Master thesis

Optimization through digitalization in the design process with reused precast concrete elements.

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Colophon

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Abstract

To reduce resource demand, the Dutch government has set the goal to be completely circular by the year 2050 [1]. Currently, most concrete is recycled into lower-grade materials at the end of life. The reuse of concrete takes less energy than recycling and reduces the demand for new concrete [2]. In this thesis the reuse process of precast concrete, precast concrete structures, and digital design are studied. A focus is placed on a precast concrete structural system with load-bearing facades and hollow core floor slabs. Furthermore, an analysis of the design process is performed. With the acquired knowledge, an algorithm is constructed that encompasses the design process. The design process starts with requirements and an element stock and ends with floorplans and a structural design. A set of Grasshopper components is developed, which perform the algorithm. With the help of the Grasshopper components, a user can perform the complete design process in 20 seconds. The components can easily be distributed, adapted, or expanded for more structural systems. This research shows that it is possible to use digital design to ease the design process of buildings with reused precast concrete and to reduce the use of virgin materials.

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1 Introduction

1.1 Motivation

Humans have a big impact on the environment. CO_2 emissions have multiplied by seven since 1940[3], and natural resources are at risk of depletion[4] while the world population keeps growing[5]. Therefore, the Dutch government has set the goal for The Netherlands to be completely circular by 2050. This means that the use of new raw materials should be reduced to zero, and all materials currently in use will be reused or recycled. The government marked the building sector as an important sector in this transition. The building sector alone is responsible for 50% of all resource use in The Netherlands.[1] With the current reuse and recycling level of old building materials, it will become difficult to reach the 2050 goal [6].

Reuse and recycling limit the use of new building materials. In most cases, great amounts of energy are needed for the recycling process causing a relatively high CO_2 impact, while reuse has a much lower CO_2 impact. Figure 1 shows the lifecycle of concrete. In data from 2013, the disposal rate of concrete in the Netherlands is very low and almost all concrete is recycled. However, the concrete is mainly recycled into lower-grade materials [7], and a lot of virgin material is still needed to fulfil the concrete demands [8].

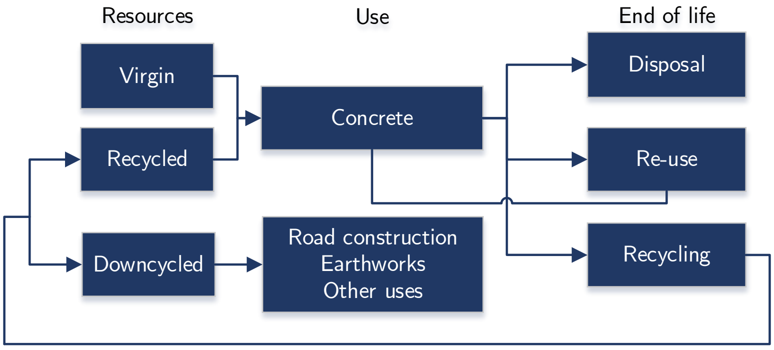


Figure 1. Lifecycle of concrete.

Reusing complete concrete elements can greatly contribute to the transition to a circular building sector; it allows for a reduced production of new concrete, preventing concrete from being recycled or becoming waste. An opportunity for reusing concrete elements lies in the current office building stock, especially the offices built from 1970 to 1990. Figure 2 shows that these buildings still occupy 29 % of the current stock and that the majority of the recently demolished buildings were built within this period.

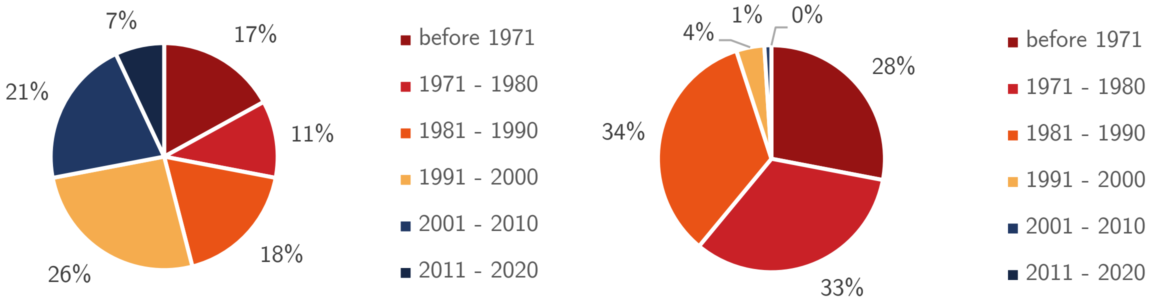


Figure 2. The construction period of the office building stock, The Netherlands (2020).(left), Demolished buildings in The Netherlands between 2011 and 2020.(right) [9].

Due to high market demand, many of these buildings were built cheaply and quickly with newly innovated precast concrete. The office users at that time had different needs than the current office user. Therefore, a lot of structurally adequate office buildings have become outdated and vacant. This effect can increase with the current trend of working from home [10]. Figure 3 shows an example of an office building built with precast concrete. The building's structural system contains load-bearing and stabilizing façades.

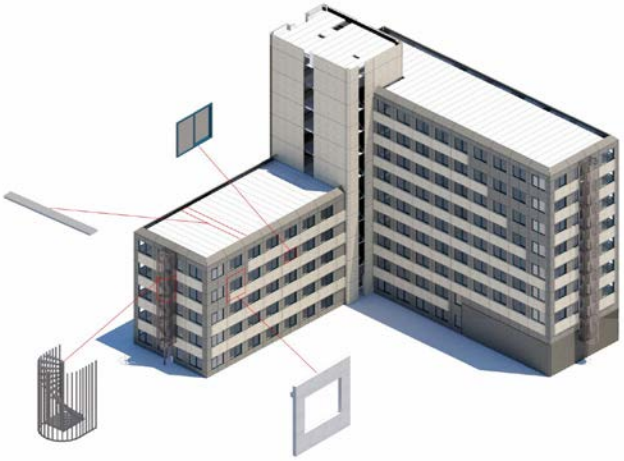


Figure 3. The Prinsenhof A building and its elements available for reuse [11].

Despite the environmental benefits of reusing concrete compared with recycling [12], the reuse of complete concrete elements is usually not even considered when a building is demolished. The most important reasons are higher costs, technical barriers, and a lack of useable design and construction codes [13]. The European ReCreate project focuses on this subject of reusing precast concrete, specifically to improve technical and economic viability[12]. Simplifying the design process of a building with reused structural elements can improve the economic viability of reuse due to the decreased time needed to create a structural design.

Digitalization has increased the productivity of the building industry over the past decades.[14] With the help of digitalization, laborious tasks or extensive calculations can be taken over by computers. In this thesis, barriers in the design process with reused precast concrete elements are reduced by digitalization.

1.2 Scope

This thesis focuses on the reuse of concrete elements from office buildings built with a load-bearing façade system in precast concrete. Designing buildings with reused concrete elements requires an unconventional design approach. The architectural design is greatly influenced by the structural design and vice versa, which are both limited by the available element stock. The design process with reused precast concrete elements is analyzed, and the difficulties are identified. Subsequently, a revised design process is developed, which overcomes these difficulties using algorithm-aided design.

To keep the project viable in a limited time, the following limitations have been set for the project in general:

- The element sizes cannot be adapted.
- The precast concrete structural system consists of hollow core floor slabs, inverted T-beams, square columns, and structural façades.

- The foundation is not incorporated.

Furthermore, the following principles have been set for the software in specific:

- The element inventory and the properties of each element are known.
- All elements in the element stock are geometrically compatible with each other.
- There is only one function per building; all loads are equal except for the roof loads.
- All columns within one building have the same height.
- Only floors from stock are used; no new floors will be created.

1.3 Research objective

This research aims to ease the architectural and structural design process of buildings with reused precast concrete elements and to minimize the use of new materials in constructing these buildings. Software that uses algorithm-aided design is created to improve parts of the design process by taking over laborious steps and providing design options within given boundaries.

The main research question can be stated as follows:

- How can the design process of buildings in The Netherlands, with reused precast concrete elements, be eased by digitalization?

To answer the main research question, the following sub-questions will be addressed in this thesis:

- Which precast structural concrete elements can be extracted from old buildings, and what are their relevant properties for a new design?
- Which structural, architectural, and practical requirements are important to consider during a design process with reused precast concrete elements?
- What does a design process with a limited structural element stock look like, and what are the difficulties in this process?
- What algorithm can be created to encompass the above-mentioned design process, considering the before-mentioned requirements and minimization of material use?
- How can software be used to perform the algorithm as mentioned above?

1.4 Thesis outline

Chapters 2.1 and 2.1.6 provide background information on the building process with reused precast concrete and precast concrete elements. Chapter 0 goes into the relevance of digital building design within this thesis. In Chapter 0, the design process is analyzed by the design of a study case. The design process of a traditional design method is compared to the design process with a limited element stock. The conclusions from the analysis are used in Chapter 4 to create an algorithm which encompasses the design of a building with reused precast concrete elements. This algorithm is then digitalized in Chapter 5, and the digital structure is explained. In Chapter 6, the digital solution is applied to the same study case as in Chapter 0. Finally, the results are discussed in Chapter 7 to Chapter 9, conclusions are drawn, and recommendations are made. The written chapters make references to the appendices, which can be found in Chapter 11. Furthermore, a booklet with all relevant scripts is created in addition to this thesis.

2 Literature

The literature part of this thesis is divided into three parts; the first concerns an overview of the complete reuse process of precast concrete, the second part elaborates on specific aspects which are important when building with (reused) precast concrete, and the last part elaborates on digitalization in building design.

2.1 Reuse process of precast concrete

In this subchapter, the basics of the reuse process of precast concrete elements will be discussed. These basics provide the context of the research objective and state of the art on the subject. The focus of this thesis is on the redesign part of the process. However, knowledge of the complete reuse process is needed to give a clear framework.

2.1.1 Inventory of available elements

The reuse process starts with identifying a set of elements which are suitable to be reused. A complete inventory is needed to perform the entire process. It is important that the elements in the stock are compatible in one building system. This means that the elements' geometrical properties must match so they can be connected without major difficulties.

Two methods can be used to create an element inventory. The inventory can be compiled from a building or multiple buildings that still have to be demounted, or the inventory can be selected from a digital database in which all locally or nationally available elements and their properties are stored. There are already a few marketplaces where you can find circular construction materials, such as Insert and circulaire-bouwmaterialen.nl [15], [16]. At present, the structural elements that are offered are mostly steel and timber elements. The supply of reusable concrete elements will likely become steadier when reuse becomes more common. If the elements are sourced from an existing building, the amount of freedom in designing is more limited than with the database method. However, the elements are more likely to match in dimensions and structural capacity.

A final database of elements should contain all important information, including their dimensions and structural capacity. Chapter 0 describes how the structural capacity of the elements can be determined.

2.1.2 Technical evaluation of the structural elements

The evaluation process of the available structural elements is summarized based on the research of Glias [17] and Dawczyński et al. [18]. The evaluation starts with the acquisition and analysis of the original design drawings or any other available documentation that can be found on the original building. Then, the elements are assessed on-site to examine mismatches between the documentation and reality, the structural integrity of the elements, and durability damages. This assessment is done by at least a visual inspection and, if possible, displacement measurements and a non-destructive evaluation of strength properties. With these tests, the dimensions, reinforcement properties, and concrete strength must be verified. The reinforcement properties can be determined with a rebar detector or a ground-penetrating radar. The most accurate method to define concrete strength is core drilling, in which a cylindrical core is taken out of the concrete, and its properties are determined by physical tests. This test will have a negative effect on the strength of the tested element; however, the results can be used for a complete batch. A non-destructive method to determine the strength of concrete is the Schmidt hammer. This method provides a quick and inexpensive measurement of the surface hardness that can be used to estimate the mechanical properties of the concrete. The downside of this method is that the reliability of the results depends on several parameters, such as the hammer type, normalization of rebound values, specimen dimensions, surface smoothness, weathering and moisture content, and analysis procedures. [19]

The results of the element inspection should be combined in a report that covers the following subjects:

- Deconstruction methods that prevent damage to the elements.
- Material properties and the strength of the elements.
- Limits of the scope of reuse of the materials.
- Necessary future repairs and/or treatments of the elements.

With this report as a base, the next steps in the reuse process can take place.

2.1.3 Disassembly

Deconstruction must be performed with great care to achieve the highest quantity and quality of elements. The elements are removed floor by floor. During this process, it is important to temporarily support parts of the structure to maintain a safe and stable remaining structure. The disassembly of one floor from the building system, as described in the scope, has the following element removal order [17]:

1. Concrete topping
2. Hollow core slabs
4. Beams
5. Columns
6. Walls

To disassemble the elements, their in-between connections need to be removed. Precast elements can have dry connections; however, a lot of the elements are connected by a wet connection. The wet connections between the prefabricated parts are not meant to be deconstructed and must be demolished. There are two types of wet connections: with reinforcement bars and without reinforcement. If no reinforcement is present, the connection can be broken by applying force because the mortar connection is usually weaker than the concrete. A chipping hammer and a rotary hammer can be used for this. [20] A different approach is needed in the frequently occurring situation where reinforcement is present in the wet connection. The best method to do this is diamond sawing. However, this method is relatively expensive and generates much noise. [21] Pneumatic hammering is possible as well; however, the high likelihood of damaging the elements invalidates this option. Hydro demolition, in which water is used to blast away concrete while reinforcement stays intact, is a viable option if the present reinforcement was designed to be demounted. Concrete can be removed locally without damage to the reinforcement, and the reinforcement can be taken apart. If the reinforcement was not designed for disassembly, a diamond saw is still needed to cut the reinforcement [22].

2.1.4 Adaptation and reparation

Dismounted elements are often not instantly ready to be reused in a new building. During dismantling, damages that need to be fixed can occur, new connections need to be prepared, and superficial repairs may be done.

Depending on the nature and extent of the damage, the damage could be fixed by filling the area with new concrete to ensure that the structural integrity is guaranteed. Also, additional concrete can be added to protect the reinforcement if the concrete cover is insufficient. Another important adaptation concerns the structural connections between the elements. The old, broken connections must be removed, and new connections must be created. Additionally, more superficial reparations can be done, such as the refurbishment of the surface of elements. All these reparations can take place at the deconstruction site, the new construction site and the storage site. [17]

2.1.5 Redesign and construction

Redesign and construction is the most important aspect of this research. At the start of the redesign, it is important to have a clear overview of all available structural elements and their properties.

The redesign is greatly influenced by the available element stock and needs to be thought through carefully. In a traditional design process, the architect gathers all relevant information and creates an initial design, including floor plans and elevations. Only afterwards, the structural engineer will be consulted to finalize the structural design. [23] This design process is shown in Figure 4.

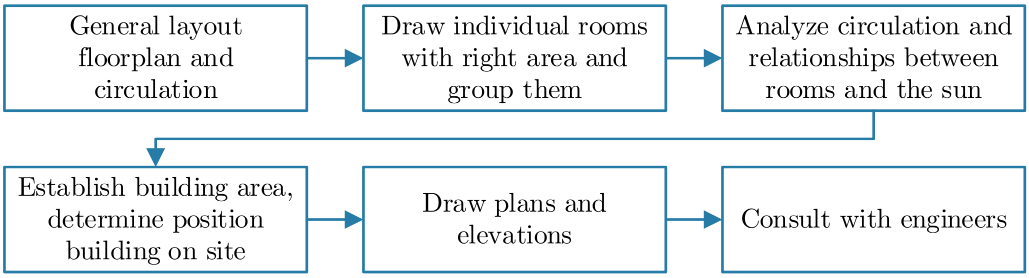


Figure 4. Traditional design process, according to [23]

The presence of a limited element stock causes this process to be disrupted because the available structural elements will not exactly fit in the original design. Therefore, the process needs to be revised. The design process with precast elements, as described in [24] and shown in Figure 5, takes the dimensional limitation of precast elements into account. The modified process already comes closer to a process that can be used with reused elements.

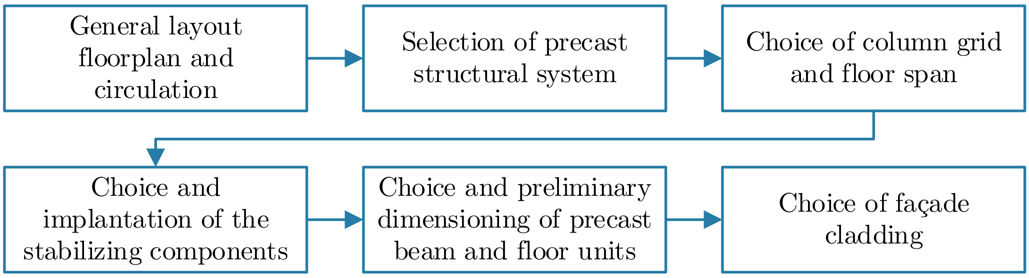


Figure 5. Design process with precast elements, according to [24].

Both [17] and [21] created a redesign by taking an already existing building design, selecting elements that match enough with this design and finally modifying the dimensions and grid of the original building design to fit the selected elements. In Chapter 0, the design process will be analyzed in more depth.

During the redesign, multiple disciplines must be considered. Structural design, architectural design, urban planning, environmental impact, and fire safety were chosen as the most important disciplines for this project. Regarding structural design, the building must withstand the loads determined by Eurocode 1 in the ultimate limit state and serviceability limit state. The architectural design includes the building's useability and exterior- and interior appearance, for which guidelines are presented in the Bouwbesluit chapters 2 and 4. For urban planning, the placement and appearance of the building in its environment must be considered, for which local regulations should be consulted. The discipline of environmental impact considers CO_2 emission, material use during construction, and the rest of the building's lifetime. Multiple methods can be used to quantify the environmental impact, of which Life Cycle Assessment (LCA) is the most widely used. Finally, fire safety measures are important to consider; the rules found in the Bouwbesluit chapter 2.2 must be incorporated into the design.

If the elements have been prepared correctly, the construction of the new design takes place in the same fashion as a conventional prefabricated concrete system, which should not be a problem for experienced contractors.

2.1.6 Example projects

In The Netherlands, there are very few realized examples in which structural concrete elements have been reused. The most successful project took place in Middelburg (1986); here, the upper seven stories of a 12-story apartment building were removed and reused to create 114 new single-family dwellings.[25], [26] All the disassembled concrete elements were reused. The project was viable because of the structural system with dry connections.

Figure 6. Deconstruction of an apartment building in Middelburg [25].

