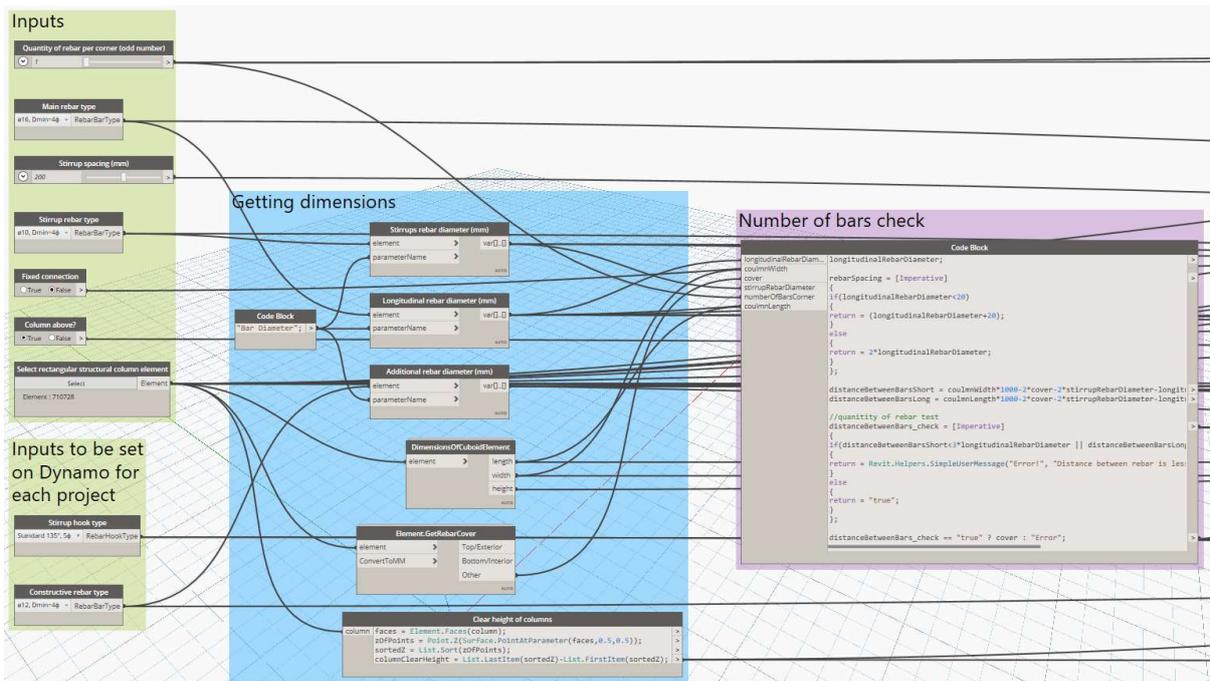
This script creates reinforcement in circular columns, giving the user the option to choose if the connection at the top of the columns is fixed or not. In case of fixed connection the development length is set to 80 x bar diameter, if not it is 25 x bar diameter. Depending on if there is a column above the selected column or not, the user can decide, if the reinforcement should be bent or remain straight. Constructive rebar is automatically generated following the same rules as the previous script.

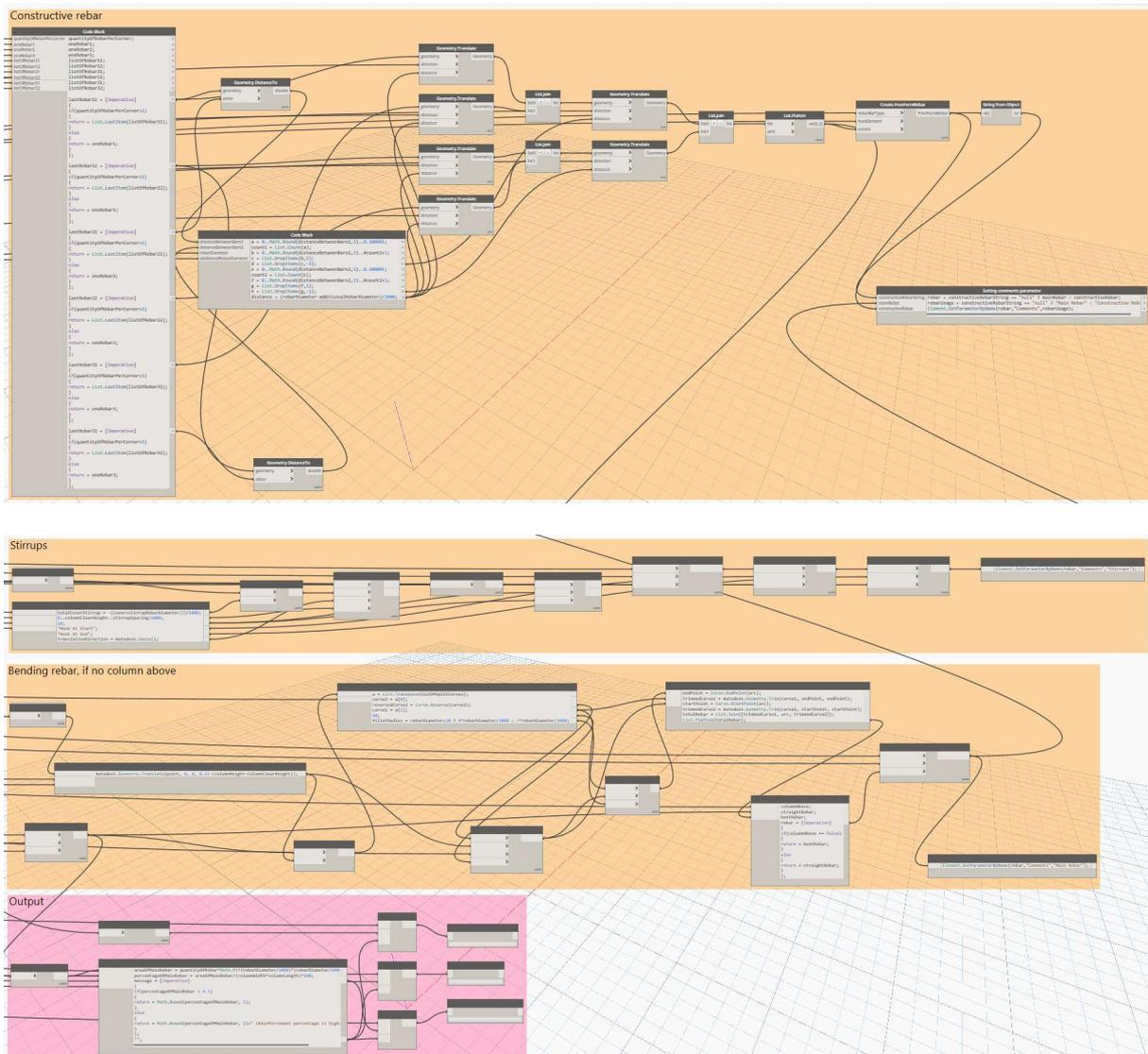




- **03_rectangular_column_corners_rebar_input**

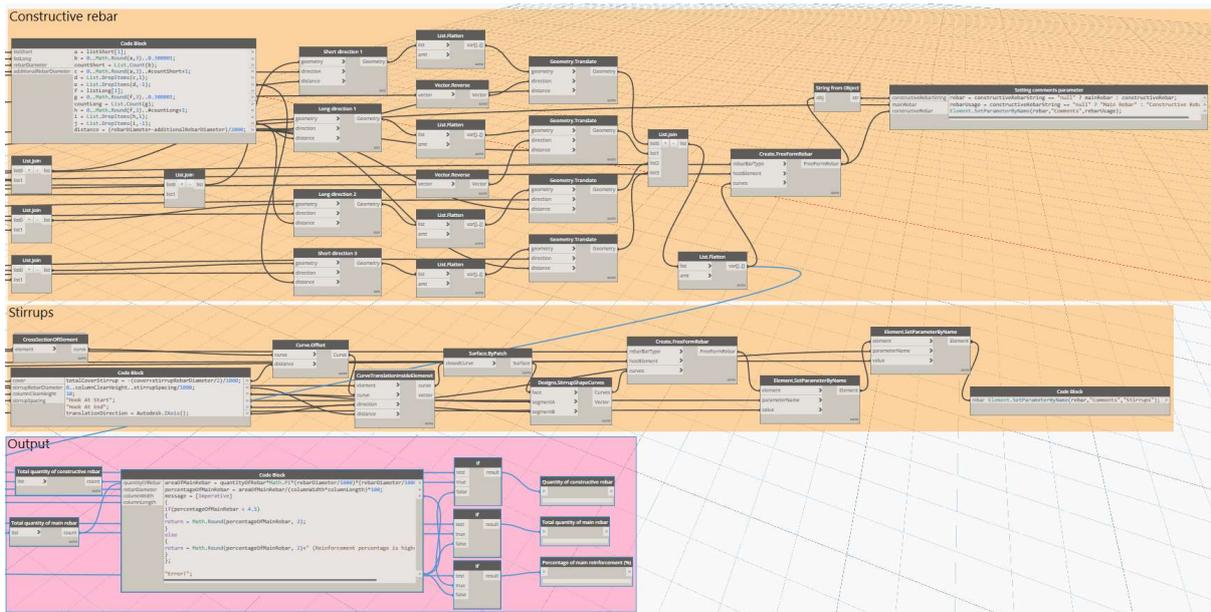
This script generates reinforcement in rectangular and square columns with bars concentrated in corners. The user is required to input the amount of bars in each corner (odd number) and bar diameter. It also gives the user the options of fixed connection or not and column above or not, like the previous script. Constructive rebar is automatically generated and follows same rules mentioned in script 01_beam_rebar_input.





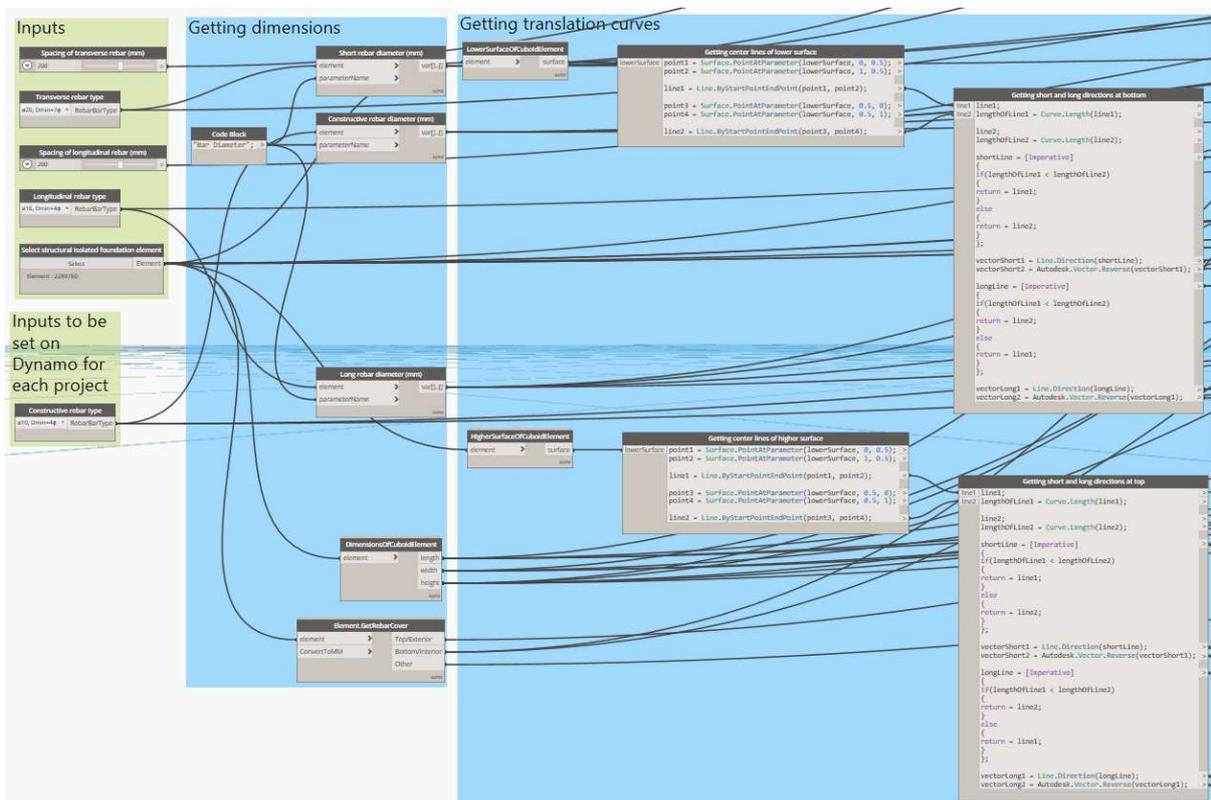
- **04_rectangular_column_sides_rebar_input**

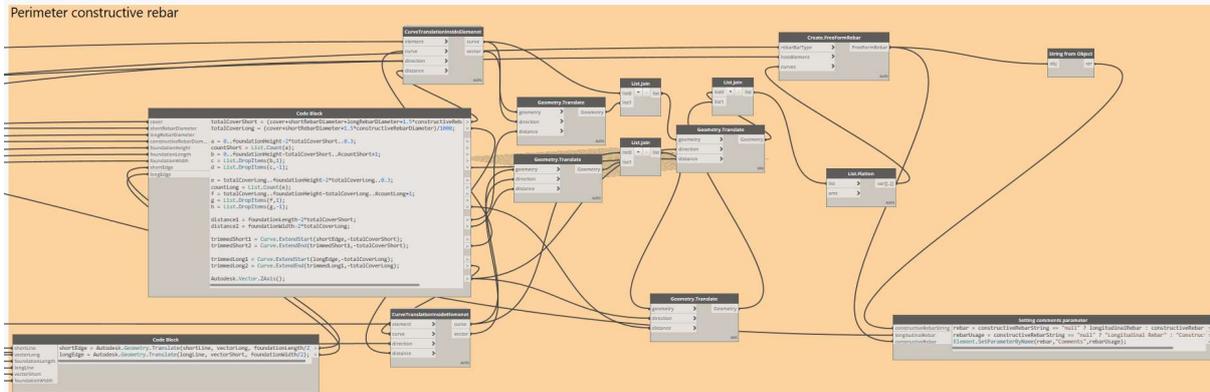
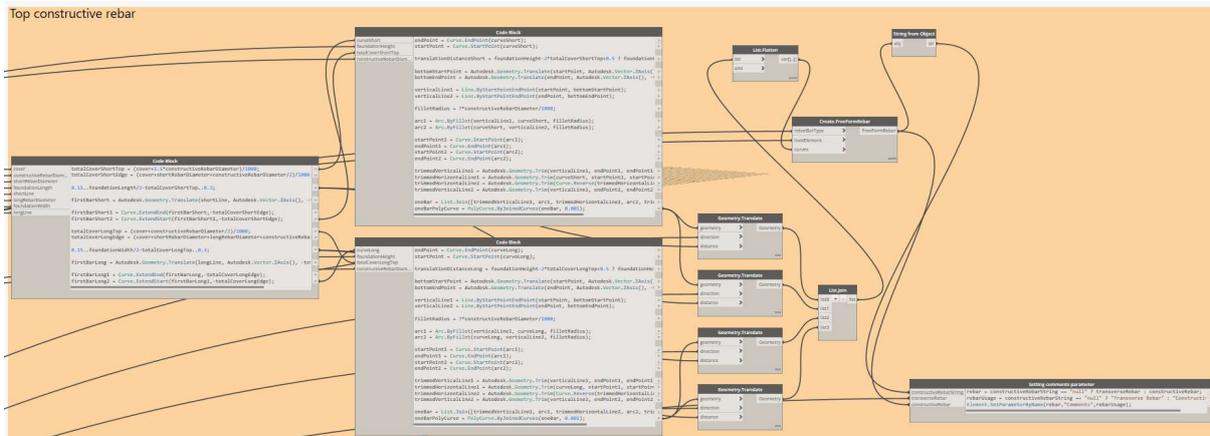
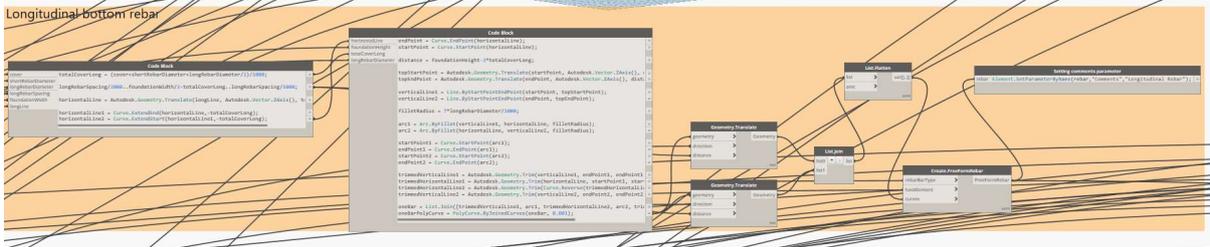
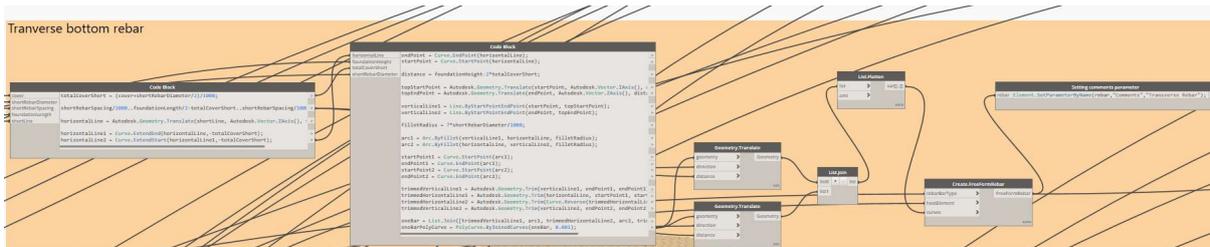
This script is also for rectangular and square columns, but bars can be distributed along the edges of the column. The user chooses the amount of bars on each side of the column main (short) and secondary (long). This script is best to be used for columns subjected to bending moment. It again has the same options for a fixed connection and bending bars. Constructive reinforcement is still generated automatically and follows the same rules.