In Vlaardingen (1999) and Maassluis (2000), the upper floors of apartment buildings were disassembled to keep the lower floors useable. Even though the disassembled elements were not reused, the projects did show that the disassembly of precast systems by breaking mortar bonds is possible.[27], [20] For the SuperLocal project in Kerkrade, an experimental expo building and two dwellings were made with complete prefab apartment cells from an old flat. This project aimed to study the possibilities within building circular dwellings. Eventually, it was decided that reusing just walls and floor slabs was not achievable; the reason for this cannot be found. The biggest challenge in reusing complete apartment units was the weight of 100,000 kilograms, which made it difficult to lift the elements out of the original building. [28]

Figure 7. Lifting out of prefab apartment cells [29].

At this moment, the dismantling of Prinsenhof A in Arnhem is taking place, as visible in Figure 8. This is an office building from 1987 with 7400 m^2 of floor surface. The dismantling started in April 2022. The concrete elements removed for reuse are mostly hollow-core floor slabs from the Dycore floor system and load-bearing façade elements. These structural elements will eventually be used for different projects; 1052 m^2 of floor slabs is used for the floor of a sports building, and the remainder of the floor slabs and all façade elements will be used on a planned knowledge center in Heerde.[30], [11], [31]

Figure 8. The Prinsenhof A building during deconstruction [32].

Glias (2013) has performed the entire reuse process except for the realization stage in his thesis "The Donor Skelet" [17]. Every step of the reuse process was analyzed, and a redesign was made. The study shows that it is technically possible to reuse structural prefab concrete elements with the methods as described in Section 2.1.1 to Section 2.1.5. Additionally, it is concluded that the biggest advantage of reused concrete elements is the reduction of environmental impact. Financially, there could further be benefits compared to demolishment and new construction. The additional costs of the reuse process are compensated by the low price of the reused elements. Therefore, the reuse process becomes more appealing if a high percentage of reused elements is used. [33]

2.2 Aspects of building with (reused) precast concrete

2.2.1 Available buildings for reuse

The available precast concrete element stock is an important factor in the reuse process. Therefore, the existing precast structural systems and building stock are analyzed.

Four main types of structural systems for precast concrete elements are as follows: [24]

- The portal frame structure, which consists of columns that are clamped into the foundations and support the roof beams.
- The skeletal structure, which is composed of columns and beams, stability is provided by a core, shear walls and/or wind bracings.
- The wall frame structure, which consists of vertical load-bearing walls and horizontal slab units.
- The cell structure, which are composed of composed of completely precast concrete cells.

These above structural systems may be completed by a floor system, roof system, and/or, a façade system. Examples of floor systems are hollow-core floors, ribbed soffit floors, massive slab floors, and composite floor-plate floors. Additionally, hollow core floors can be used in a roof system; prestressed ribbed units and prestressed saddle-roof units are also available options.

To specify a building system, the building stock, especially the precast concrete building stock, is analyzed. The buildings that are interesting for reuse have a long structural lifetime but a shorter functional lifetime because these buildings are more prone to becoming vacant and being demolished when the structure is still in good condition. Therefore, office buildings are chosen to be further analyzed. The trends and needs in office buildings change approximately every ten years; an important trend change is the preferred location of offices [34]. In the last ten years, 2718 office buildings were demolished in The Netherlands. Of these demolished buildings, 67% were built between 1970 and 1989.

Table 1. Demolished buildings in The Netherlands between 2011 and 2020 [9].

Construction period	%
before 1950	9
1950 – 1959	4
1960 – 1969	15
1970 – 1979	33
1980 – 1989	34
1990 – 1999	4
2000 – 2009	1
after 2010	-

The graph in Figure 9 shows that the buildings from this period still occupy a significant part of the current national office stock [9].

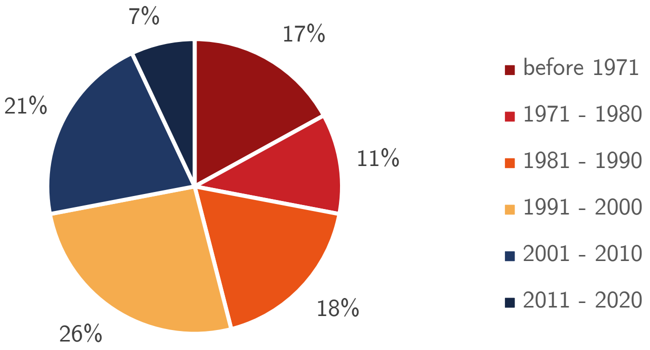


Figure 9. The construction period of the office building stock, The Netherlands (2020) [9].

Due to high market demand, many buildings from this period were built cheaply and quickly with newly innovated precast concrete. The office users at that time had different needs than the current office user. Therefore, many structurally sound office buildings have become outdated and vacant. The number of vacant buildings can increase with the current trend of working from home [10]. If the building is in a desired location, refurbishment is a valuable solution. However, dismantling or demolishment is the only option for buildings in unwanted areas.

2.2.2 Available elements for reuse

Some of the precast building systems consist of a combination of a façade system, a skeletal system, and floors. This can be translated into a building with load-bearing façades, with hollow core slabs spanning up to 18 meters in between. A row of columns and beams is added for larger buildings to complete the system [35]. This building system allows for large column-free spaces, and therefore flexibility in floor plans. This is the building system, as shown in Figure 10, on which the research will be focused.

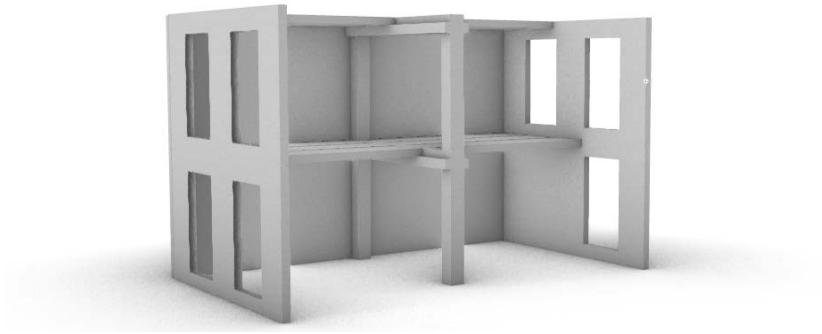


Figure 10. Visualization of the precast concrete building system considered in this thesis.

From this building system, multiple precast concrete elements can be extracted. Load-bearing façade elements are located on the outside of the structure. These elements contain relatively many openings for windows. On the inside of the structure, load-bearing walls can be found. These can be oriented in the same direction as the façade elements and the perpendicular direction. The floor and roof system consist of hollow core slabs. The most used standard width for these slabs is 1200 millimeters. Square columns and inverted T-beams support the middle of the building. Dimensional tolerances are already important to be considered with new prefab elements [24]; these tolerances become even bigger with reused elements because the dismantling process is not as precise as the fabrication process.

2.2.3 Structural integrity

The most essential requirement to have structural integrity in a precast structure, is to create a coherent entity from individual parts. Structural coherence is a critical issue in precast concrete because it involves the framework in total, the precast concrete elements themselves, and the connection in-between those elements.

The walls, façades, and columns carry the vertical loads from the hollow core slabs to the foundation. It is difficult to create moment-fixed connections between precast elements for horizontal forces; thus, horizontal stability can be achieved with the following systems:

- restraint of columns in foundations
- in-plane stiffness of shear walls
- diagonal bracing
- floor and roof diaphragms

As shown in Section 2.2.2, the system retrieves its stability from its floor and roof diaphragms and the in-plane shear stiffness of the load-bearing façade elements. To ensure this system works, sufficient connections between the walls must be made which transfer shear, tensile, and compressive forces. Furthermore, the floor-to-floor connection needs to facilitate diaphragm action. To make the facades and floors collaborate, the connections between the different element types are crucial; the principal way to achieve a coherent structure is by ties. [24] The structural details that are needed to provide the element collaboration as described are marked in Figure 11.

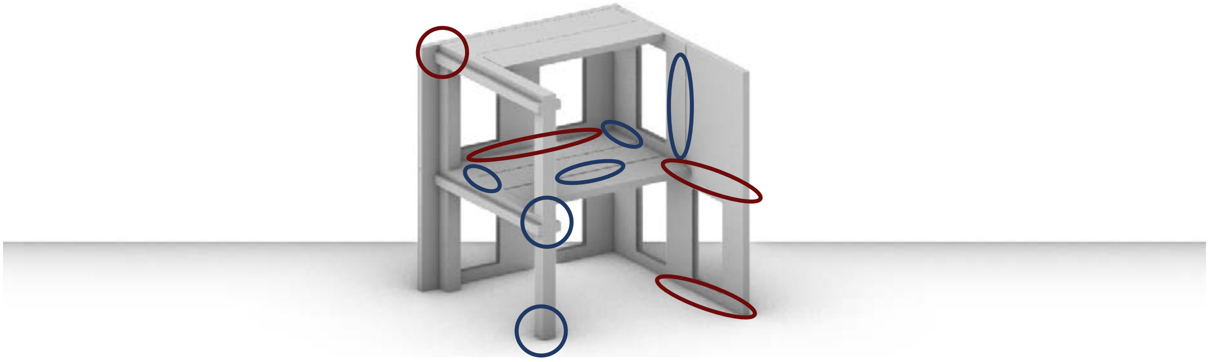


Figure 11. Locations of important connections.

The connections circled in dark blue have been analyzed by Volkov [36] and are shown below. Not all connections as proposed by Volkov are validated, and for the connections circled in red, no example was found. Therefore, more research is needed regarding these connections.

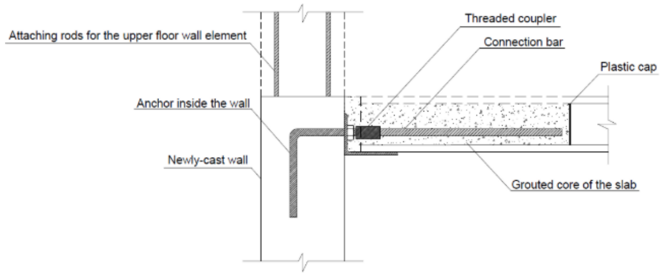


Figure 12. Floor - wall connection [36].

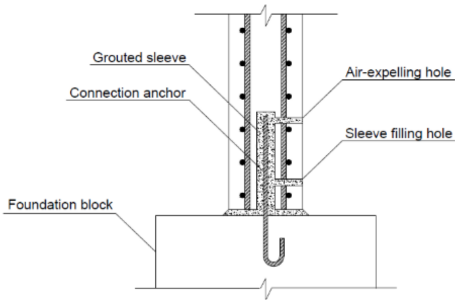


Figure 13. Wall - foundation connection [36].

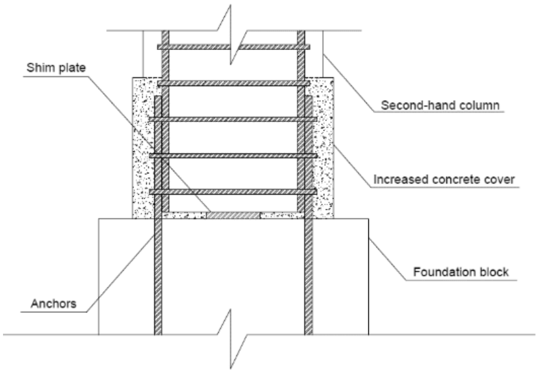


Figure 14. Column - foundation connection [36].

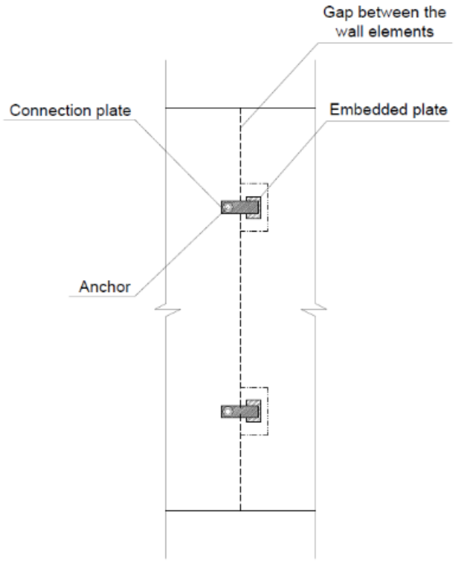


Figure 15. Wall - wall connection (shear) [36].

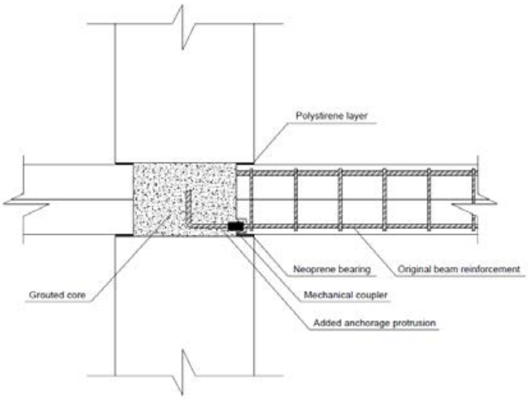


Figure 16. Column - Beam - Beam - Column connection [36].

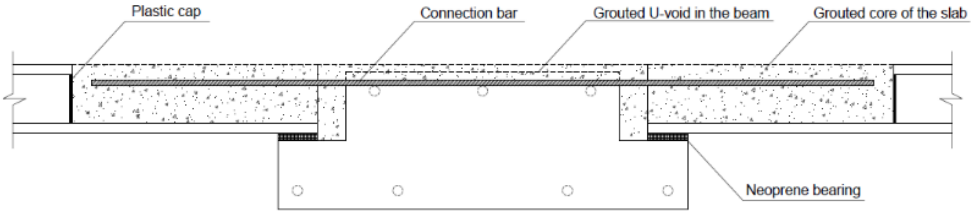


Figure 17. Floor - beam connection [36].

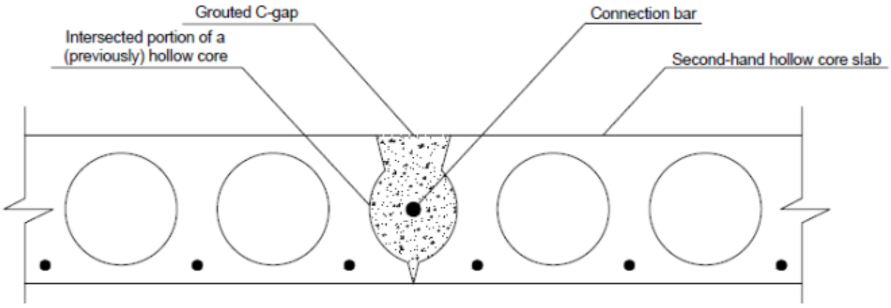


Figure 18. Floor - floor connection [36].

2.3 Digital building design

Digital design has existed for over 55 years. Figure 19 shows the timeline from the start of the development until now.

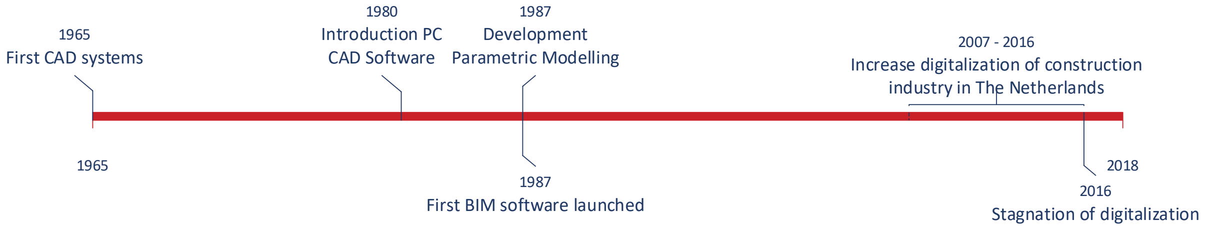


Figure 19. Timeline of digital building design evolution.

Initially, digital design was used to save time for architects by replacing paper and pen. This was done on specialist Computer Aided Design (CAD) systems by specialized users. Later, when the PC was invented, architects could use CAD as software. New developments started, and parametric modeling and assigning attributes to model objects became an option. These developments lead to the origin of Building Information Modeling. BIM saves time and effort for designers by facilitating the creation of graphic presentations and managing data in an organized manner.[37] Today, BIM is widely used in the construction sector in the Netherlands, which has, together with other digitalization strategies such as using robots, increased the sector's productivity.[14] This has not yet been the case in the UK [38], which is visible in Figure 20, where the productivity of the construction industry since 1970 is shown.

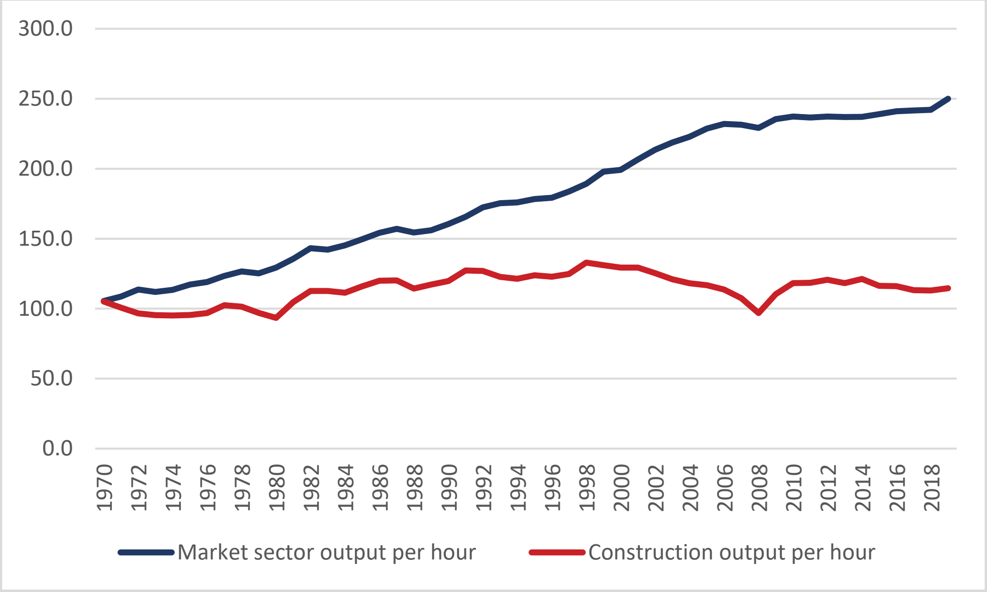


Figure 20. Productivity of the UK construction industry, 1970 to 2020 [39].

Digitalization in the construction industry has many advantages. The efficiency in data management increases, which prevents mistakes. Additionally, companies can use data to analyze their processes and to make substantiated decisions.[40] In the past few years, the digitalization rate of the construction sector in The Netherlands has decreased significantly. The industry must keep increasing its digitalization by applying digital design methods to keep up with other sectors to increase its productivity. In the next subchapters, the digital design methods which apply to this specific thesis will be named and explained.