- **05_isolated_foundation_rebar_input**

This script generates reinforcement in isolated single foundations. The user needs to input the diameter and spacing of transverse and longitudinal rebar at bottom. The script only deals with bottom rebar as structural reinforcement. Top rebar and the rebar generated along the circumference of the foundation are considered constructive and automatically generated.



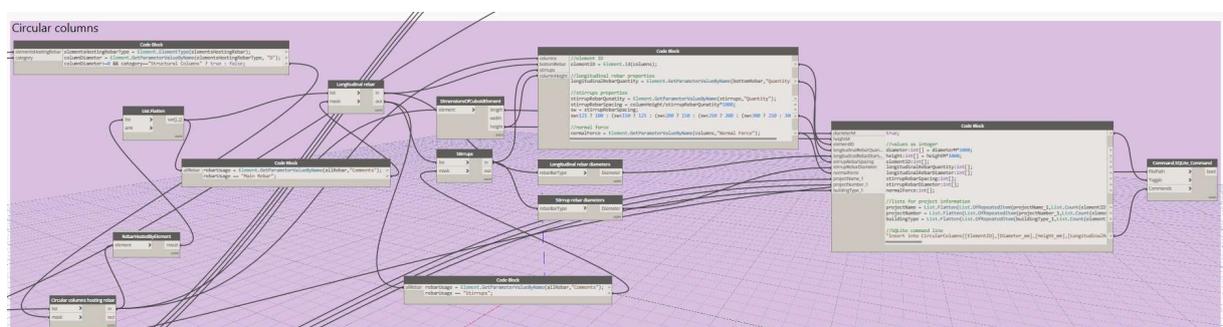
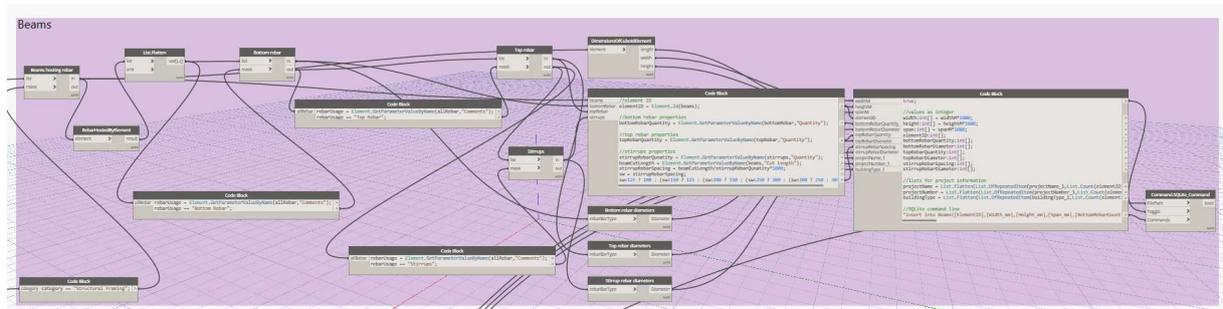
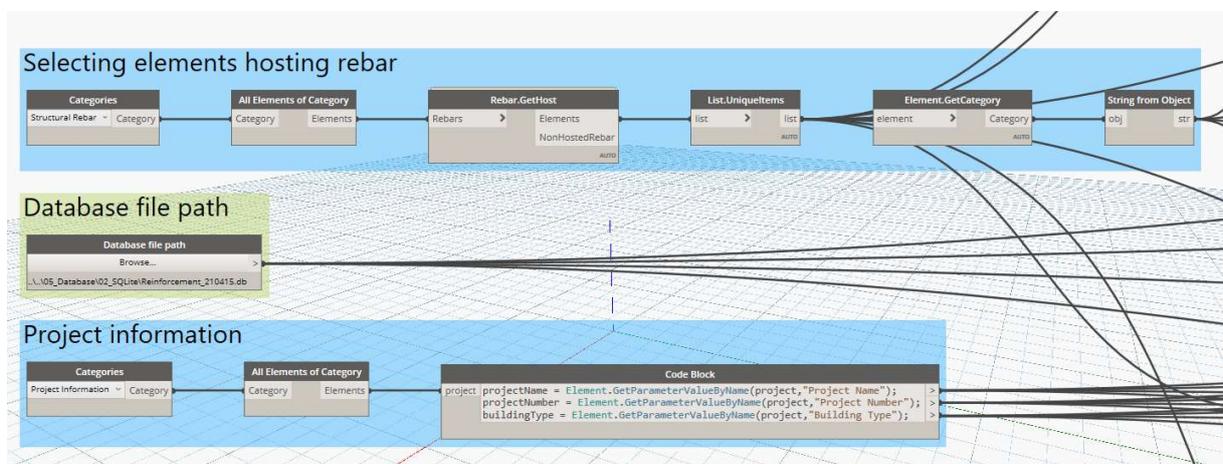


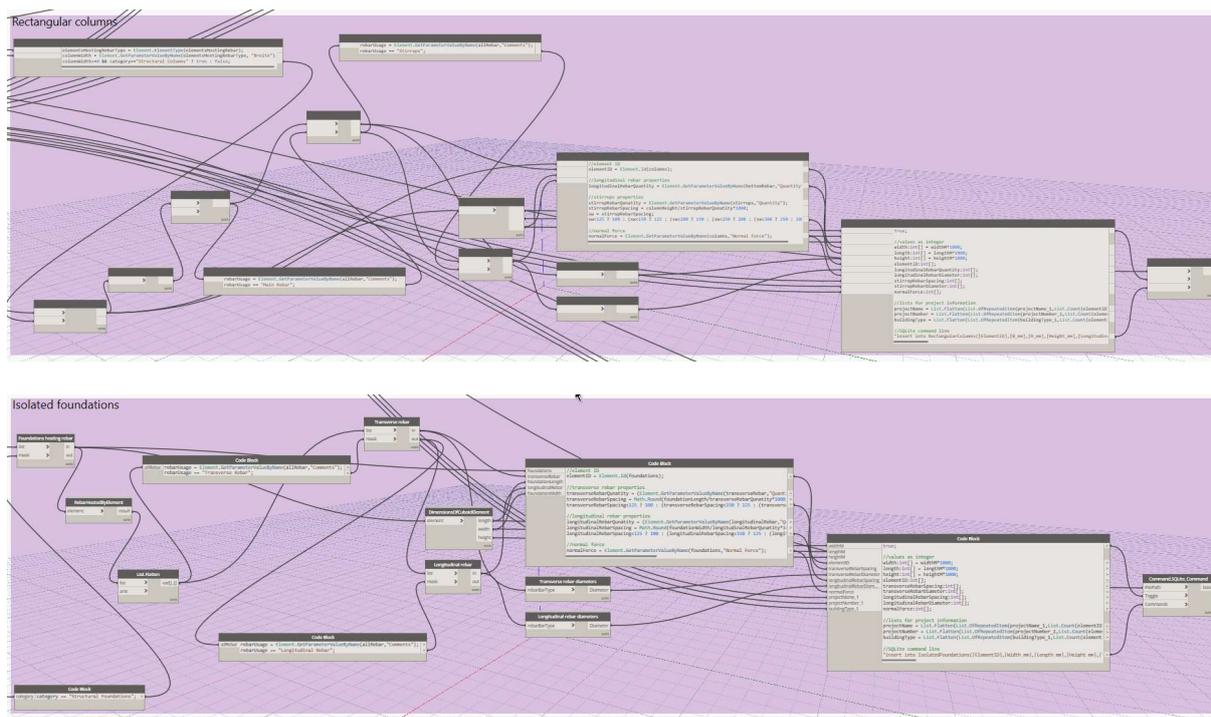
A.3 Exporting to Database

- **06_rebar_to_database**

This script was designed to read all beams, columns and isolated foundations elements hosting rebar and export element ID, dimensions and rebar information to database. It can as well read project information parameters and export them to database. The script is grouped into the following groups:

1. Input, the only input here is the database file path (green)
2. Elements hosting rebar selection and reading project information (blue)
3. Arranging information and exporting to database tables (purple)





A.4 Second Stage Scripts

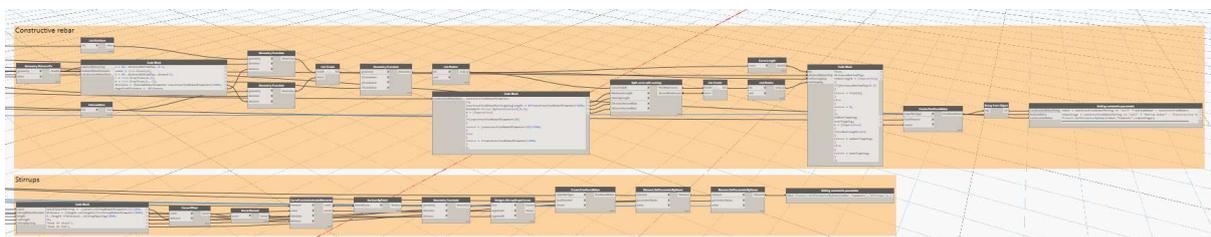
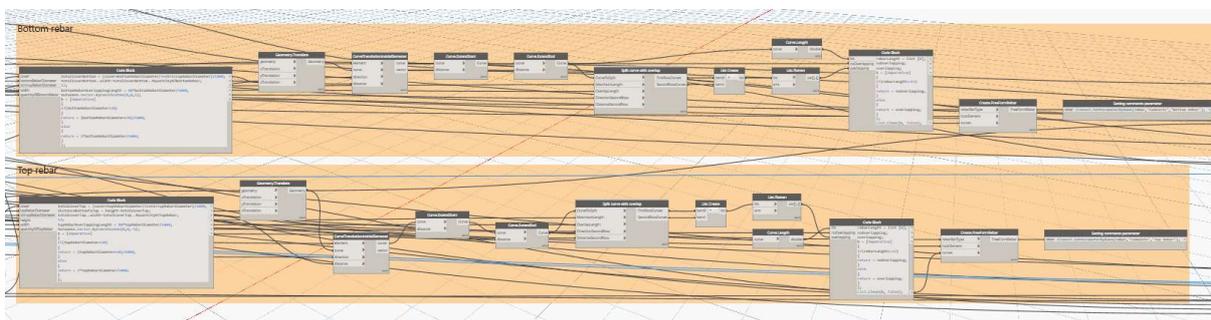
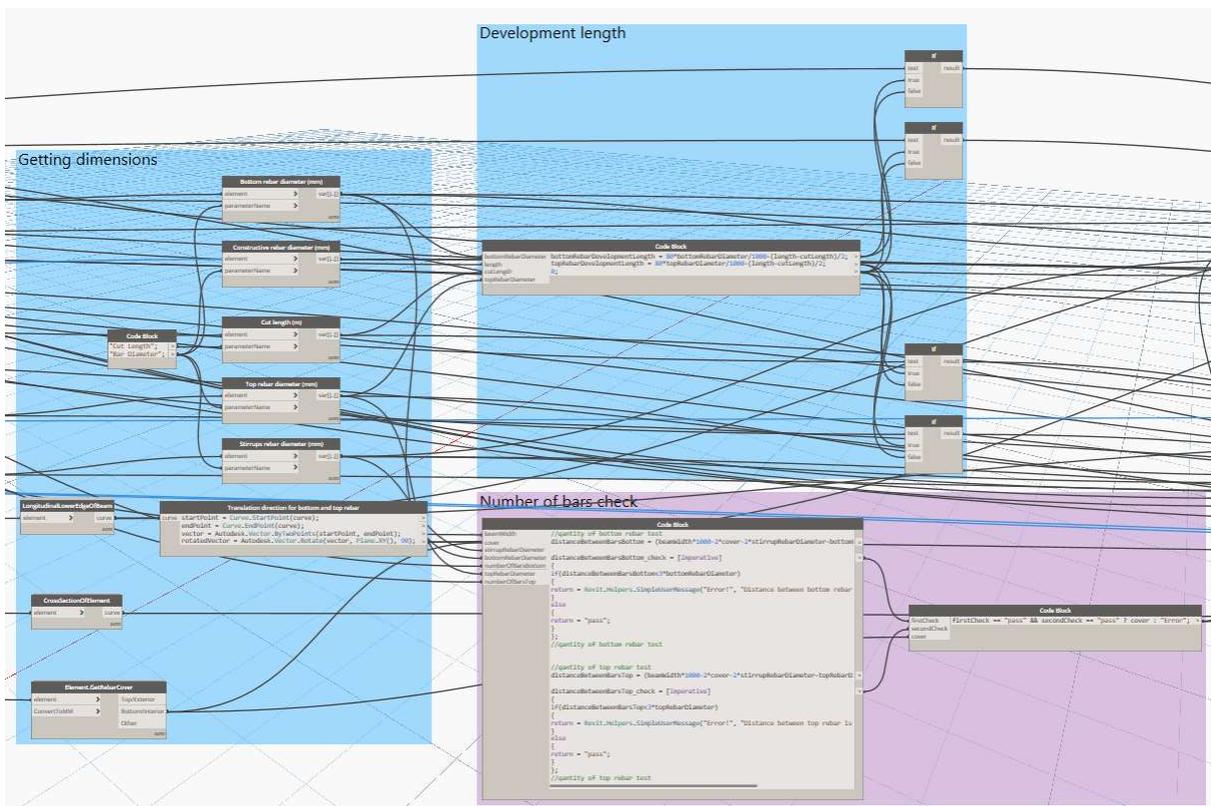
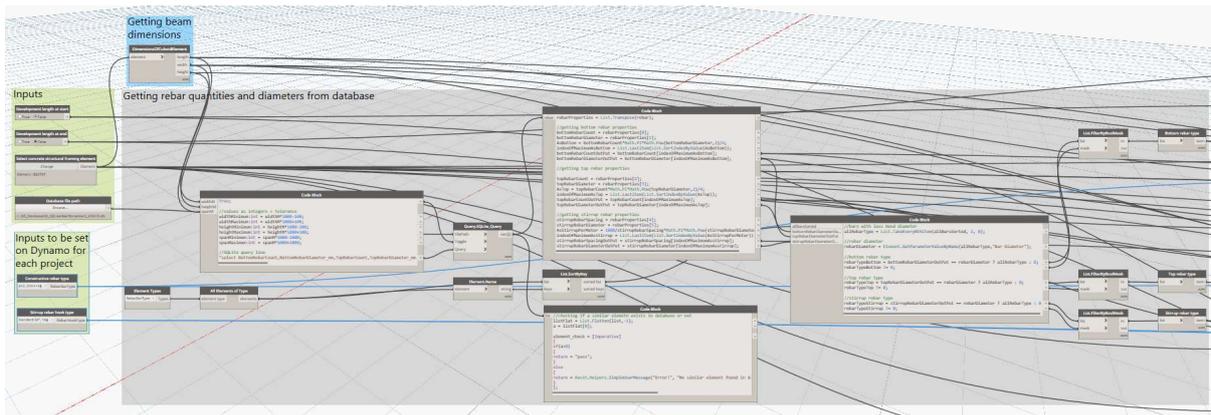
Second stage scripts generate reinforcement in beams, columns and isolated foundations, but without any human input of the amount of bars or diameter. In order to get these input parameters an iterative search is carried out through the information saved in the database. Reinforcement is generated based on the most similar element to the selected element in terms of dimensions and load. If there is no element within the range of the selected element, an error message pops up and the user is asked to use manual input scripts for this element. Each script is grouped into the following groups:

1. Inputs (green)
2. Getting dimensions and curves of element (blue)
3. Getting rebar information from database (grey)
4. Structural checks (purple)
5. Rebar generation (orange)
6. Output (red)

The scripts are listed as follows:

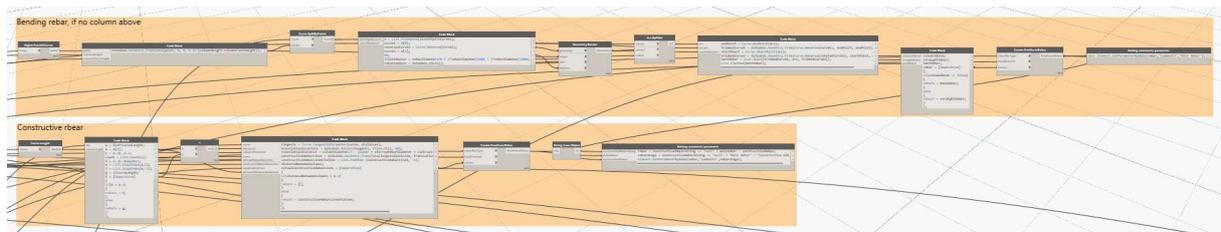
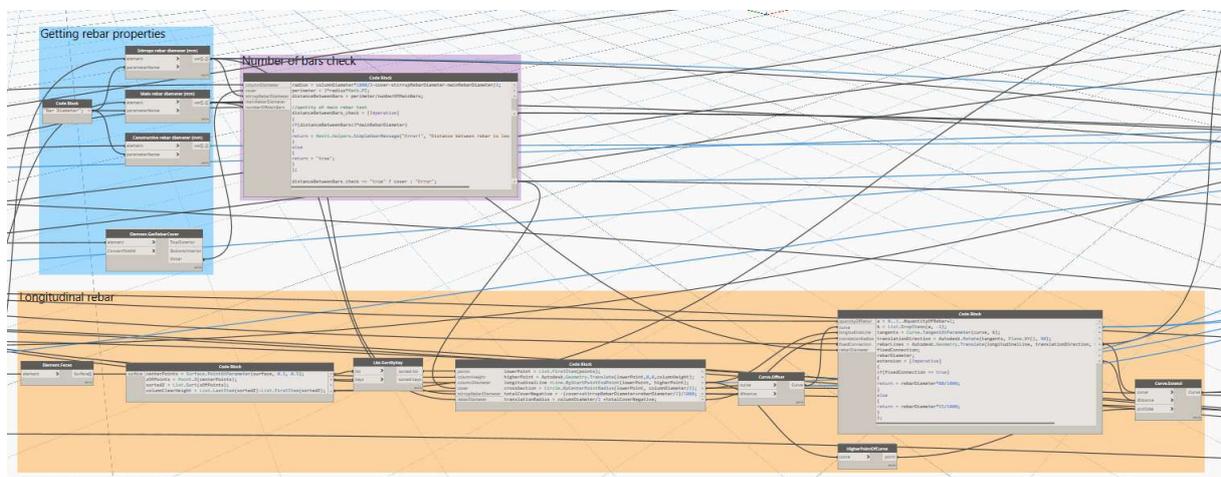
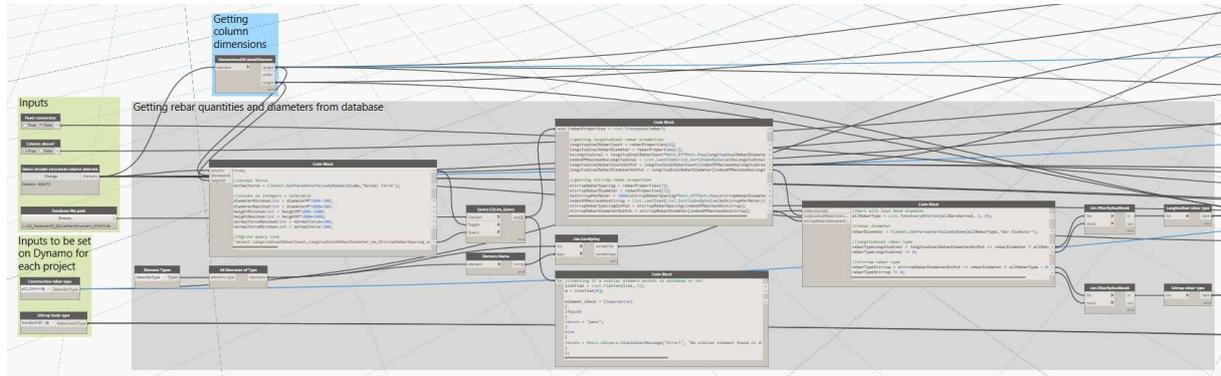
- **07_beam_database_input**