2.3.1 Algorithm-Aided Design (AAD)

Algorithm-Aided Design refers to using algorithms to aid in the design process. An algorithm can be defined as “Any well-defined computational procedure that takes some value, or set of values, as input and produces some value, or set of values, as output. An algorithm is thus a sequence of computational steps that transform the input into the output.” [41] This definition is visualized in Figure 21. Every well-defined method with an input to reach a goal can be classified as an algorithm.

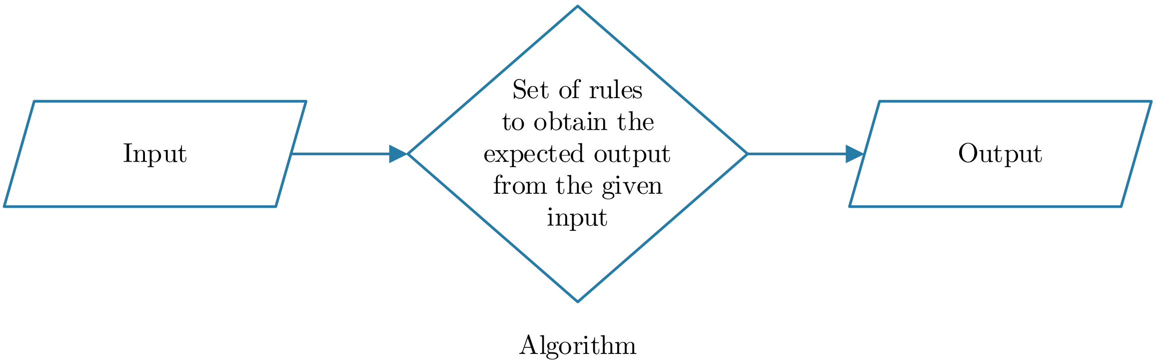


Figure 21. Visualization of an algorithm.

The real power of AAD emerges when a computer performs it. The computer allows for executing complicated, labor-intensive algorithms, and many repetitions of the same algorithm.

2.3.2 Software for Algorithm-Aided Design

For the application with a computer of AAD, profound knowledge is needed on both the construction industry and programming is required because all design and calculation steps must be converted into code before a computer can perform them. However, most architects and structural engineers do not have the skills to do this. Therefore, software platforms with a user interface are created, allowing the designer to use pre-scripted elements in their projects.

For algorithm-aided design, the algorithms must be very goal-specific. Therefore, there are no general AAD software platforms. Consequently, the user must specify their own algorithm for the design problem at hand. Visual programming environments have been developed, which make the use and creation of digital algorithms widely accessible. Visual programming works by creating a network of nodes that are connected by data streams. Each node contains a piece of code that represents an algorithm. The user connects nodes in a specific order, resulting in one big code. The visual connection method allows the user to have a clear overview of the structure of the code. Programmers create the nodes, which designers and engineers can use for their specific design goals. Grasshopper is an example of a well-established visual programming environment. It works within Rhinoceros 3D and is used worldwide by architects, designers, and engineers [42]. Figure 22 shows a small part of visual script in Grasshopper in which a cube is created. The script starts with a component that makes a 2D rectangle based on a plane, an x-length, a y-length, and a corner radius. The resulting rectangle is, together with a height, used as an input for the component which creates the cube.

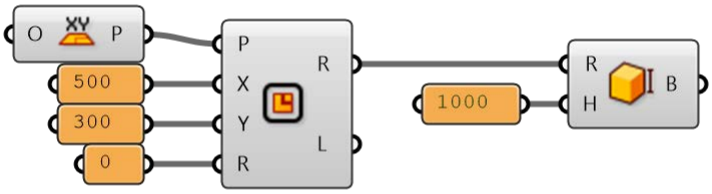


Figure 22. Grasshopper script for cube creation.

The result from this script can be viewed in Rhino and is shown in Figure 23.

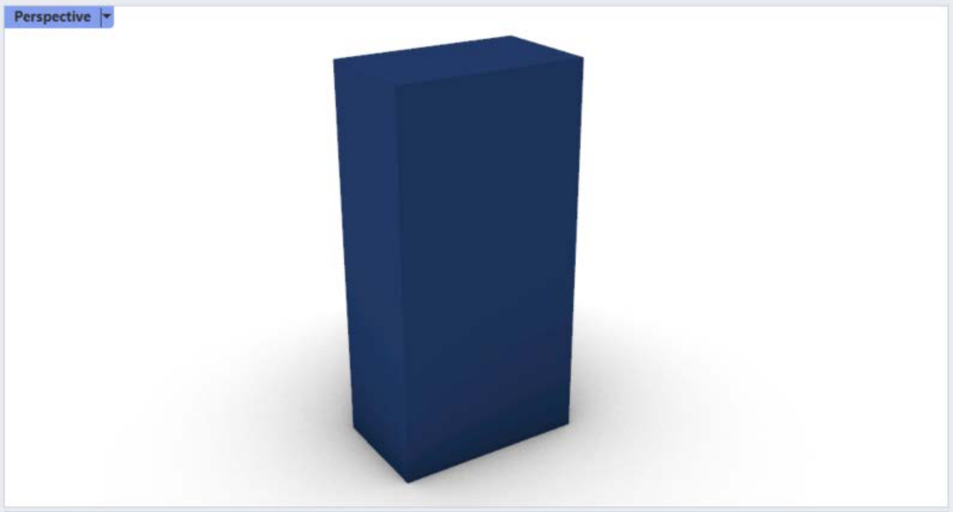


Figure 23. Rhino 3D result from Grasshopper script.

Components can be created and shared freely; multiple component packages can be downloaded from the sizable Grasshopper community on the internet.

2.3.3 Application in this thesis

The construction sector needs persons who have knowledge about both the built environment and programming to take full advantage of the possibilities within the sector's digitalization. In this thesis, components for Grasshopper will be programmed to remove barriers and increase productivity in the reuse process of precast concrete. An algorithm will be developed, which will be incorporated into a set of Grasshopper nodes that allow the user of the components to create and assess multiple design options. It will be possible for the user to make quick, substantiated design decisions based on data during the design process.

3 Analysis of the design process

In this chapter, the design process of an office building is analyzed. This analysis is based on the original process, which was realized, and a design process in which a limited element stock was used to create a building with the same design brief. Both designs were made by hand.

The design goal is a new office building for the Van Berkel Group. A plan of requirements and an initial analysis were acquired from Buro Kade. In the figure below, the area plan is shown. Besides the office, the area includes industrial halls, parking spaces, and a workshop.

Figure 24. Area view

The design process concerns the office building; the other functions are left out in this design analysis. A plot of 30 by 60 meters in the area plan is designated for the office. According to the requirements from the client, important aspects of the building design are practical useability, durability in terms of use and materials, the working climate, and environmental friendliness. Multiple functions must be present in the design; the list of all functional requirements can be found in Appendix A.1. The desired appearance of the building is described as distinctive and timeless. Furthermore, it is important that the building emphasizes the company's social culture.

3.1 Traditional design process

BuroKade created the realized design of the office for the Van Berkel Group. Architect Gijs Hoeijmans was interviewed about his design process for this project. The interview transcript can be found in Appendix A.3. A summary of this design process is schematized in Figure 25.

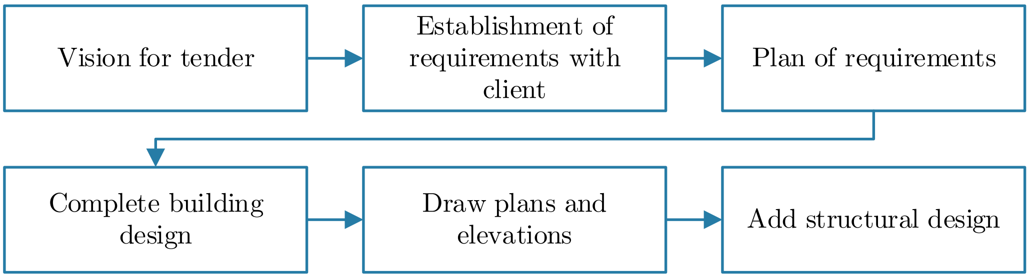


Figure 25. Original design process of the office for Van Berkel Group

An important note from this design process in the context of this thesis is that the building has been architecturally designed with little regard to the impact on its structural design. There has been some consideration of the structure by the definition of a grid; however, this has not been very influential on the final design, which is visible in the figure below.

Figure 26. Realized building

Figure 27 shows the structural design that was fitted to the architectural design. The ground floor consists of mainly concrete columns and walls (in grey) and some steel columns (in red), supported by a strip and footing foundation. On top of these, a wide slab floor is placed. The wide slab floor supports the steel columns of the first floor that support steel beams. Hollow core roof slabs (in blue) are placed on the steel beams. The brown façade elements are made from timber and are not load-bearing.

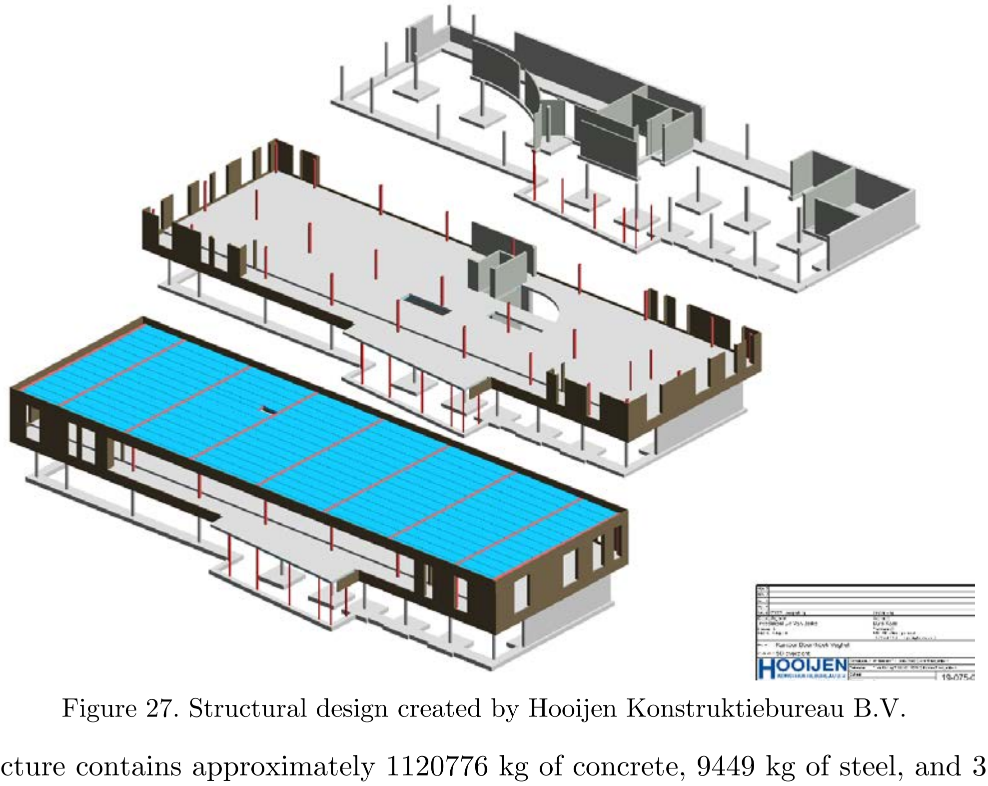


Figure 27. Structural design created by Hooijen Konstruktiebureau B.V.

This structure contains approximately 1120776 kg of concrete, 9449 kg of steel, and 36750 kg of calcium silicate brick. The weights of the materials, multiplied with their kilogram of carbon dioxide equivalent per kilogram ($kgCO_2e/kg$) from the ICE database results in a total embodied carbon value of 166836 $kgCO_2e$. [43]

3.2 Design process with reused concrete elements

In this subchapter, a building is designed for the same building brief as in the previous subchapter. Figure 28 shows a flowchart that summarizes all steps in the design process.

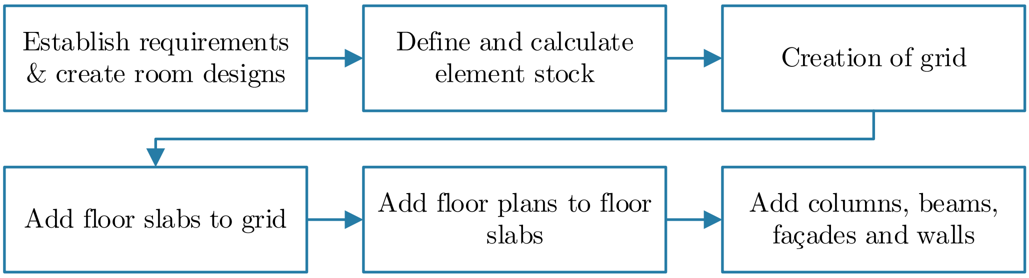


Figure 28. Design process as performed in the redesign by hand

The plan of requirements, as shown in Appendix A.1, was used as the starting point for the redesign process. From this plan of requirements, it can be concluded that at least 1200 m^2 of available floor space is needed to fit all rooms. Other constraints for the design are a maximum of two stories (by the architect from the mass study), a building depth that is maximal 2.5 times the window height plus the hallway width, and the building must be placed within the 30 by 60-meter plot.

Based on the expected square meters, an element stock for the redesign is chosen. The element stock is based on the research of Glias [17], from which 'stock A' was selected as a suitable stock. This stock was retrieved from an office building located at Hogehilweg 1 in Amsterdam. The element stock has been simplified, and missing information is completed and adapted based on known values from other prefab elements and logical guesses. These fictional adaptations ensure that the resulting element stock is completely viable for reuse, which allows for a clear reuse process. The used element stock can be found in Appendix A.4.

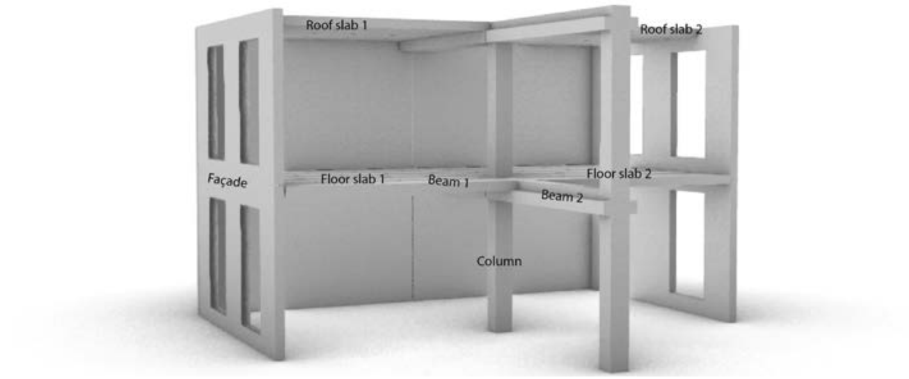


Figure 29. Structure for structural analysis

The figure above shows the structural system of the element stock, which shows the configuration in which the elements should be used. The system consists of hollow core floor slabs, inverted T-beams, square columns, and structural façades. In this system, the floors lay on top of the beams or are connected just below the top of the façades. The beams lay on top of columns, and in the case of multiple stories, the columns are placed vertically above each other with beams in between. The system is not limited to two floor spans but can be expanded by adding an extra row of columns. The load capacity values for each of the different structural elements are already defined in the stock. A calculation was performed to check which elements and element combinations from the stock can carry the loads of a typical two-story office building, when arranged as shown in Figure 29. The roof slabs, hollow core slabs (HCS), and beams are checked for their maximum bending moment and shear force. The walls and façades are checked for maximum normal force. The loads used to perform the calculation are shown in Table 2.

Table 2. Loads on a typical office building.

Roof		**1st floor & Ground floor**	
Permanent loads		Permanent loads	
Self-weight HCS	2.7 kN/m²	Self-weight HCS	2.7 kN/m²
Concrete topping	1.0 kN/m²	Concrete topping	1.0 kN/m²
Roof cover	0.2 kN/m²	Finishing	0.2 kN/m²
Variable loads		Variable loads	
Roof not accessible	1.04 kN/m²	Office	2.5 kN/m²
Solar panels	0.15 kN/m²		

A specific calculation approach is needed to reduce the time spent on finding all compatible element combinations. The chosen approach is based on checking the combinations which are most likely to not suffice to the unity check. The precise results of the calculations can be found in Appendix A.7. The calculation starts with checking the floor with the greatest span (6960 mm) for moment and shear with the formulas below.

$$q_{ed\,HCS} = Q_{HCS} * Y_Q + G_{HCS} * Y_G \tag{3.1}$$

$$M_{ed\ HCS} = \frac{1}{8} * q_{ed\,HCS} * L_{HCS}{}^2 \tag{3.2}$$

$$V_{ed\,HCS} = \frac{1}{2} * q_{ed\,HCS} * \ L_{HCS} \tag{3.3}$$

$$UC_{M\,HCS} = \frac{M_{ed\,HCS}}{M_{rd\,HCS}} \tag{3.4}$$

$$UC_{V\,HCS} = \frac{V_{ed\,HCS}}{V_{rd\,HCS}} \tag{3.5}$$

This check is okay, from which we can conclude that a floor with the same moment and shear resistance but a smaller span will also suffice.

Next, the longest beam is checked in combination with the largest floors using calculations 3.6 to 3.10.

$$q_{ed\,beam} = \frac{L_{1\,HCS} * (q_{ed\,HCS} + W_{ed\,HCS})}{2} + \frac{L_{2\,HCS} * (q_{ed\,HCS} + W_{ed\ HCS})}{2} \tag{3.6}$$

$$M_{ed\ beam} = \frac{1}{8} * q_{ed\,beam} * L_{beam}{}^2 \tag{3.7}$$

$$V_{ed\,beam} = \frac{1}{2} * q_{ed\,beam} * \ L_{beam} \tag{3.8}$$

$$UC_{M\,beam} = \frac{M_{ed\,beam}}{M_{rd\,beam}} \tag{3.9}$$

$$UC_{V\,beam} = \frac{V_{ed\,beam}}{V_{rd\,beam}} \tag{3.10}$$

The bending moment in the beam with a length of 7100 caused by the two largest floors is 442.3 kNm while the resistance of the beam is 189 kNm. Therefore, this beam – floor combination is not useable. A beam length smaller is tried until the unity check of the beam is below 1.0. From here, it can be concluded that all shorter beams with the same strength will also be able to carry that same floor combination. Thus, the rest of the same strength beams do not have to be checked, resulting in a reduced number of calculations. This process is repeated for each floor combination.