This script has the same functionalities as script 01_beam_rebar_input, but without any human input of the reinforcement parameters.



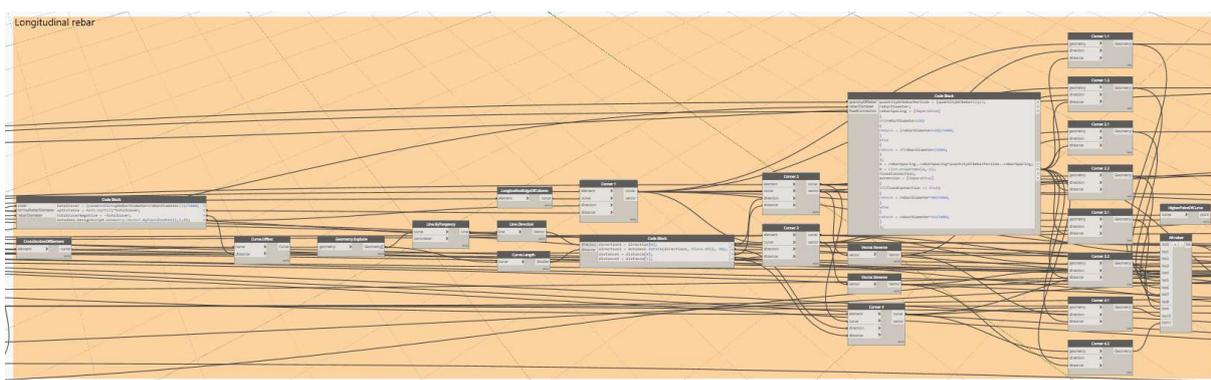
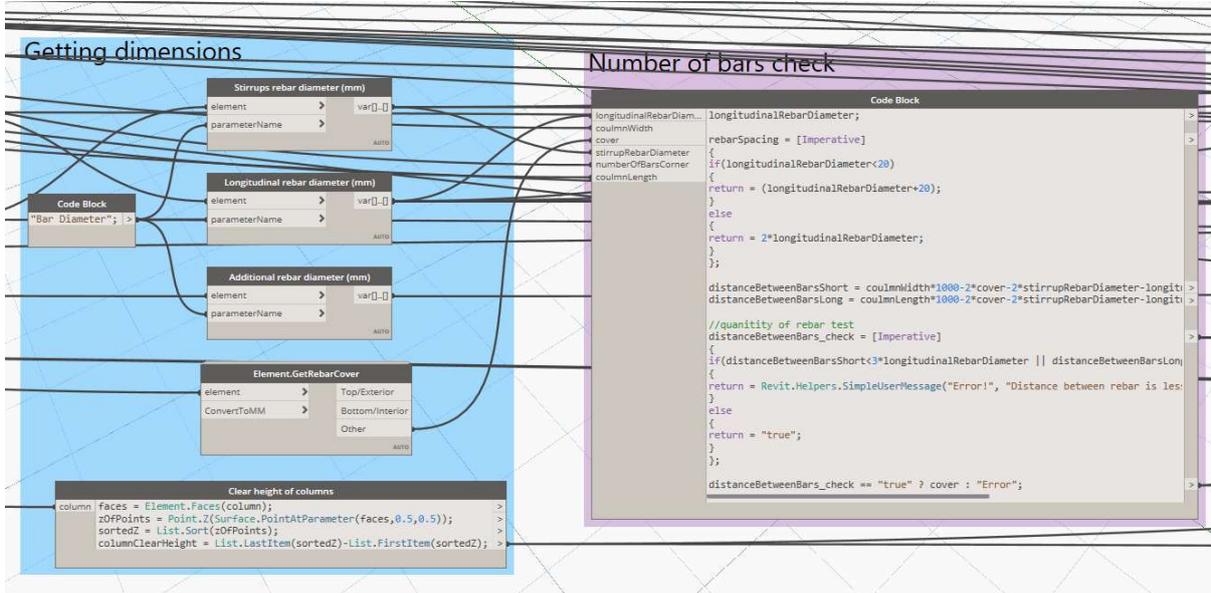
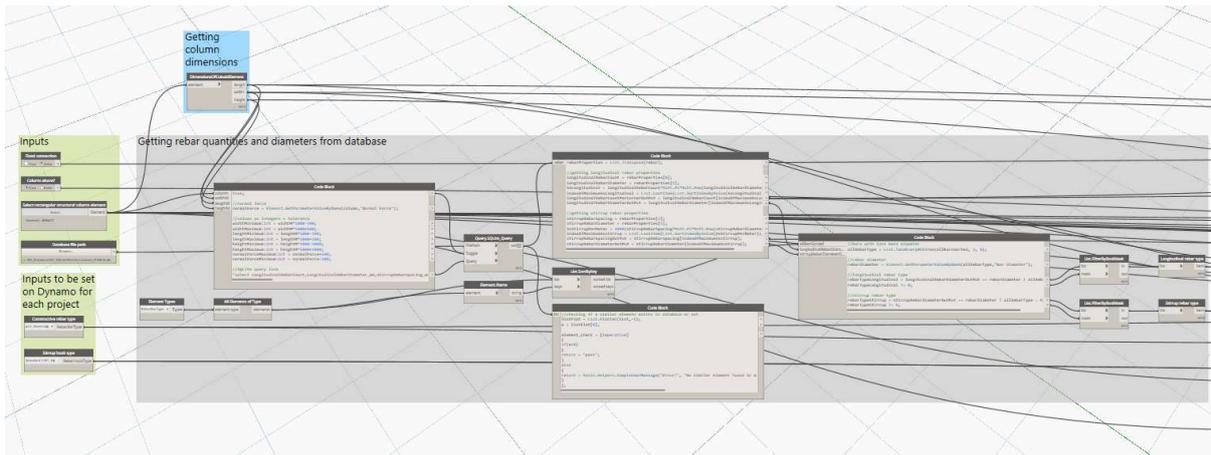
- **08_circular_column_database_input**