Finally, the structural capacities of the columns, façades, and walls were considered with the calculations below.

$$N_{ed\ column} = q_{ed\ beam}\left(\frac{1}{2}L_{beam2} + \frac{1}{2}L_{beam1}\right) + \frac{W_{ed\ beam1} + W_{ed\ beam2}}{2} + F_{ed\ columns\ above} \quad (3.11)$$

$$F_{ed\ column} = N_{ed\ column} + W_{ed\ column} \quad (3.12)$$

$$UC_{column} = \frac{N_{ed\ column}}{N_{rd\ column}} \quad (3.13)$$

The only column type in stock has a normal force resistance of 2789.7 kN. When this column is combined with the two largest beams (7100 mm) and the two largest floors (6960 mm) the load on the column due to the roof is equal to 685.97 kN, and due to a floor 1667.3 kN. From which can be concluded that the column is able to carry one floor with a roof. Due to the requirements, the building will not have more than two stories. Therefore, all the possible element combinations can be used for the columns. Equations 3.14 to 3.17 show the calculations which are used to determine the maximum floor capacity of the façades and walls.

$$N_{ed\ facade} = L_{facade} * \frac{L_{HCS} * (q_{ed\ HCS} + W_{ed\ HCS})}{2} + F_{ed\ facades\ above} \quad (3.14)$$

$$UC_{facade} = \frac{N_{ed\ facade}}{N_{rd\ facade}} \quad (3.15)$$

$$N_{ed\ wall} = L_{wall}\left(\frac{L_{1\ HCS} * (q_{ed\ HCS} + W_{ed\ HCS})}{2} + \frac{L_{2\ HCS} * (q_{ed\ HCS} + W_{ed\ HCS})}{2}\right) + F_{ed\ walls\ above} \quad (3.16)$$

$$UC_{wall} = \frac{N_{ed\ wall}}{N_{rd\ wall}} \quad (3.17)$$

From these calculations it is concluded that the facades and walls also have enough resistance to carry at least two stories with the largest floors.

All required rooms were designed to fit within a grid width of 3600 mm. This was done based on the interview with the architect Ivo van den Thillart, which can be found in Appendix A.3. The standardization of the rooms makes it easier to fit the rooms into a structural grid later in the design process. The room designs can be found in Appendix A.6. The design of the building shape started with laying out a grid based on the width and length of the available hollow core slabs, as shown in Figure 30. Multiple grid options were created in which the maximum building depth and the number of floors in stock were present as limiting factors.

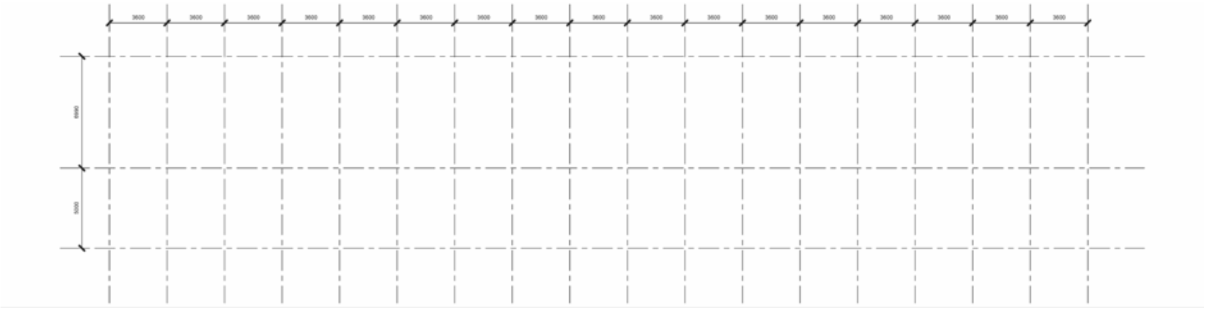


Figure 30. Structural grid

The grid in Figure 30 resembles the shape of the original design of the building; therefore, this grid was chosen to be elaborated into floorplans. To save time, no other grid configurations were translated into floor plan designs. However, it would be interesting to be able to explore multiple design options if the process was less time intensive. Figure 31 and Figure 32 show the floor plans placed on the grid.

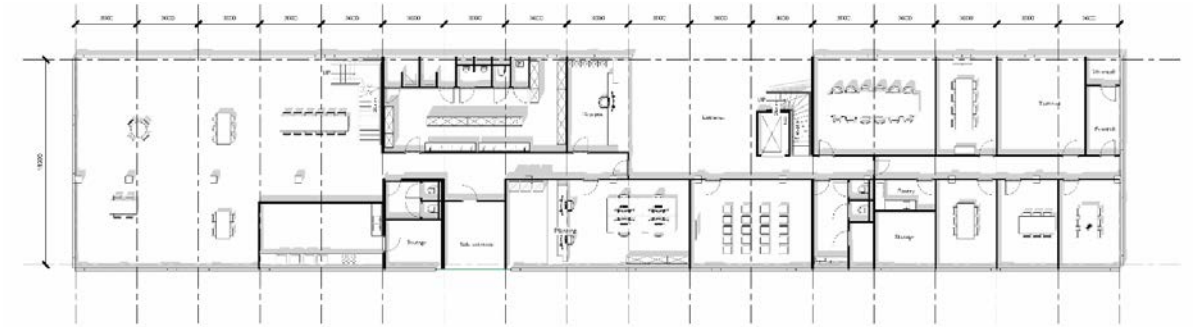


Figure 31. Floor plan ground floor

Figure 32. Floor plan 1st floor

After the floor plans were created, the structure was added to the design with the structural restrictions in mind. The most difficult part of this design step was to find combinations of wall and beam lengths that fit with the floor plans because the wall, beam, and floor dimensions do not match perfectly. Additionally, the wall openings need to fit with the daylight requirements of the rooms. Therefore, the rooms were divided into three daylight requirement categories, as shown in Figure 33.

Figure 33. Daylight requirements

The walls were fitted to the floor plan by starting at one side of the building and measuring the needed wall length, then the light requirements were checked at that location, and a wall was chosen which fits the requirement. The wall was placed, and its length was deducted from the total length. These steps were repeated until the remaining wall length came close to zero or negative. If the total wall length was too big, the last wall was removed, and a smaller wall was tried, and if that was not close enough, two walls were removed. This process was repeated until a right configuration was found. The resulting structural design from this process is visible in the figures below.

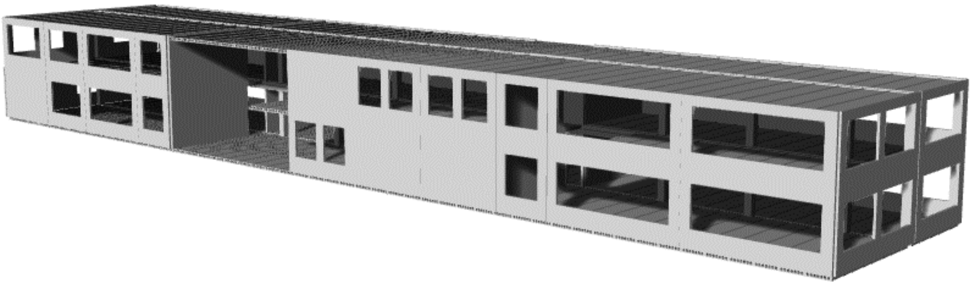


Figure 34. Front 3D view of the structure.

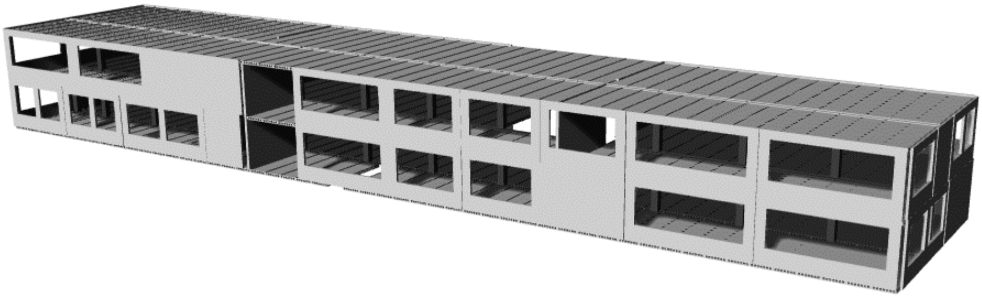


Figure 35. Back 3D view of the structure.

If the walls are fitted perfectly with the floor plans, the difference in length between the placed walls and the floor plans is zero. In this design, the flexibility in this difference is increased by adding customized façade parts at the entrances, where new materials are used. Another option to increase flexibility is to create connection parts for the corners of the building. It would be interesting to create a design for a reusable modular corner connection element for projects like this. Another option would be to add a new complete wall or beam element to overcome the difference.

Figure 36 shows a more detailed view of one of the corners of the structure; here, it becomes visible how the elements are placed in relation to each other.

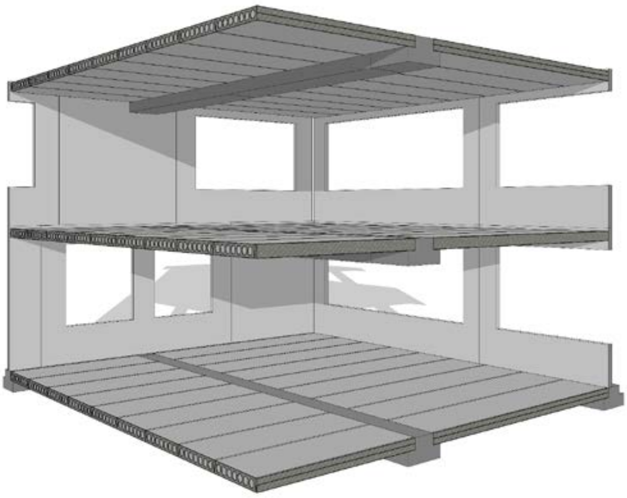


Figure 36. Section view.

The figure below gives an isolated view of the placed beams and columns along the internal grid line, along with perpendicular structural walls.

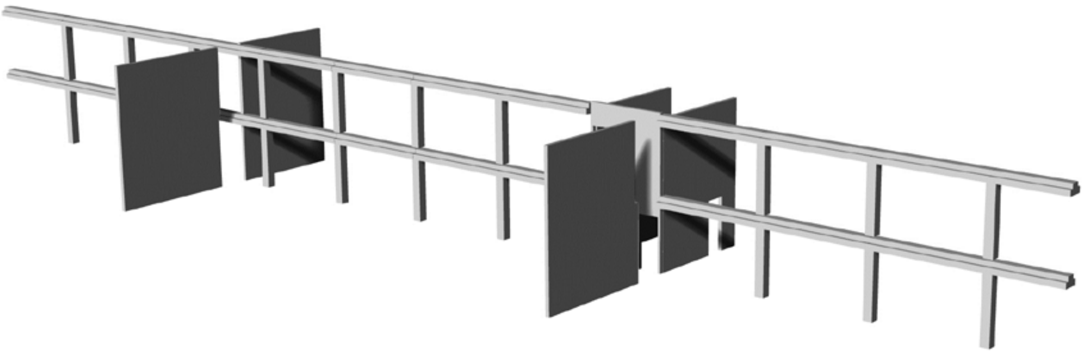


Figure 37. Beams, columns, and walls.

In total, 294 hollow core slabs, 24 beams, 24 columns, and 53 façades are used in the structure.

The structure contains approximately 984000 kg of reused concrete. This weight is a slight overestimation because the weight of the façades was calculated without openings, and the beams were calculated as if they had rectangular sections. A final structural check of the designed structure is not performed because all elements are used in configurations that have been marked as viable in the calculation at the beginning of the process. The building is stabilized by the load-bearing façades which surround the complete building and the internal walls.

Most steps in the performed design process were quite laborious. Therefore, for each design step, the first option that sufficed to meet the requirements was chosen. Consequently, only a few options were explored, and better options might exist.

3.3 Comparison of the design processes

The functional design and the architectural vision for the building are the common thread in the traditional design process. The complete architectural design and functional design are created before the structural design is considered. The structural design is fitted with the rest of the design. The design process is completely different when a limited element stock is used. The available structural elements and, therefore, building shapes need to be considered from an early point in the process. The functional design will be made with the restrictions of the available floor slabs. And the architectural design is largely dependent on the final structural and functional design.

It is difficult to compare the material usage in both designs because different structural systems are used, and both numbers are not exact numbers but approximations. Additionally, no numbers can be found in the literature on the embodied carbon in reused concrete. However, it can be deduced that great amounts of materials can be saved by reusing concrete.

Reusing concrete elements reduces the architect's freedom of design; however, many design options are still available. The exploration of these design options is laborious because the coherence to the element stock must be checked for each adjustment. Consequently, the design process becomes more of a puzzle, and the possibilities for creativity are limited. Integration between the element stock and the architectural, functional, and structural design is very important. This might put off architects and structural engineers from building with reused concrete.

With the help of a design algorithm discussed in Chapter 4, the steps performed in the redesign become clearer and easier to reproduce. The design process by hand is analyzed to include the steps in an algorithm. This design process could be iterative, meaning steps are repeated, adjusted, and repeated until a solution is found. For this thesis, it is tried to create a linear process, which will be more easily accessible due to easier understandability and shorter calculation time.

4 The design process in an algorithm

This chapter presents the algorithm that is created based on the findings in Chapter 0. Figure 38 shows a summary of the algorithm visualized in a flowchart.

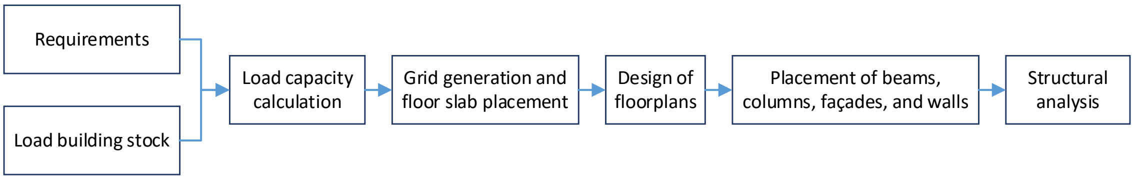


Figure 38. The general algorithm in a flowchart

Each step of the algorithm will be discussed in more detail below. A small example is shown in the framed parts of the text.

4.1 Requirements

The requirements needed for the design process are the building plot dimensions, the maximum number of stories, the maximum building coverage ratio, the building function, the maximum building depth, and the desired area. Some small calculations are performed to check if the requirements do not contradict each other. The algorithm flowchart is visible in Appendix A.9.1. An example set of requirements is shown below.

Example requirements

Function: Residential
Maximum stories: 2
Maximum building coverage ratio: 70%
Desired area: 100 m^2
Maximum building depth: 10 m
Plot: 14 x 9.5 meter

Figure 39. Plot outline

4.2 Building stock

The building stock contains all elements available for the reuse process. Multiple element types are possible, including floors, beams, columns, façades, and walls. Each element has geometrical properties, including its length, height, and width, and its strength for governing internal moment, shear, and normal forces. Additionally, the façade elements have a value that describes the amount of daylight that is let through on a scale from 1 to 3. An example building stock is shown below.

Example building stock

The elements in the building stock below are created for the example, they do not refer to a real element stock or real elements.

Table 3. Example building stock

Type	Qty	L (m)	H (m)	W (m)	M_{rd} (kNm)	V_{rd} (kN)	N_{rd} (kN)	Daylight
Floor 1	6	4	0.2	1.2	60	80	-	-
Floor 2	15	7.5	0.2	1.2	60	80	-	-
Beam 1	1	1.0	0.45	0.72	100	200	-	-
Beam 2	1	2.6	0.45	0.72	100	200	-	-
Beam 3	1	2.6	0.45	0.72	150	300	-	-
Column 1	1	0.3	2.6	0.3	-	-	500	-
Column 2	1	0.4	2.6	0.4	-	-	890	-
Façade 1	4	1.5	3.05	0.1	-	-	300	1
Façade 2	2	2	3.05	0.1	-	-	300	1
Façade 3	2	1.5	3.05	0.1	-	-	250	2
Façade 4	3	2	3.05	0.1	-	-	250	2
Façade 5	7	1.5	3.05	0.1	-	-	200	3
Façade 6	13	2	3.05	0.1	-	-	200	3

4.3 Structural calculation

The structural calculation consists of a preliminary assessment of the building stock in combination with the requirements. The same formulas are used as described in Section 3. Loads are applied on the floors based on the building function, and the resulting internal moment and shear forces are compared to each floor's capacity. Every floor that can withstand the loads is then checked in combination with all the beams, façades, and walls. The beams are checked for shear force and moments, and the façades and walls are checked for normal forces. Each combination that suffices the checks is stored. Not every column–beam–floor combination is checked to reduce calculation time and size. Instead, the beam-floor combinations are grouped based on the lengths of the beams and the floors, regardless of their other properties. And from each group, for one combination is checked how many floors could be carried by the column. The calculations corresponding with the example stock are shown below.

Example structural calculation

Check 1: floors

Table 4. Floor calculation

Floor	Imposed load	Own weight	M (kNm)	V (kN)	UC M	UC V
Floor 1	4.89 kN/m^2	2.7 kN/m^2	15.18	15.18	0.25	0.19
Floor 2	4.89 kN/m^2	2.7 kN/m^2	53.37	28.46	0.89	0.36

Check 2: beams

Table 5. Beam-floor combination calculation

Beam	**Floor A**	**Floor B**	**M (kNm)**	**V (kN)**	**UC M**	**UC V**
Beam 1	Floor 1	Floor 1	3.16	12.65	0.03	0.06
	Floor 1	Floor 2	4.55	18.19	0.05	0.09
	Floor 2	Floor 2	5.93	23.72	0.06	0.12
Beam 2	Floor 1	Floor 1	21.39	32.89	0.21	0.16
	Floor 1	Floor 2	30.73	47.28	0.31	0.24
	Floor 2	Floor 2	40.09	61.67	0.40	0.308
Beam 3	Floor 1	Floor 1	21.39	32.89	0.11	0.11
	Floor 1	Floor 2	30.73	47.28	0.15	0.16
	Floor 2	Floor 2	40.09	61.67	0.20	0.21

Check 3: columns:

Table 6. Column-beam-floor combinations

Combi	**Beam length A (m)**	**Beam length B (m)**	**Floor length A (m)**	**Floor length B (m)**
1	1	1	4	4
2	1	2.6	4	4
3	2.6	2.6	4	4
4	1	1	4	7.5
5	1	2.6	4	7.5
6	2.6	2.6	4	7.5
7	1	1	7.5	7.5
8	1	2.6	7.5	7.5
9	2.6	2.6	7.5	7.5

They can be combined with two different columns, which results in 18 combinations in total. If each beam of 2.6 meter would be considered in a distinct combination, 36 combinations would be made.