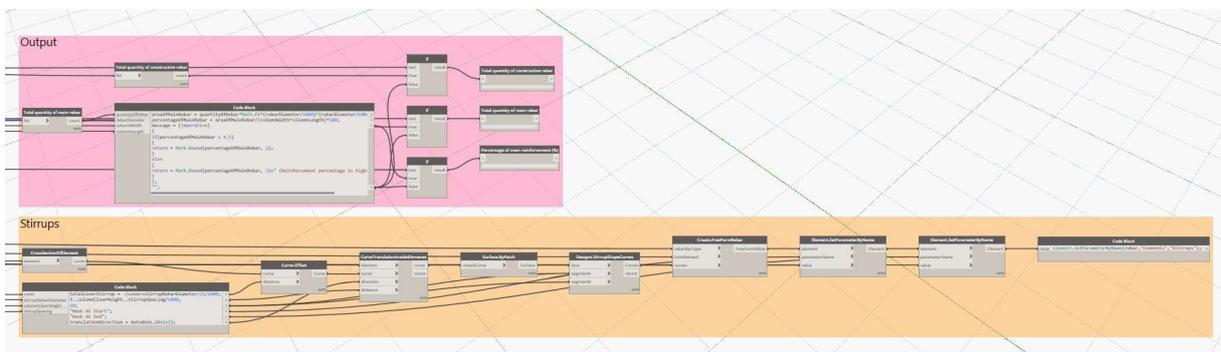
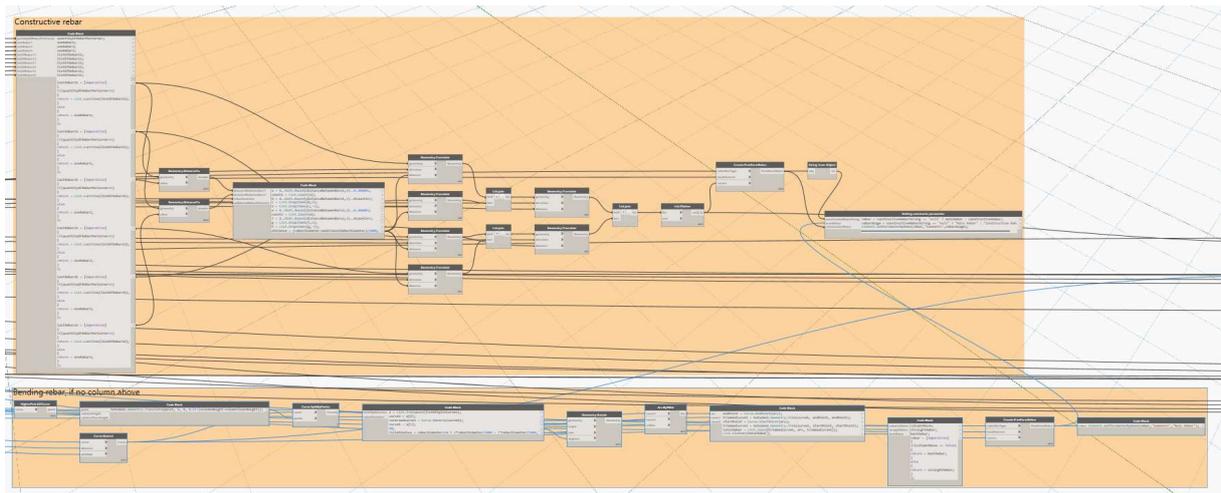
This script has the same functionalities as script 02_circular_column_rebar_input, but without any human input of the reinforcement parameters.



- **09_rectangular_column_corners_database_input**

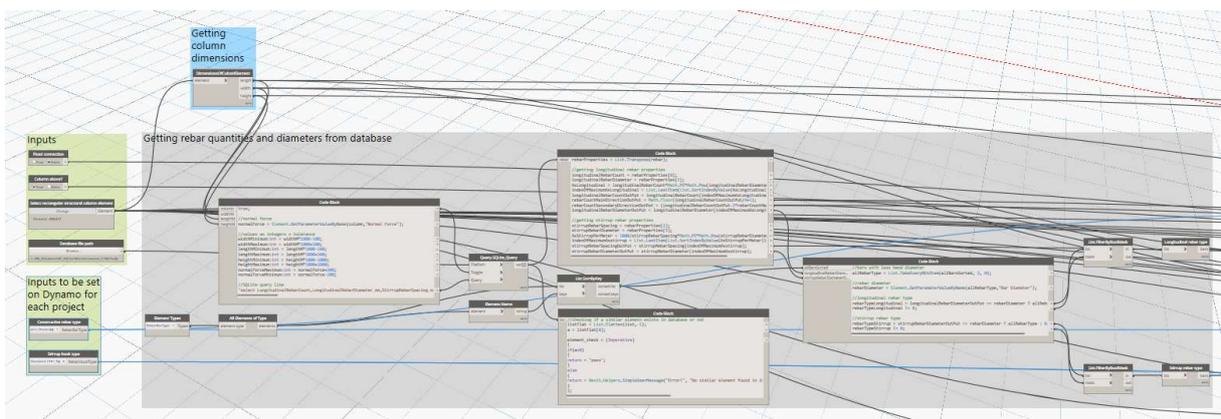
This script has the same functionalities as script 03_rectangular_column_corners_rebar_input, but without any human input of the reinforcement parameters.

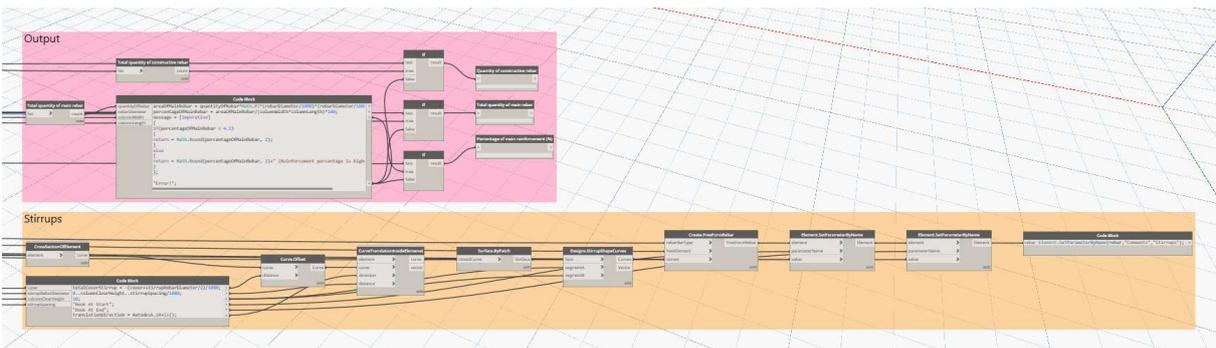
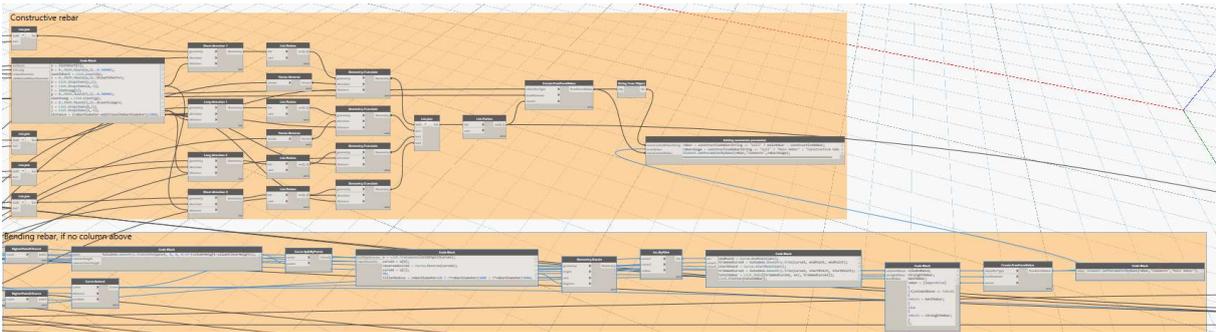
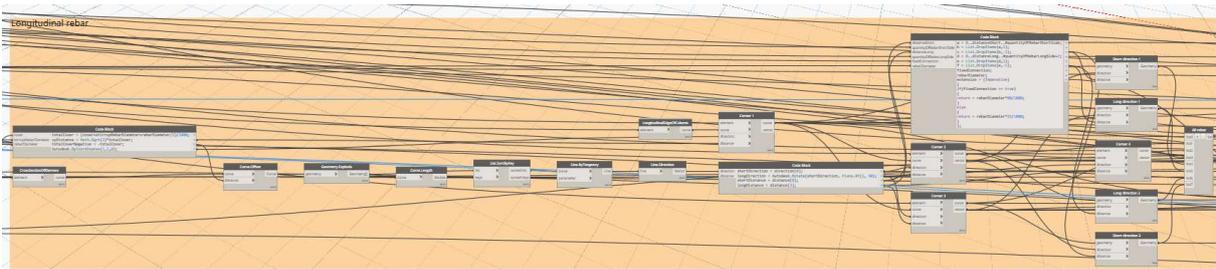
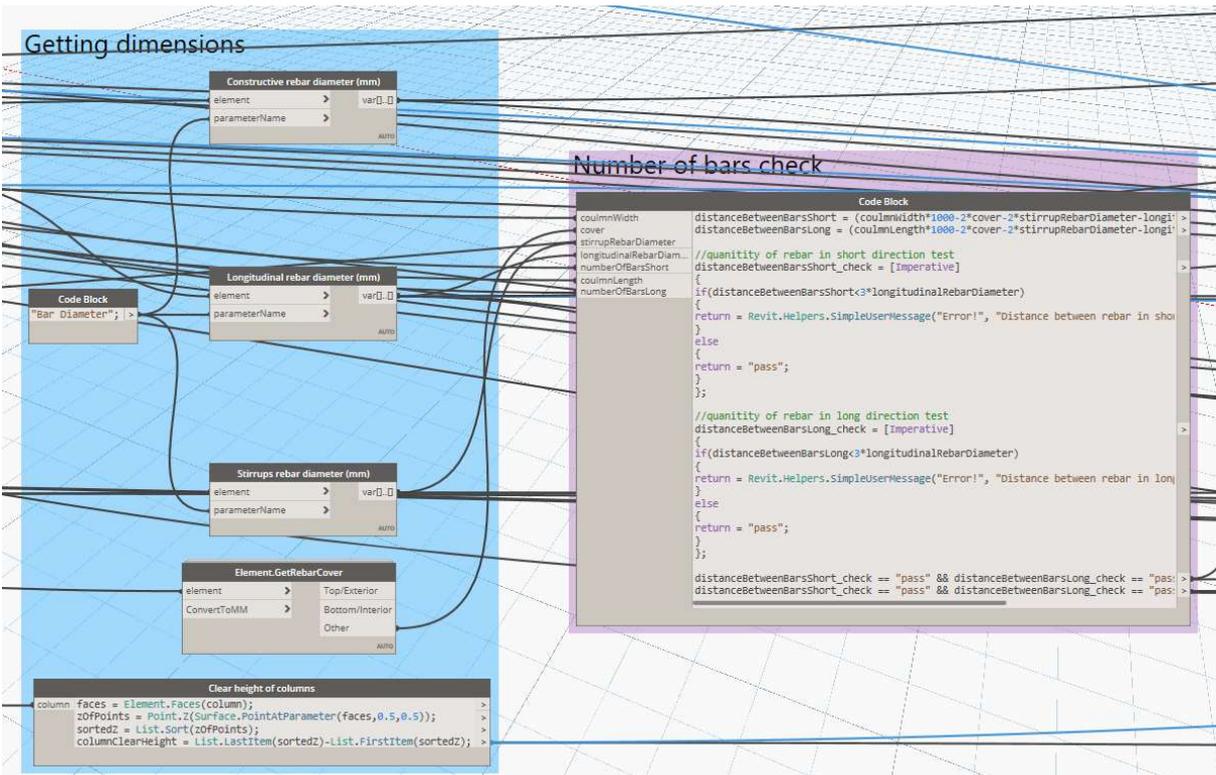