Table 7. Column calculation

Combi	**kN / floor**	**Max stories column 1**	**Max stories column 2**
1	25.30	19	35
2	45.54	10	19
3	65.78	7	13
4	36.38	13	24
5	65.47	7	13
6	94.56	5	9
7	47.44	10	18
8	85.39	5	10
9	123.34	4	7

Check 4: façades

Table 8. Façade calculation

Façade	kN / floor 1	Max stories floor 1	kN / floor 2	Max stories floor 2
1	18.98	15	35.58	8
2	25.30	11	47.43	6
3	18.98	13	35.58	7
4	25.30	9	47.43	5
5	18.98	10	35.58	5
6	25.30	7	47.43	4

4.4 Grid generation and floor slab placement

The grid generation starts with the choice of a point randomly somewhere along the plot perimeter line. Next to this point, the first grid cell is placed. The sizes of the grid cells are in one direction determined by the width of the floors in stock and the number of floors that will be placed simultaneously, and in the other direction by the lengths of the floors in the element stock. Starting from the first grid cell, the rest of the plot is populated with other cells. An example of the grid generation is shown below.

Example grid generation

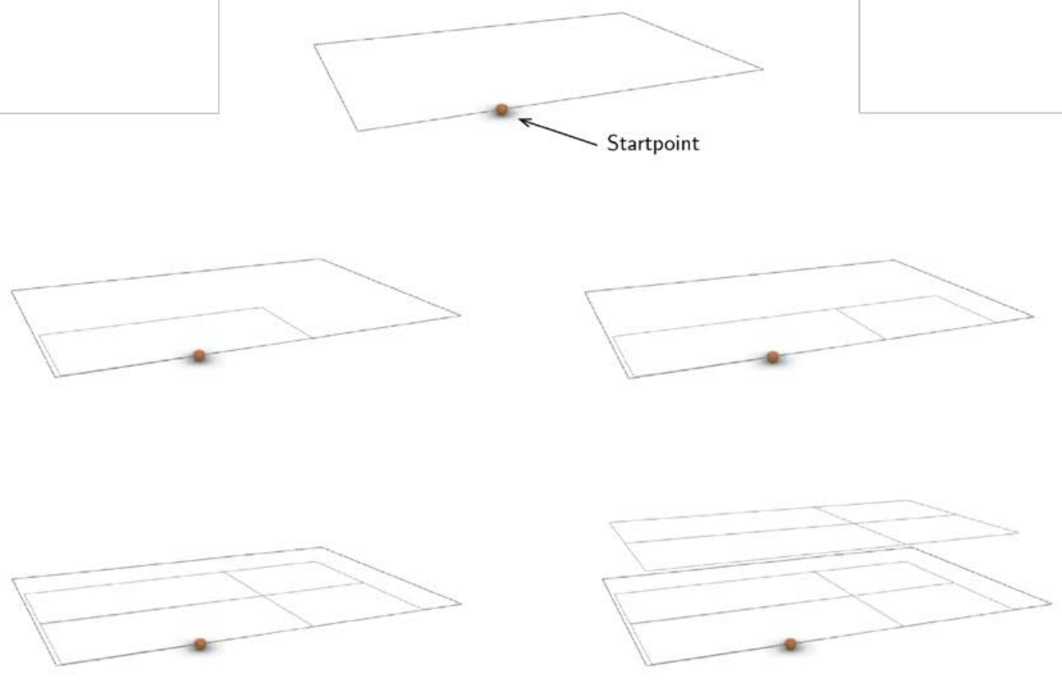


Figure 40. Example grid generation

The placement of the floors starts at the location of the first grid cell. The distance to all the other grid cells is determined from this point. The grid cells will be considered for placement of floors one by one, with the closest grid cells first. Before a grid cell is filled with floors, the following requirements must be met:

- There are enough floors of this length in the floor stock.
- The building width does not exceed the maximum building width by filling this grid cell with floors.

The placement of floors stops when the desired area is reached when each cell has been analyzed for placement or when the floor stock is empty. Below, an example of the floor placement is shown.

Example floor placement

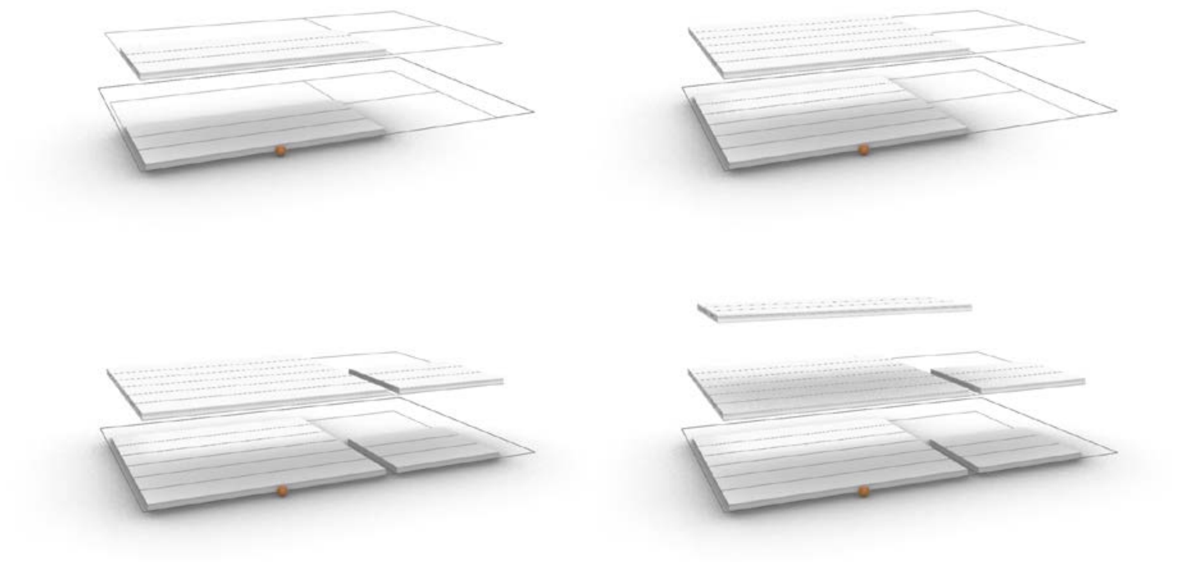


Figure 41. Floor placement

The described process can be performed multiple times and will yield different results. Afterward, the results are analyzed based on the resulting area, conformity with the beam and façade stock, and volume/envelope-area ratio. A multi-criteria analysis is used to choose the best result. In this analysis, the adherence to the area requirement, the coherence between the expected element use and the element stock, and the volume-envelope ratio are weighed.

4.5 Design of floor plans

The architectural floor plans must be designed onto the placed floor slabs because the slabs form the basic shape of the building. This design can be made by hand or by an algorithm.

The design of the floor plans itself is out of the scope of this thesis, and therefore, no algorithm is designed for this purpose. Below an example of a floor plan design is shown.

Example design of floor plans

Figure 42. Floor plan design

4.6 Placement of beams, columns, and façades

The placement of the beams and columns is a separate process from the placement of the façades. First, the locations on which the beams and façades need to be placed are identified based on the already placed floors.

The beams need to be placed where two floor-ends meet each other to support those floors. This results in beam locations in terms of a location line. These lines are then considered for beam placement in a specific order. To ensure that the columns for each story are placed on top of each other, all location lines that are vertically placed above each other will have beams located to them at the same time. This results in multiple groups of vertical lines. These groups will be ordered based on the grid distances next to them, with the lines next to the greatest grid distance first. As a result of this order, the beams which carry the highest loads will be placed first. This reduces the material use when a new beam needs to be used instead of a reused beam. The beams are assigned to a location line by finding the combination of beams that best fits the length of the location line.

Example placement of beams

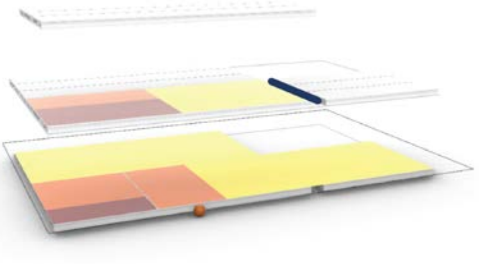


Figure 43. Beam location line.

The length of the beam location line is 3.6 meter. In the figure below, all possible combinations with the beams from the stock are made.

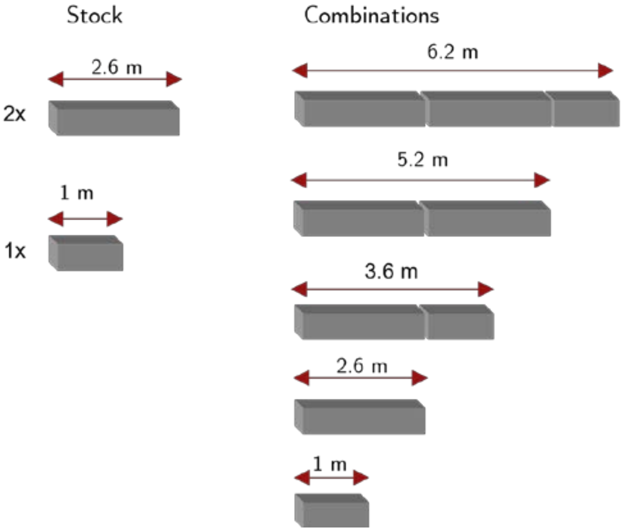


Figure 44. Beam stock and possible combinations.

The combination which has a length of 3.6 meter is chosen. In the figure below, the combination is placed into the structure.

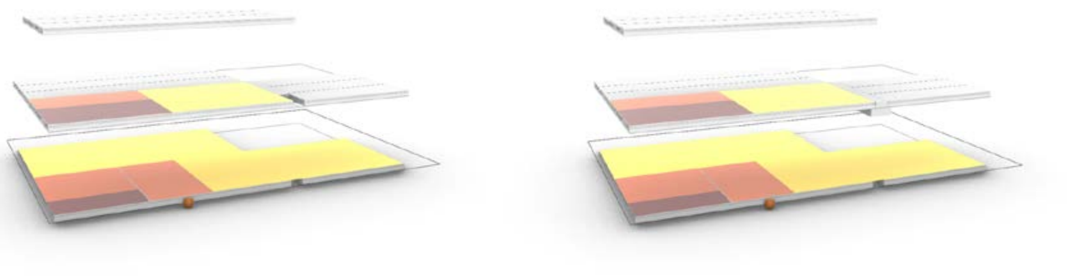


Figure 45. Placement of beams.

The placed beams determine the locations on which the columns need to be placed. Placement of the columns takes place per set of column locations that are vertically above each other. For each column, it is determined how many columns, and therefore floors, are above it. Combined with the knowledge of which beams and floors they support, the corresponding column-beam-floor combinations are selected. From which the column with the lowest resistance is selected for placement.

Example placement of columns

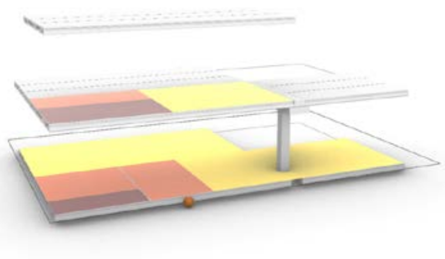


Figure 46. Placement of columns.

For the placement of the façades, first, the floor plan outlines are analyzed to determine the daylight requirement of each part of the façade. From here, the outlines are divided into smaller lines with the same daylight requirement. Then, the best length combination of façade elements with this daylight requirement is determined. For each façade length in the combination, placeable façades with equal lengths are found. Then the façade with the lowest strength and, therefore, highest unity check is placed.

Example placement of façades

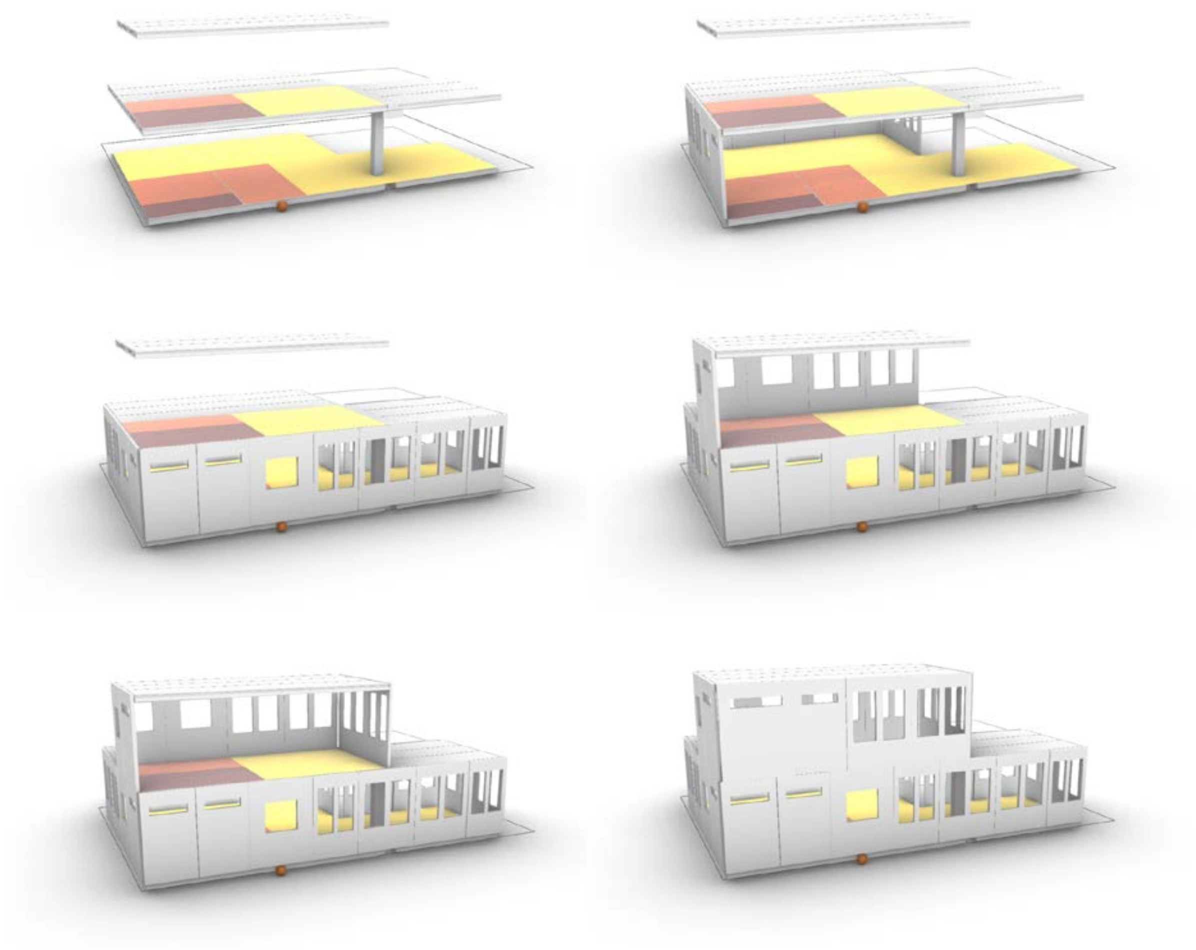


Figure 47. Placement of façades.

5 Digitalization of the algorithm

5.1 The complete design process in components

The Rhinoceros and Grasshopper environment was used to bring the algorithm from Chapter 4 into practice. As already explained in Section 2.3.3, Grasshopper gives the possibility to design in Rhino through visual code, for which pre-scripted components that perform an algorithm are used. The algorithm from Chapter 4 has been incorporated into a series of Grasshopper components visible in Figure 48.

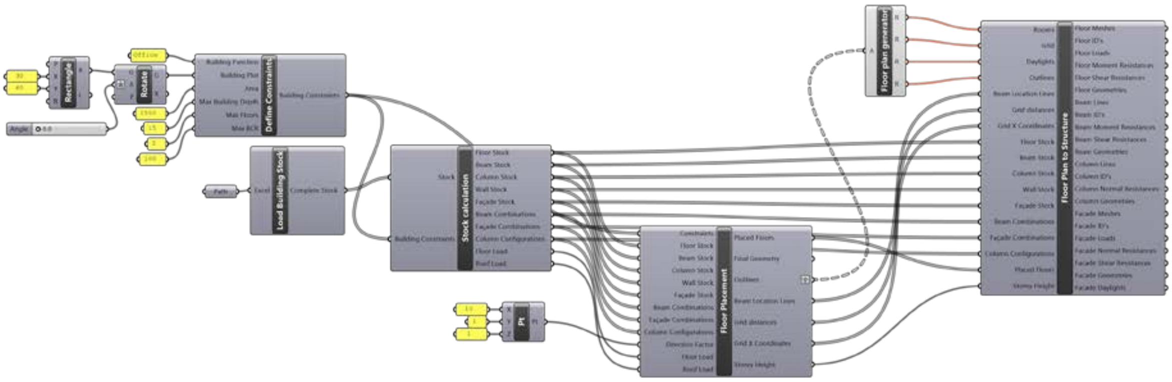


Figure 48. Grasshopper script.

The components are created in Visual Studio, an integrated development environment where developers can write and edit code. Within Visual Studio, an extension called 'RhinoCommon and Grasshopper templates for Rhino 7' was used. The extension provides a template (included in the script booklet item B.1) for an empty Grasshopper component for Rhino 7. Every component was built with the help of this template. The C# scripting language was used to code the respective algorithms within these components.

Within Grasshopper, the components can easily be switched out for other components or by manual data input in line with the input requirements for the subsequent components. The component package can be expanded by adding components with similar functions, including different algorithms and components that perform new algorithms. This gives the user more influence on the process because a choice can be made on which components will be used.

5.2 The components in detail

In this subchapter, every component used in the complete script is discussed from a technical point of view. The actual code inside the components can be found in the script booklet.

5.2.1 Import building stock

The component loads the building stock from a Microsoft Excel spreadsheet file into the Grasshopper environment. The script can be found in script booklet B.2.

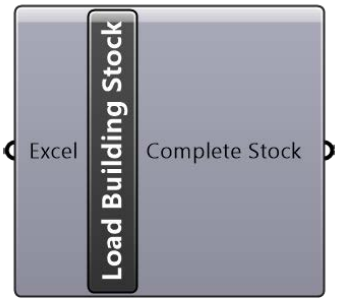
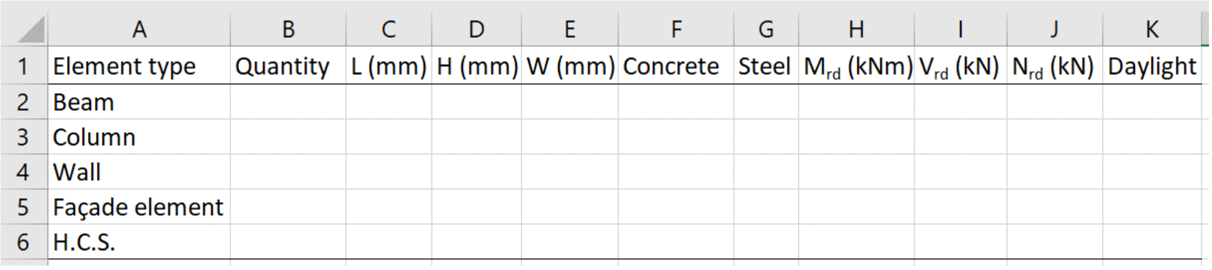


Figure 49. ‘Import Building Stock’ component.