- **10_rectangular_column_sides_database_input**

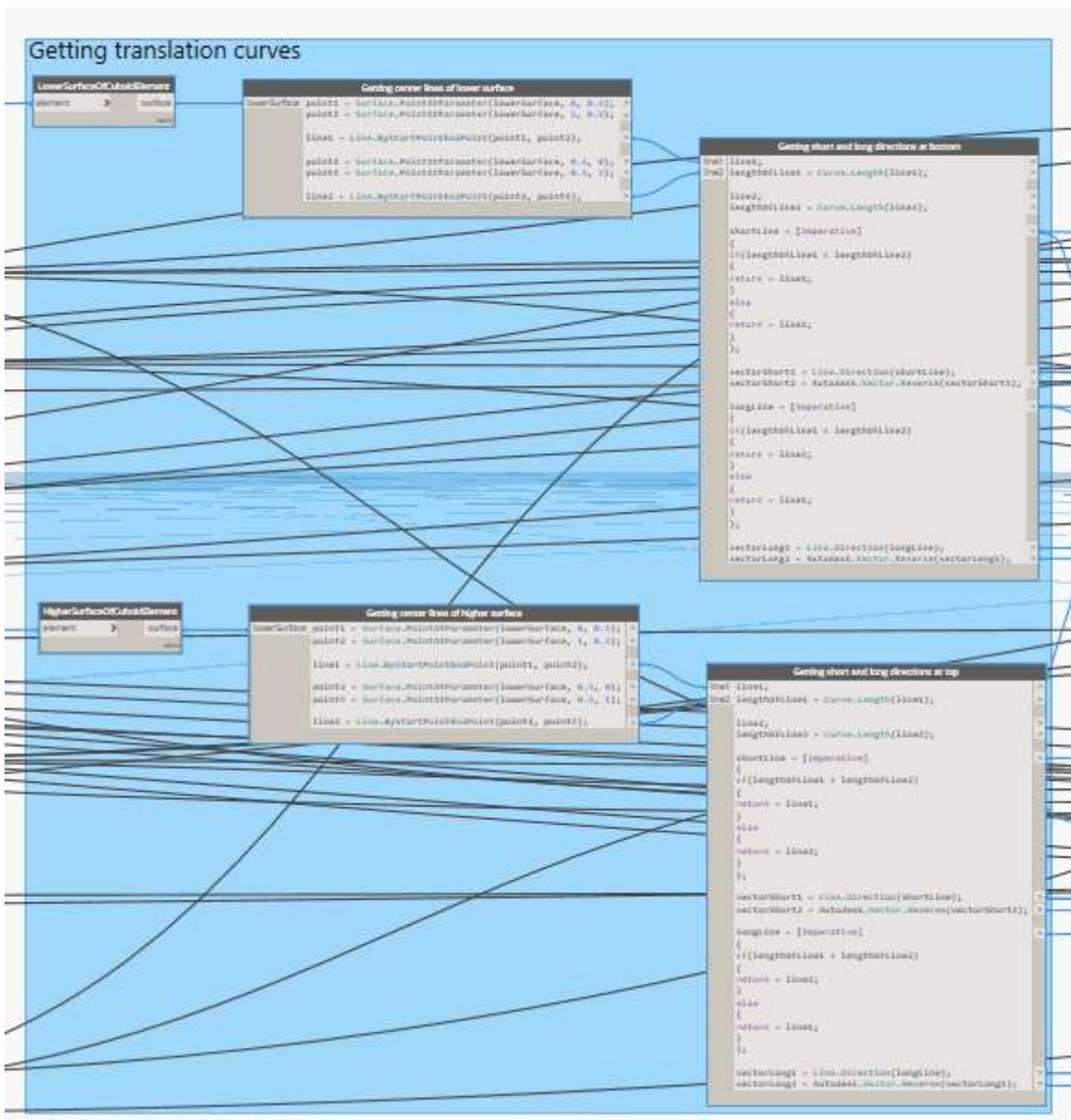
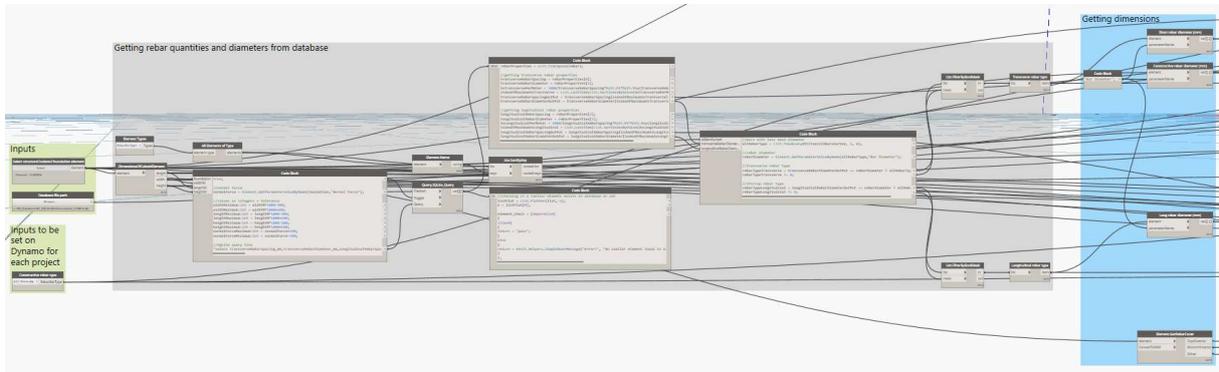
This script has the same functionalities as script 04_rectangular_column_sides_rebar_input, but without any human input of the reinforcement parameters.