The code inside this component uses the Microsoft.Office.Interop.Excel assembly, which allows interoperation between a Microsoft Excel file and a C# script. With this assembly, an Excel sheet is analyzed row by row, and from this data, a list containing all stock data is created.

The used Excel file should be constructed in a specific way, as shown in Figure 50. If this formatting is not applied correctly, the stock import will fail.



	A	B	C	D	E	F	G	H	I	J	K
1	Element type	Quantity	L (mm)	H (mm)	W (mm)	Concrete	Steel	M_{rd} (kNm)	V_{rd} (kN)	N_{rd} (kN)	Daylight
2	Beam										
3	Column										
4	Wall										
5	Façade element										
6	H.C.S.										

Figure 50. Excel input screen.

The amount of detail included in the aforementioned Excel table is limited in line with the scope of this project. For instance, holes in walls and facades or cut-outs in beams are not considered. For this to be possible, another import method could be created which supports geometry data, such as IFC files, or an import by hand in Grasshopper. Another useful addition might be to add an element ID. In the other components, the elements are identified by the combination of their properties; this process becomes easier and faster if a unique ID is used.

5.2.1 Define constraints

In this component, the user can set the constraints of the design process to be performed. The script can be found in script booklet B.3.

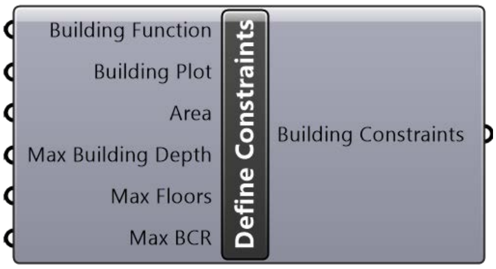


Figure 51. ‘Define Constraints’ component.

The code inside this component is very simple. Multiple inputs are taken in and checked to see if they are of the correct data type. Some checks are performed to find contradictions, and a warning is given if one is found. Finally, the inputs are combined into one output list.

5.2.2 Stock calculation

This component defines the possible element combinations. Its script can be found in script booklet B.4. As input, it takes in the results from the previously discussed components.

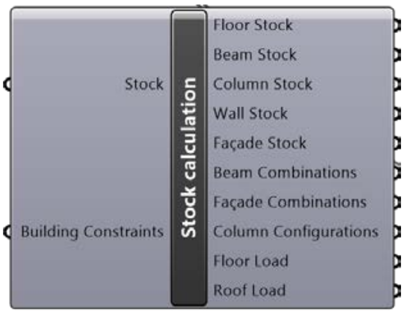


Figure 52. ‘Stock Calculation’ component.

The script contains the calculations as discussed in Section 3. All elements loaded by the Load Stock component (section 5.2.1) are assumed to be geometrically compatible and fitting in the load-bearing façade system.

In the current script, internal walls are left out because they are not used in the building system of the scope. If components were to be made for other structural systems, a wall calculation must be added for structural systems in which internal walls have an essential function. Furthermore, an addition to the script could be made, including automatically calculating elements' structural load capacities. Due to this addition, the script will not be dependent on the inclusion of element properties in the stock.

5.2.3 Floor placement

The component that takes care of the placement of the floors is shown in Figure 53. Its script can be found in script booklet B.5. All inputs, except the Direction Factor, are outputs of the previous components. The Direction Factor, on which will elaborated in Chapter 0, is added by the user.

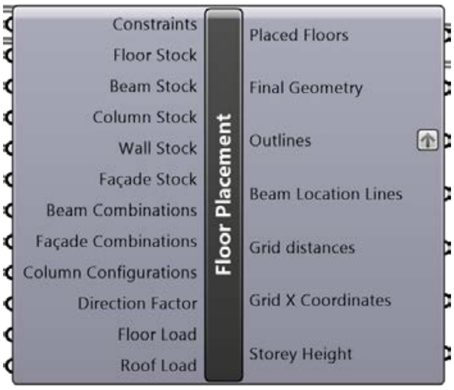


Figure 53. ‘Floor Placement’ component.

The generation of the grid starts with the definition of a starting point. In the script, this point is chosen randomly somewhere on the plot outline. It is an option to let the user pick this starting point, which allows for more influence on the design. Next, the grid is created, the grid generation starts with the creation of a list of placeable grid lengths. This list is based on the floors in the element stock and in which ratio they are present. After the list with all lengths is created, the list is randomized. For the placement of the first grid cell, the first length of the list is taken and a cell with this dimension is created. This is repeated for the other grid cells while looping through the list. This creates a semi random grid cell placement, a more structured method of defining the grid distances can be developed with a specific algorithm.

The Direction Factor is defined by a 3D Point, where each coordinate equals a direction factor. The factor multiplies the x, y, and z distance of the grid cells to the starting point. The higher the factor in a certain direction, the less prone the script will be to place floors in that direction.

Every time the script runs, n * m floor placement options are generated. In the current script, n is equal to the maximum story height defined by the constraints, and m is equal to 5. For n times, the number of floors considered is alternated between 1 and n. These values could be adjusted to explore more design options, but they are kept quite low to reduce calculation time.

A multi-criteria analysis is used to assign a score to each generated result. The analyzed criteria are adherence to the area requirement and the volume-envelope ratio. For each result, the difference between the area requirement and realized area, and the ratio between the volume of the building and the façade surface is calculated. These numbers are normalized and placed on a scale from 0 and 100. For each result these scores are summed up and the score is reduced with a reduction value if the expected element usage does not match the stock. The floor configuration with the highest score is selected as the output. In the current script, the reduction value is set at 10 because this value will have a significant impact on a score between 0 and 200. This reduction value and the rest of the scoring system have not been analyzed thoroughly. A study on this subject might improve the results given as output from this component. It is an option to provide the user with influence on which features are more important in the scoring system.

5.2.4 Design of floorplans

The floor plans are generated with the help of a Grasshopper plugin called Magnetizing Floor Plan Generator [44]. The outlines of the placed floor slabs, together with the desired rooms and corresponding areas, are input for the component. The output consists of a set of surfaces, one for each placed room. The floor plan generation itself is not part of the scope of this project and is merely used to easily run and test the rest of the script without manually creating floor plans. The floor plan generator components do not work perfectly; for example, it cannot design multiple stories simultaneously. However, in this research, the components give a fast method to work through the complete design process. It is recommended that the method is improved or a better approach is created for future use in practice.

5.2.5 Floor plan to structure

The component that takes care of the placement of the beams, columns, and facades is visible in Figure 54. The script can be found in script booklet B.6. The inputs of the component are all results from the previous components. Therefore, the user can not influence the outcome of this component.

Figure 54. 'Floor Plan to Structure' component.

Geometrical Lines define the locations where the beams and façades need to be placed. It is tried to find the combination of beams or façades which match the line as closely as possible. In the software science environment, this problem is called the Subset Sum Problem (SSP). This problem often arises in practical applications, for example, when a truck must be loaded as full as possible without exceeding a weight limit. The solution to this problem is discussed in the next subchapter. In the current script, the combination closest to the goal length is chosen to be placed. It could be an option to add more criteria, such as the number of beams, and use a multiple criteria analysis to find the best solution.

The outputs of this component can be used to visualize the designed structure in Rhino. They could also be imported into a CAE environment for thorough structural analysis; however, it is important to understand the output of this component and the inner workings of the CAE tool to ensure the results are correct. Furthermore, a connection to a BIM environment could be made.

Subset sum problem

The goal of this subset sum problem is to find the combination of lengths (beam and façade elements in element stock) closest to the goal length (location line on which elements need to be placed). The simplest solution is an iterative solution; it contains a generic algorithm that creates every possible combination. This approach results in 2^n possible combinations, resulting in an exponentially increasing calculation time for each extra length in the set. This is not a problem for small element stocks; however, when the amount of placeable elements grows, the calculation time increases in like manner. The calculation time can be reduced by developing a specific algorithm for the situation. The resulting algorithm is shown as a flowchart in Appendix A.9.5. A piece of code was written which performs this algorithm. In this code, recursive functions were used. Recursive functions are pieces of a script that call themselves within their own code. This allows for the generation of many combinations without a huge number of lines of code. Two cases are used to demonstrate the difference between the iterative method and the recursive method. The situations are described below, and the test results are shown in Table 9.

- Case 1

  Goal length = 175

  Set = { 9, 17, 17, 22, 43, 75, 77, 102, 138, 184, 184 }
- Case 2

  Goal length = 3000

  Set = { 6, 15, 36, 58, 79, 90, 103, 167, 375, 457, 743, 903, 1034, 2634, 3742 }

Table 9. Subset sum results comparison.

	Iteration method	Recursion method
Case 1		
Best 5 found subsets	17, 17, 22, 43, 77, sum = 176 9, 22, 43, 102, sum = 176 75, 102, sum = 177 17, 22, 138, sum = 177 9, 17, 75, 77, sum = 178	102, 43, 22, 9, sum = 176 77, 43, 22, 17, 17, sum = 176 138, 22, 17, sum = 177 102, 75, sum = 177 77, 75, 17, 9, sum = 178
Average elapsed time	163.3 ms	20.3 ms
Case 2		
Best 5 found subsets	36, 58, 79, 90, 103, 2634, sum = 3000 15, 36, 58, 90, 167, 2634, sum = 3000 6, 90, 103, 167, 2634, sum = 3000 6, 58, 167, 375, 457, 903, 1034, sum = 3000 6, 36, 79, 103, 167, 375, 457, 743, 1034, sum = 3000	2634, 167, 103, 90, 6, sum = 3000 2634, 167, 90, 58, 36, 15, sum = 3000 2634, 103, 90, 79, 58, 36, sum = 3000 1034, 903, 457, 375, 167, 58, 6, sum = 3000 1034, 743, 457, 375, 167, 103, 79, 36, 6, sum = 3000
Average elapsed time	10845.6 ms	99 ms

From the two examples, it is clear that the recursive code performs significantly better than the iterative code in terms of calculation time when the lengths set becomes bigger. Additionally, the results from the recursive method are the same as the best results from the iterative method, which is the desired outcome.

However, even with the recursive method, keeping the goal length and set size as small as possible is still important. When the combination count becomes too large, a computer does not have enough memory to continue the execution of the script, which results in an error.

6 Study case and model validation

A case study is done to show the results that the script produces and to validate the script. The same design brief was used as in Chapter 3 - Analysis of the design process. The plan of requirements and the element stock can be found in Appendix A.1 and Appendix A.4. The inputs and outputs of the components are discussed below.

6.1 Design generation

The design process starts with defining the constraints, as shown in Figure 55. The 'Rotate' component allows the user to place the grid in another direction on the plot.

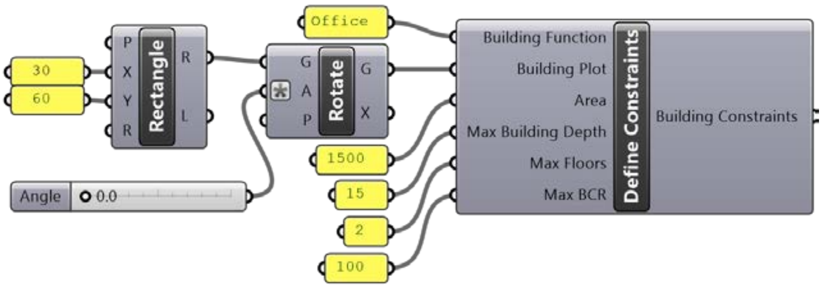


Figure 55. Input constraints.

In the 'Floor Placement' component, the user can influence the design with the Direction Factor, which is visible in Figure 56.

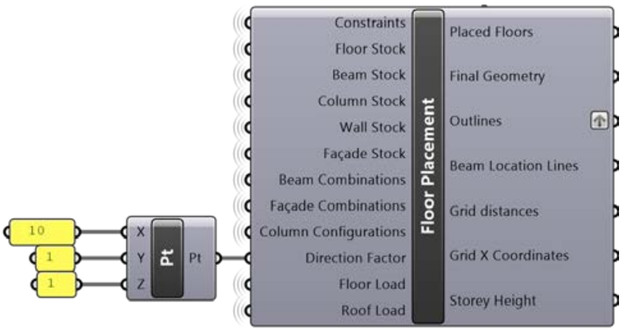


Figure 56. 'Floor Placement' with Direction Factor.

Both Figure 57 and Figure 58 have a Direction Factor of (10, 1, 1), which results in a favor for placing floors in the Y and Z directions. The plot is rotated 90 degrees in Figure 58. Figure 59 shows a result with the same rotation as Figure 58 but with a Direction Factor of (1, 1, 1). With this Direction Factor, the shape of the building will be more irregular.

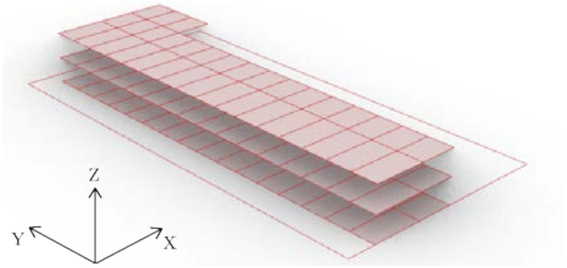


Figure 57. Floor configuration 1.

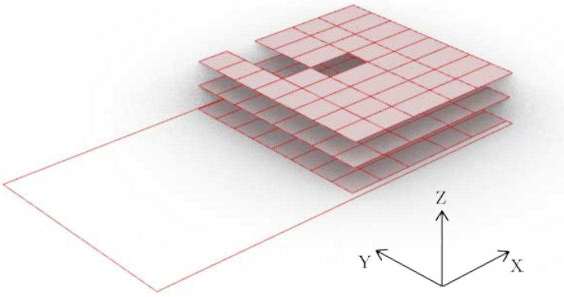


Figure 58. Floor configuration 2.

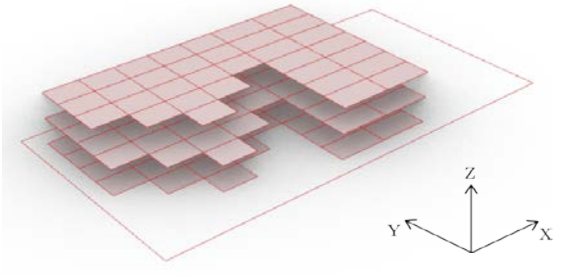


Figure 59. Floor configuration 3.

The ‘Floor Placement’ component was run multiple times until the configuration, as shown in Figure 60, was found. This configuration was chosen to perform the rest of the design process because of the simple shape, which would make floor plan generation easier. The floor plan area is 1483 m^2, 17 m^2 below the desired area.

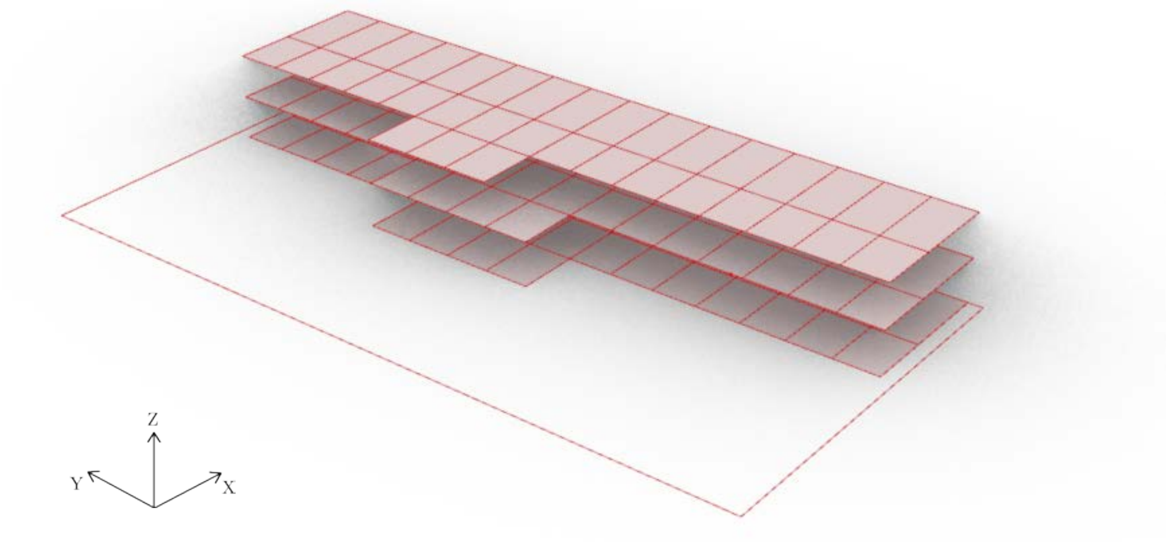


Figure 60. Chosen floor configuration.

Onto this floor configuration, the floor plans are generated, and all necessary information is put into the ‘Floor Plan to Structure’ component. The figures below show the placed beams, columns, floors, and the general shape of the building.

Figure 61. Placed beams and columns.

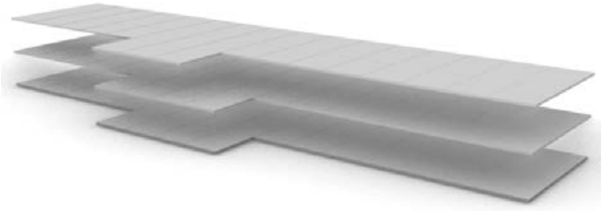


Figure 62. Placed floors.

In total, 321 floors, 31 beams, 27 columns, and 67 façade elements were placed. Which approximately results in a total of 1038025 kg of concrete. This value is determined based on façades without openings and rectangular beams; therefore, there will be some overestimation.

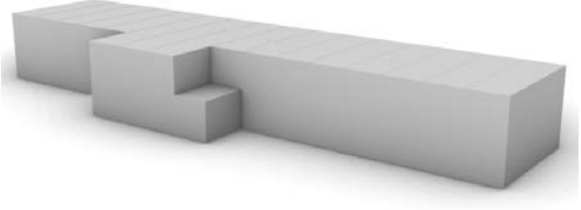


Figure 63. Building shape.

The figure below shows the daylight requirement of the generated floor plans together with the daylight properties of the placed façades. Yellow means little to no daylight, orange means medium daylight and red is a high daylight requirement. The dark blue parts are new façade elements. From the pictures, it can be concluded that the placed façades match quite well with the daylight requirements.

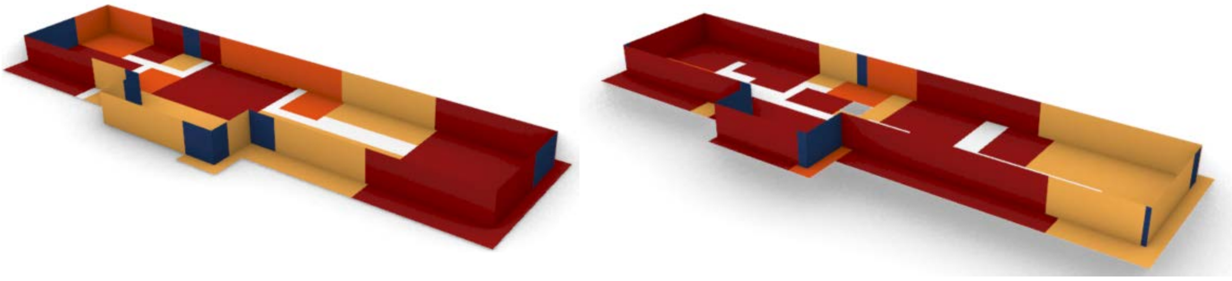


Figure 64. Façade and floor plan daylight requirements for the ground floor (left) and the first floor (right).

In Figure 64, it can be seen that 16 new façades (shown in dark blue) were used, which cover 44 meters of the complete façade distance. Therefore, the reused façade length is equal to 85.3% of the total perimeter. Figure 65 shows the presence of new elements for the beams, columns, and floors. The green elements are reused, and the red elements are new. For the columns and slabs, 100% of the elements are reused. Five new elements have been used for the beams, which have a total length of 14.50 meters. This is equal to 89.7% of reused beam length.

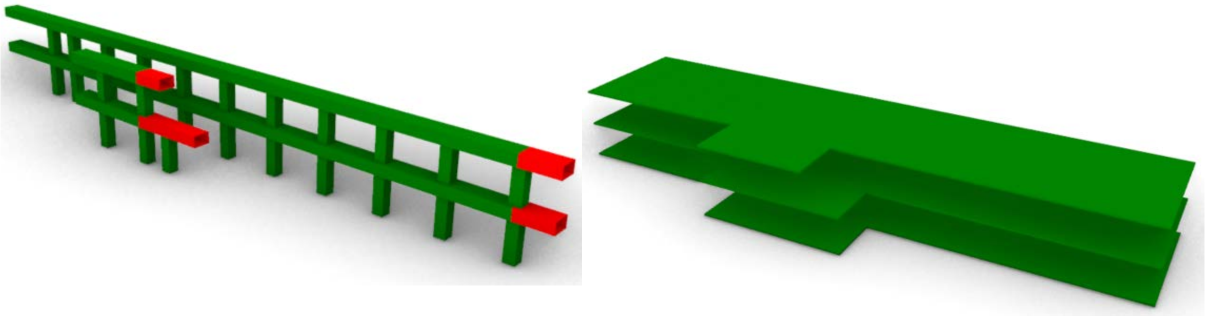


Figure 65. New and reused elements.

Table 10 shows the average calculation time for each component in this study case. This shows that the complete design process can take place in 20.17 seconds.

Table 10. Calculation times of the components.

Component	Calculation time
Define Constraints	< 1ms
Load Building Stock	4.32s
Stock Calculation	44.6ms
Floor Placement	368.8ms
Generation of Floor Plans	15s
Floor Plan to Structure	432.2ms

6.2 Structural design verification

To verify if the generated design is structurally sound, a calculation by hand was performed.

The loads in the beams, columns, and façades, due to imposed loads, were calculated, for which the same calculations were used as in Section 3. A table with results can be found in Appendix A.7. The results show that all elements can withstand the imposed and dead loads on the structure.

A situation was found that was not considered in the 'Stock Calculation' component. This situation occurs at the location where the size of two stories is different, as shown in Figure 66. Here, a façade is supported in two points, on top of another façade and on top of a column. The façade will behave like a big beam. And the column will support the weight of seven floors, three beams, and two facades.

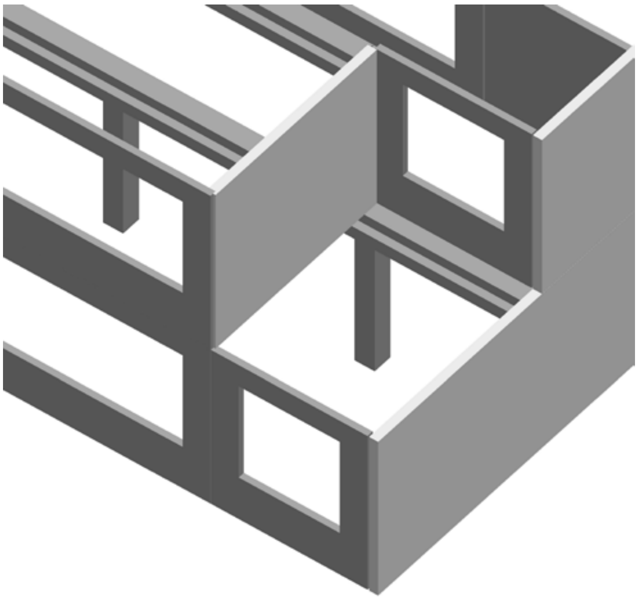


Figure 66. Unaccounted for situation.

Within this study case, this unaccounted-for situation does not cause problems because all columns have enough capacity. However, when more stories are added, or if the columns have less strength, problems might arise. Therefore, in all similar situations a new column will be placed. The strength of the column can then be adapted to the specific situation. Another problem arises when there are multiple consecutive façades without support. Here, extra columns, or a supporting beam, or wall, should be added manually.

Apart from the situation mentioned above, all element configurations are considered in the calculation component. Most elements in this study case have a great overcapacity. Therefore, the study case was performed again with an additional set of elements with lower strengths. This confirmed that elements will not be placed if they will not suffice the unity check.

In terms of functionality, the script can be executed in a short amount of time, and the facades are matched very well to the daylight requirements of the floor plans. Additionally, the placed floor plan area is close to the desired floor plan area, and the use of new elements is limited.

7 Discussion

The project aims to ease the architectural and structural design process of buildings with reused precast concrete elements and to optimize the use of reused elements in these buildings. The developed algorithm and corresponding Grasshopper components show that a building can be designed quickly with a limited number of new elements. However, a scope was embedded for the project's feasibility. This chapter discusses the consequences of this scope and what steps will be needed to create an all-encompassing solution.

This discussion is divided into two parts. The first part concerns the general subject of this thesis: the design process and the reuse of precast concrete elements. The second part discusses specifically the inner workings of the scripted components.

7.1 General

The algorithm is specifically made for an element stock of a load-bearing façade system. This excludes all other building systems. If other structural systems are to be included, the order of the general algorithm can stay the same. However, the selection of which elements to place and how they relate to each other will differ for each building system. For example, for a system in which internal walls stabilize the structure, beams would need to be placed instead of façades. Additionally, the placement of structural walls would have to be included, as the stability of this system is not automatically guaranteed. For the case of this project, it is assumed that the load-bearing façades stabilize the building, and further stabilizing measures are not needed. Therefore, they are not incorporated into the algorithm.

Furthermore, the geometrical properties that are included in the script are limited to a width, height, and length. This causes a limitation, for example for the placement of the façades in which the size and location of the windows cannot be taken into account. This might cause a problem when a beam is connected directly above a window.

The designed framework is not limited to reused precast concrete; it could apply to every structural system with a limited element stock. These situations will become more prevalent in the future due to more and more buildings being designed to be demountable.

7.2 The script

Multiple adaptation options can improve the results generated by the script.

Firstly, in the current script, the geometric compatibility of the elements is not considered. The only geometrical properties that are considered are the lengths of the beams, façades, and floors. It is assumed that all elements that are loaded into the building stock can be placed together in one structural system. This means that the user must make a correct selection of geometrically compatible elements before using the script. If this is not done, the resulting design might not be feasible for construction.

Secondly, regarding the 'Floor Placement' component, the multi-criteria analysis for floor placement has not been thoroughly tested. It is certain that positive properties are favored, and negative characteristics are disfavored. However, the exact influence of each criterion is unknown. Furthermore, it depends on the specific situation which criterion might be more important, therefore, it is not guaranteed that the best solution will be chosen.

Third, the ‘Floor Plan Design’ components are just used to run the rest of the script without the need for a floor plan design by hand. The floor plans that are created with these components are not useable in real situations.

Finally, in the ‘Floor Plan to Structure’ component, the subset sum problem solution works very well for placing the beams. However, the chosen combination is the one that comes closest to the goal length. There are no other criteria on which the choice is based, and there might be other subset combinations that better adhere to the floor plans. Additionally, at this moment, the subset combination lengths are made to exactly fit the length of the location line by replacing the smallest element in the subset combination with a new element with exactly the right length to create the goal length. This results in a new element in almost every combination, which would rather be avoided. Furthermore, the floor plans are designed before the structure placement component is executed so that they can be taken into account for the placement of the columns and the beams. At this moment, this is not incorporated into the code. This could result in columns placed at undesirable locations on the floor plan. Additionally, the columns are not placed in a specific order; this could result in sub-optimal use of the available element stock because columns with high strength might be placed in locations with relatively small loads. Later, no columns might be left in stock for a location with higher loads, and a stronger new column should be used, which could have been avoided.

The most important flaw in the script is mentioned in Chapter 6.2. An unaccounted-for structural configuration was found in the study case. This configuration occurs when two vertical stories do not have the same shape. This results in façades that are not located on top of another façade. Due to this flaw, a design that is not structurally sound might be generated. A ‘new’ column will always be used in this configuration to make sure the placed column is strong enough, and a manual check is needed to make sure the façades are correctly supported. However, in an ideal situation, the ‘Stock Calculation’ component and ‘Floor Plan to Structure’ Component will include this configuration so that the generated design is correct.

8 Conclusions

For this thesis, an algorithm and script implementation were developed to perform multiple steps of the design process with reused precast concrete elements. With the goal to ease the architectural and structural design process and to minimize the use of virgin materials. This was achieved by answering a set of sub-questions defined in Chapter 1.3. All in all, the combination of the knowledge acquired provides an answer to the main research question.

8.1 Sub-questions

Which precast structural concrete elements can be extracted from old buildings, and what are their relevant properties for a new design?
In this thesis, it was chosen to focus on a structural system consisting of hollow core floor slabs, inverted T-beams, square columns, and structural façades. This system is also used in the Prinsenhof A building, which is the pilot of the Recreate project. Additionally, much information on the system can be found in literature. In this system, the floors lay on top of the beams or are connected just below the top of the façades. The beams lay on top of columns, and in the case of multiple stories, the columns are placed vertically above each other with beams in between. The elements' length, width, and height are important for the shape and size of the building design. The strength properties, including shear strength, normal resistance, and moment resistance, determine in which configurations the elements can be used.

Which structural, architectural, and practical requirements are important to consider during a design process with (reused) precast concrete elements?
All elements used for the design should be geometrically compatible within the same structural system, and they should be placed according to this system. The structure should be strong enough and stable, and all desired functions should be included in the floor plan design. For a usable final design, it is critical that the designed structure does not interfere too much with the functional design of the building. Furthermore, the designer must have enough influence on the shape and size of the building for the architectural design.

What does a design process with a limited structural element stock look like, and what are the difficulties in this process?
A building can be designed using reused precast elements in multiple ways. A common method is to create the architectural and functional design first, and afterward, the right structural elements are found to fit within this design. Another option is to make the structural design first and later fit the architectural and functional design to the structure. The final method is creating the architectural, functional, and structural design simultaneously. In this thesis, the latter approach is chosen because only looking at an optimal structure creates an unusable building, and purely looking at functionality results in the unnecessary use of new elements and, thus, unnecessary environmental impact. The most difficult part of this design process is the element stock's influence on the functional and architectural design.

What algorithm can be created to encompass the above-mentioned design process, considering the before-mentioned requirements and minimization of material use?
An algorithm is created in which the elements are analyzed, the grid is generated, and the floors are placed. Next, the floor plans are created, and finally, the beams, columns, and façades

are placed. This design order allows for a compromise between useability and structural element use. The floor slabs are placed based on the requirements, and a pre-check is done to see if there are enough structural elements to place the rest of the structure. The floor plans should easily be fitted to the floor slabs due to the requirements that are met. The facades are placed based on the floor plans so that light requirements are met. Additionally, the placement of beams and columns could be based on the floor plans to prevent interference.

How can software be used to perform the above-mentioned algorithm?
A set of Grasshopper components was developed in Visual Studio. They each include a part of the algorithm. These components allow users with limited programming knowledge and Grasshopper to run the code and perform the algorithm. The users can influence the design process by adapting the inputs of the components, and extra components can easily be added to include more or different functions.

8.2 Main research question

How can the design process of buildings in The Netherlands, with reused precast concrete elements, be eased by digitalization?
An algorithm is constructed which addresses the difficulties in the design process with reused precast concrete elements. This is done by combining knowledge of precast concrete structures, the design process with a limited element stock, and algorithm-aided design. This algorithm, combined with knowledge about programming and digital design environments, is used to create a set of components for Grasshopper. These components use the calculation ability of a computer to perform the design algorithm. With the help of the components, a user can perform a complete design process in 20 seconds. Multiple design options are considered within the components, and one is chosen based on a multi-criteria analysis. The straightforward order of the design process in the components ensures that the designed structure is structurally viable and useable from a functional point of view. Additionally, the process is easy to understand, and calculation time is kept low compared to an iterative process. Improvements in the components could allow for even better integration between the structural and functional design and a more optimal use of the available element stock. The set of components can easily be adapted and expanded to include more structural systems, not only for reused concrete but also for other types of element stocks. A finished set of components can easily be distributed, so that everyone who has access to Rhinoceros and a bit of knowledge of Grasshopper can use them.

To conclude, the project has shown the potential to digitalize parts of the design process with reused precast concrete elements. With the help of a set of Grasshopper components, barriers to building with reused precast concrete elements can be removed. This is done by reducing the time spent on the process, simplifying the design process, and optimizing the use of the element stock.

9 Recommendations

This thesis provides the first steps in digitalizing the design process with reused precast concrete elements. More research, improvements, and additions are needed to create an all-encompassing digital tool that can be used in practice. Therefore, a set of recommendations is given. The recommendations are divided into two parts. The first part concerns the general subject of this thesis: the design process and the reuse of precast concrete elements. The second part gives recommendations specifically for the inner workings of the scripted components.

9.1 General

A couple of extra components could be added to expand and improve the functionality of the component package. The first addition is an option to incorporate more geometric properties via other import methods, such as an IFC import or the import of 3D Rhinoceros objects. Second, an extra component that checks the geometrical compatibility of the imported elements could be added, which makes a selection of elements based on the requirements. This ensures that the final design will always be feasible for construction. Third, a better method to create floor plans might be included. It could be a sensible idea to let the user design all rooms by hand first and let an algorithm place these rooms onto the floor slabs, as was done in the study case redesign by hand. Additionally, compatibility for more structural systems can be added, which includes adding structural walls and a thorough stability check. For example, a difference between two types of façades can be made in the element stock, stabilizing and non-stabilizing. At the end of the design process, it could be analyzed if there are enough structural façades to stabilize the building. This could be done by analyzing the orientation and location of the stabilizing elements in combination with the building outlines and comparing this to existing designs. If there are not enough stabilizing elements, an analysis would be needed, which determines where walls can and need to be placed to stabilize the structure.

Furthermore, it would be a useful addition to integrate the results from the 'Floor Plan to Structure' component in a CAE environment such as SCIA or Karamba. This needs to be done precisely because if the input is wrong, the results will be useless. The final step could be to export the results of the components, including connection details, into a BIM environment (E.g., Autodesk Revit).

9.2 The script

The following changes may improve the components that have already been created.

In the 'Floor Placement' component, the multi-criteria analysis can be investigated further so that the results become more reliable, and the user can be given more influence on each criterion's importance in this analysis.

In the 'Floor Plan to Structure' component, the placement of the beams and columns can be optimized to reduce the possible interference with the floor plans. The subset sum calculation determines which set of beams matches the goal line the best and selects this. This selection could also consider the number of beams in the set. The fewer beams, the fewer columns will be placed; therefore, the chance of interference with the floor plans is smaller. Additionally, the configuration in which beams are placed can be improved. The distance from columns to internal walls could be measured for each possible configuration to select the configuration with the closest distance to the internal walls. Furthermore, the use of new elements could be minimized in the ‘Floor Plan to Structure’ component. At this moment, the smallest element in the selected combination is replaced by a new element that exactly fits the remaining length. This new element use could be reduced by modifying the rest of the structure, adding a margin that can be solved with detailing, or adapting the length of one or more element(s). The use of elements can be optimized as well by placing the columns in a specific order; the columns that support the most floors and the biggest grid distances should be placed first.

Finally, the unaccounted-for configuration, as described in Chapter 6.2, must be incorporated into the script or its occurrence should be prevented. To prevent the situation, each story should have the same shape for this building system, which limits the number of design options. Incorporation in the script adds a great amount of complexity to the calculation of the stock and the placement of the elements. Therefore, it is recommended to keep the shape of the building equal through all stories.