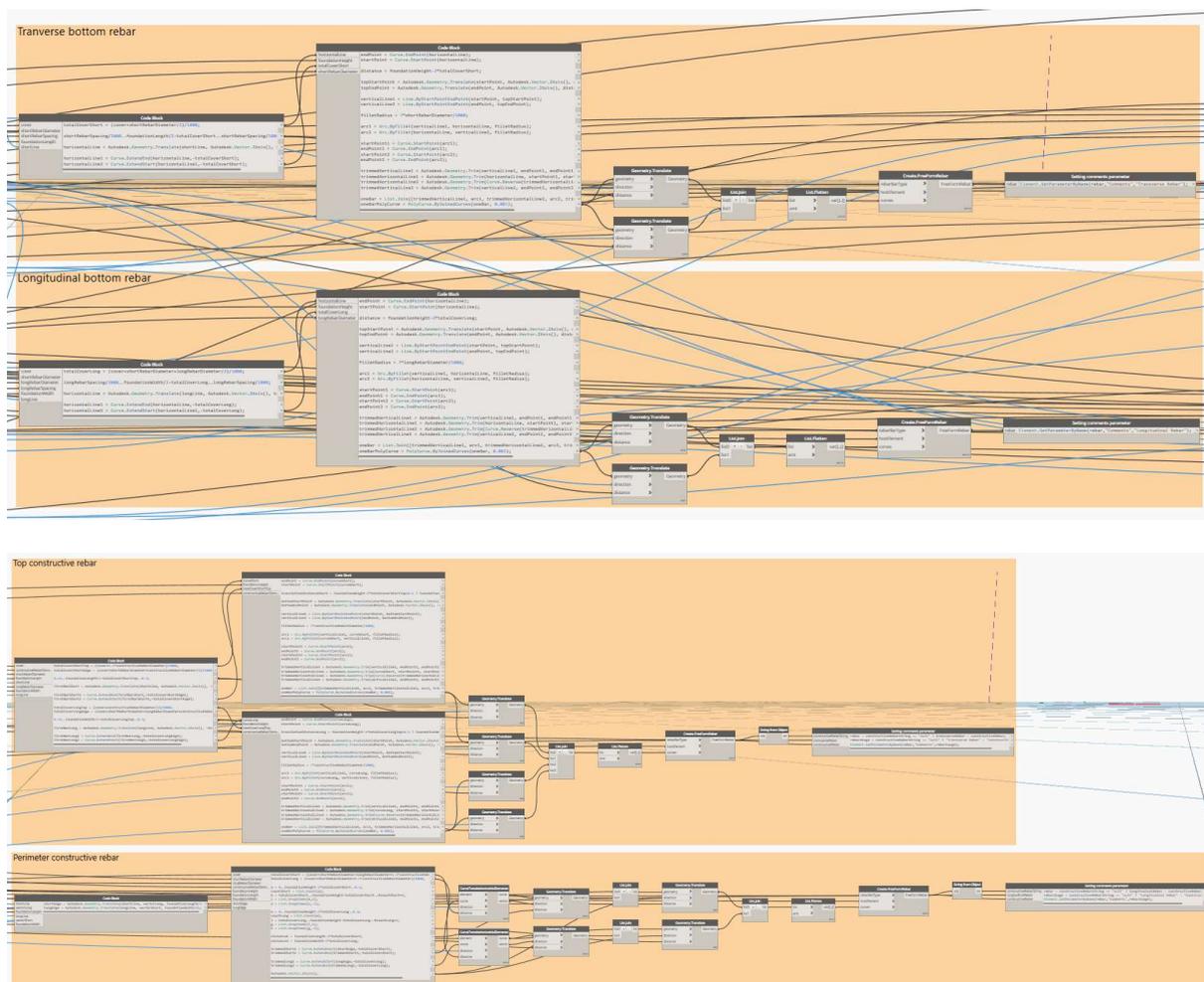




- **11_isolated_foundation_database_input**

This script has the same functionalities as script 05_isolated_foundation_rebar_input, but without any human input of the reinforcement parameters.





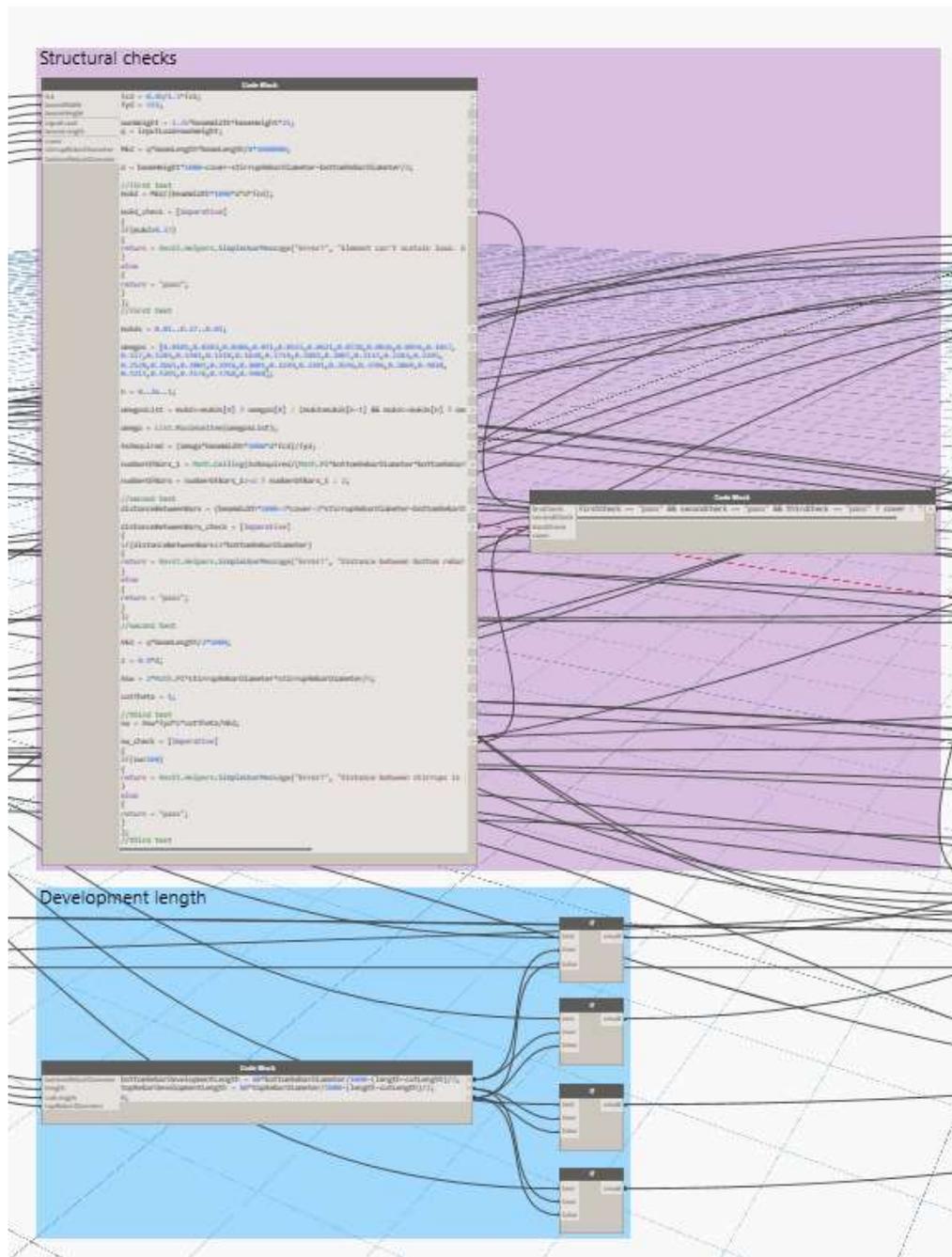
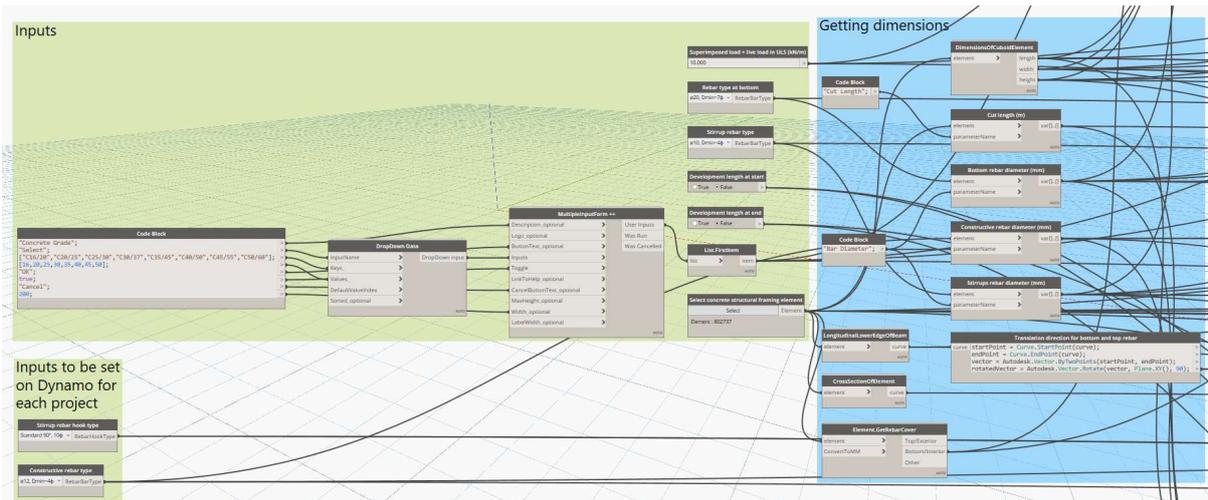
A.5 Load Input Script

- **12_beam_load_input_simply_supported**

This script is capable of calculating the required reinforcement for a simply supported beam using only the linear load acting on the beam as input. The user can also select the concrete grade from a drop list that pops up after running the script. It is also possible to choose the preferred bar diameter by the user.

This script is grouped into the following:

1. Inputs (green)
2. Getting dimensions and curves of element (blue)
3. Structural calculations (purple)
4. Rebar generation (orange)



Appendix B

The enclosed CD contains the following content:

- The written part of the work as a PDF document
- Dynamo scripts and custom nodes produced in the research
- Database files

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Declaration

I hereby declare that I have completed this Master thesis independently. Only the sources and tools explicitly named in the thesis were used. I have marked as such any ideas that have been taken over literally or analogously.

I also assure you that this thesis has not yet been the subject of any other examination procedure.

Munich, 22. June 2021

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