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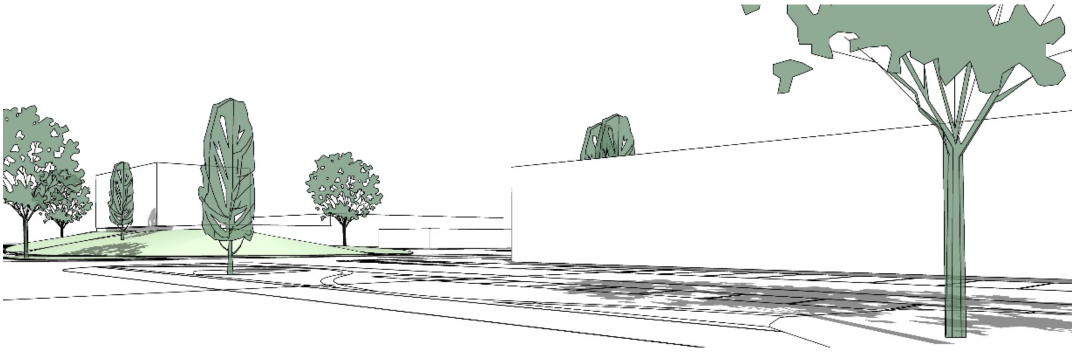
11 Appendices

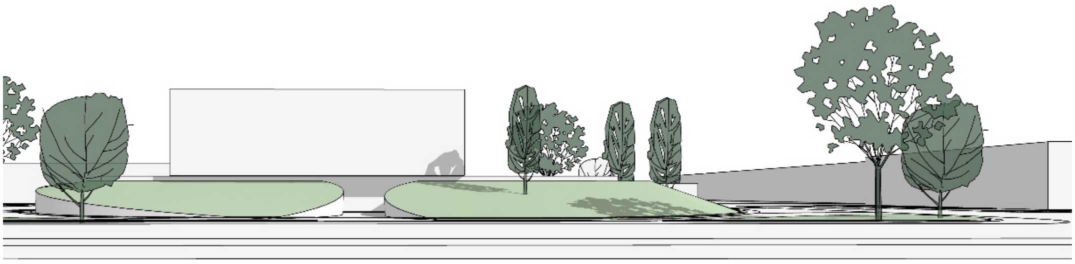
A.1. Table of requirements for office Van Berkel Group

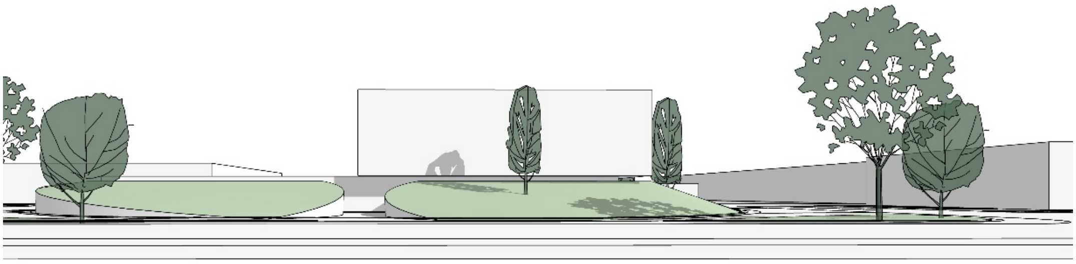
Name	**Amount**	**Notes**
Main entrance	1	Must be connected to planning counter.
Side entrance	1	Entrance to 24-hour zone.
Office 1 person with sofa	2	For managing board.
Office 2 people	1	For procurement administration
Office 3 people	2	Communication & ICT
Office 4 people	2	KAM & flex office audits
Office 5 people	3	HR, Financials, project administration
CAD-office 5 people	1	Business office
CAD-office 6 people	1	Executors
Office 6 people	1	Planning
Focus working space		
Meeting while standing spot close to office		
Open conversation rooms / place to call		
Meeting room 4 people	4	At least 1 on ground floor, spread over building, close to workplaces.
Meeting room 6 people	1	Ground floor, in and external meetings
Meeting room 8 people	1	Ground floor, in and external meetings
Meeting room 12 people	1	
Class/Instruction room	2	For 16-20 persons.
Presentation room	1	For > 20 persons.
Counter space employees and counter space weighbridge	1	Next to planning.
Canteen / Multifunctional room	1	35 sitting + 75 standing places, bar, planning board and mailboxes
Kitchen	1	Next to or part of canteen.
Multifunctional outside area: lunch, meeting, events	1	Next to canteen.
Pantry on each floor	1	
Staircase	1	
Emergency staircase	1	
Elevator	1	
Circulation space	1	
Toilets on each floor	1	For guests and visitors.
Toilet for disabled	1	At least 1 in the building.
Toilets for field staff	1	Ground floor.
Locker and dressing room	1	Big hand washing capacity, 50 lockers
Copy room on each floor	1	May be combined with plotting and repro.
Plotting room	1	
Repro room	1	
Server room	1	Above ground level.

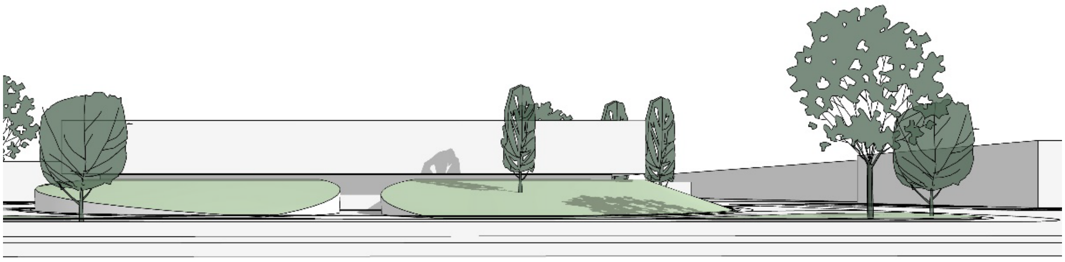
Technical room heating	1	
Technical room general	1	
Cleaning cupboard on each floor	1	
Storage cleaning agents	1	
Storage office supplies	1	
Storage marketing and communication	1	
Storage kitchen	1	
Archive room financials	1	
Archive room projects	1	

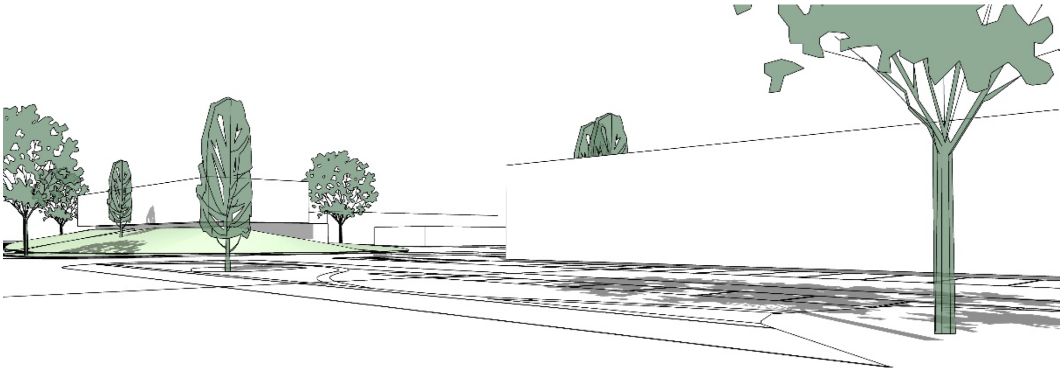
A.2. Mass study by BuroKade











A.3. Interviews with Ivo van den Thillart and Gijs Hoeijmans

Ivo van den Thillart, Architect, date

Could you describe your design process when you design with a limited element stock?

I work with the idea of a circular building box. The program is captivated in a building block which is as simple as possible. After an analysis which we have performed, it turned out that the complete building program of an office and a production location can be grasped within two grid sizes.

An important factor in our designs are the shearing layers of Stewart Brand, (figure added for reference). The outer shells have the lowest rate of change, which means that the structure of building is very important in its environmental influence. Therefore, the structure needs to be flexible because this allows adaptation to every possible function.

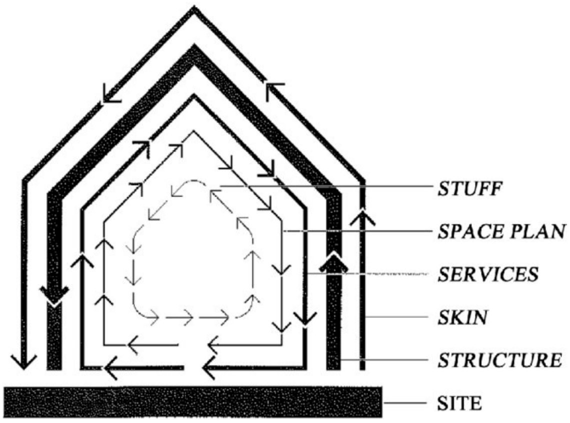


Figure 67. Shearing Layers of Stewart Brand [45]

We have tried to create a design with reused prefab concrete elements for the WeenerXL building. The original idea was to reuse floor slabs from a parking garage. These parking garages have a high rate of standardization due to the limitations of parked cars. The approach that was taken, was to start with a program of requirements, from here a grid size was chosen in which all room functions can be fitted. Sadly, the complete process was dependent on the dismantling and supply of the slabs, which took too long, therefore another structural material was chosen.

Multiple disciplines come together in one design, (i.e., architectonic/functional design, structural design, building physics, costs, and urban design.) Which one is the most important in this design process?

When we look back at the shearing layers of Stewart Brand, the structural design becomes very important in terms of environmental impact. We think it is important to not only look at the impact during the construction stage, but also during the lifetime of the building. Therefore, we favor the use of the “skeleton and infill” principle. This might cause the structure to be more expensive, but it allows the building to have a significantly longer lifetime due to a very flexible functional design. Due to the use of this skeleton structure, the structural design becomes more important in the architectural design. It might even become the most important discipline, or its at least determinative. The concept of form follows function becomes more important.

Which difficulties arise in the design process with a limited element stock?

For the functional design, it can be quite difficult that you are limited within a specific grid. This is especially the case if there is limited space or a more complex shape.

Gijs Hoeijmans, Architect, date

What was the first step in the design process of the office for the Van Berkel Group?

The start of the design process was driven by an invitation to tender. For the tender, a vision was created. An important wish from the client is equality between all employees, which also should be visible from the building. The connection from the office and the management board to the rest of the company is important.

Figure 68. Vision for office building by BuroKade

A vision was created in which the office lays in a rolling landscape like a villa. The ground floor lays partly underground as a concrete bunker. In the bunker storage and other facilities are placed, on the light side of the ground floor, working places are places. The entire first floor is used as social space in which the canteen and meeting areas are located. Also, an idea for the appearance of the building was created, a grid and floor plans were created within this appearance. This vision had been created based on the wishes of the client and is still a preliminary design. The vision as created for the tender is shown in Figure 68.

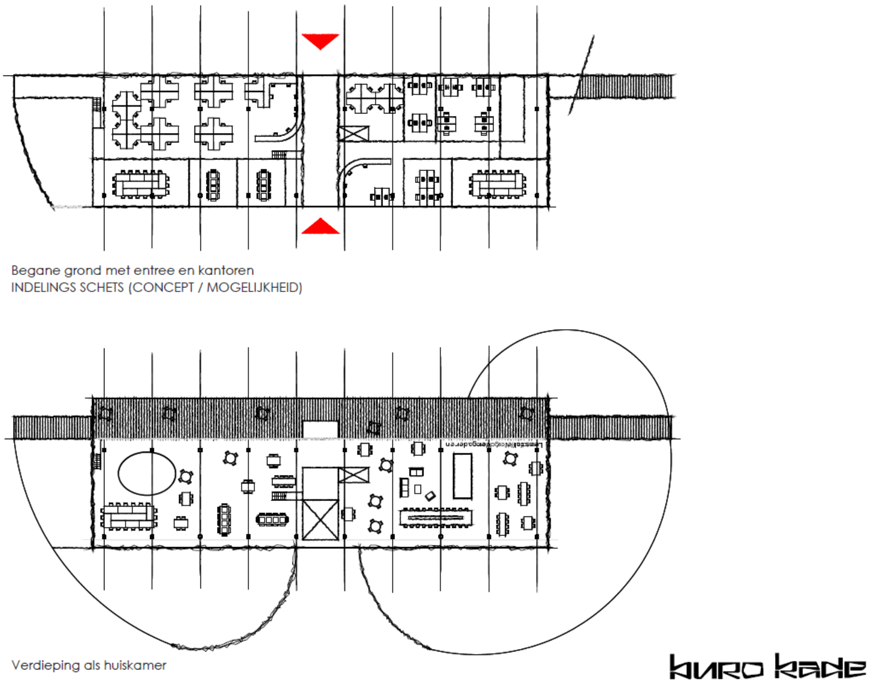


Figure 69. Preliminary floor plans

Based on this vision, BuroKade was rewarded the possibility to create the final design for the office.

How did the regular design process take place?

From here the design process started again, but with the vision as presented in the tender as a starting point.

The first step was to have a good conversation with the client about the requirements of the building. From here a plan of requirements is created for the rest of the design, which is shown in Figure 70.

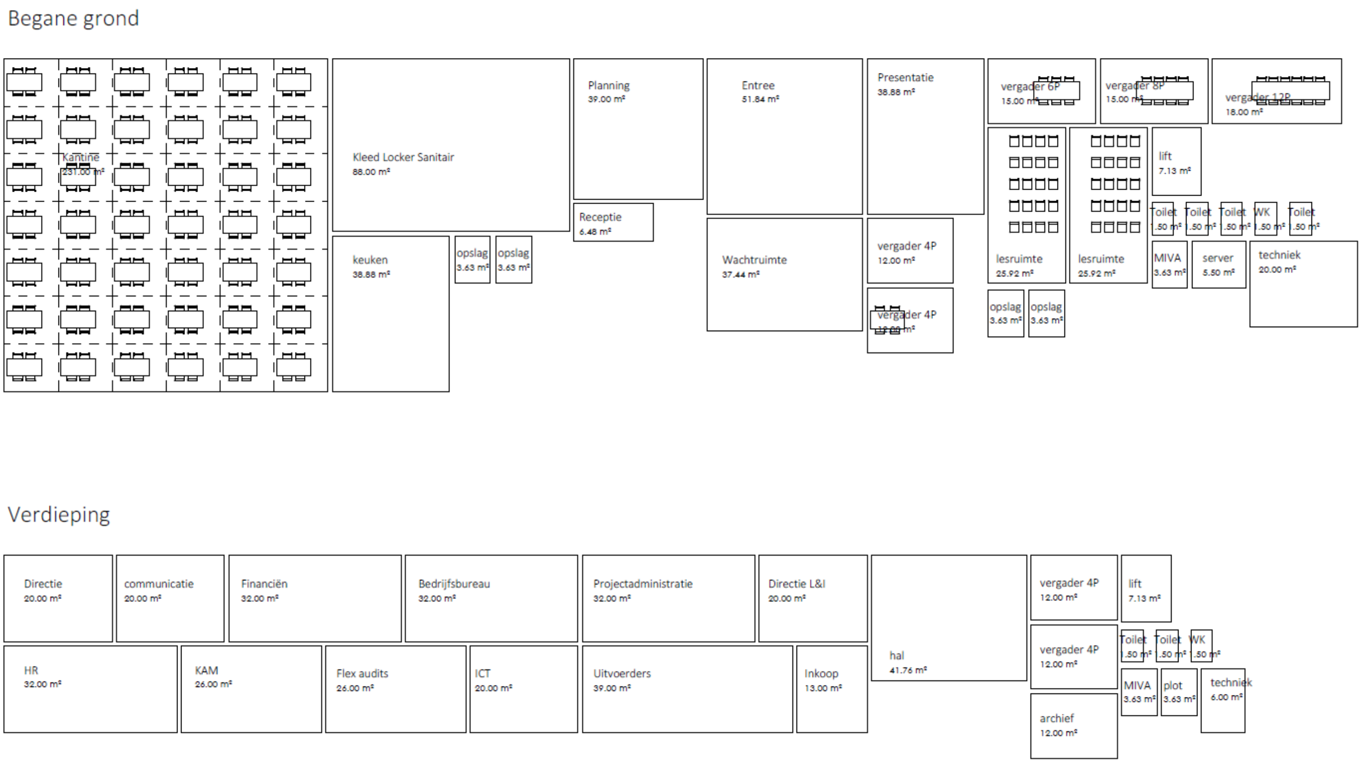


Figure 70. Visualized plan of requirements of the office for Van Berkel Group

With the plan of requirements in mind, the complete building, including floor plans and façades were designed.

Did you take the structural design into account in your architectural design?

During the design process the structure was considered in terms of a grid which was placed in the design on which the floor plans are created. However, the real structural design was created after the final design was finished. The structural design did cause some minor changes in this final design stage. Aside from those minor changes. the structure did not have a big impact on the final design. This is the case in most design processes, the architect does not like to change its architectural design in favor of a more logical or simpler structural design.

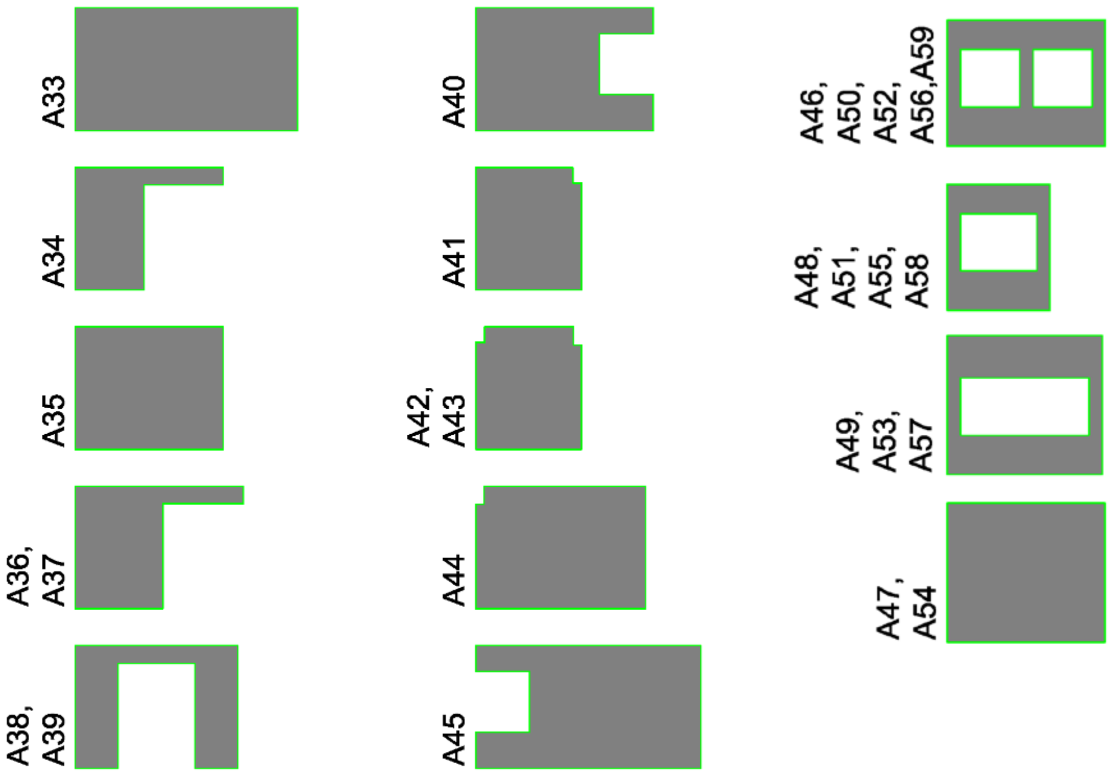
Figure 71. Final design render

A.4. Element stock for redesign

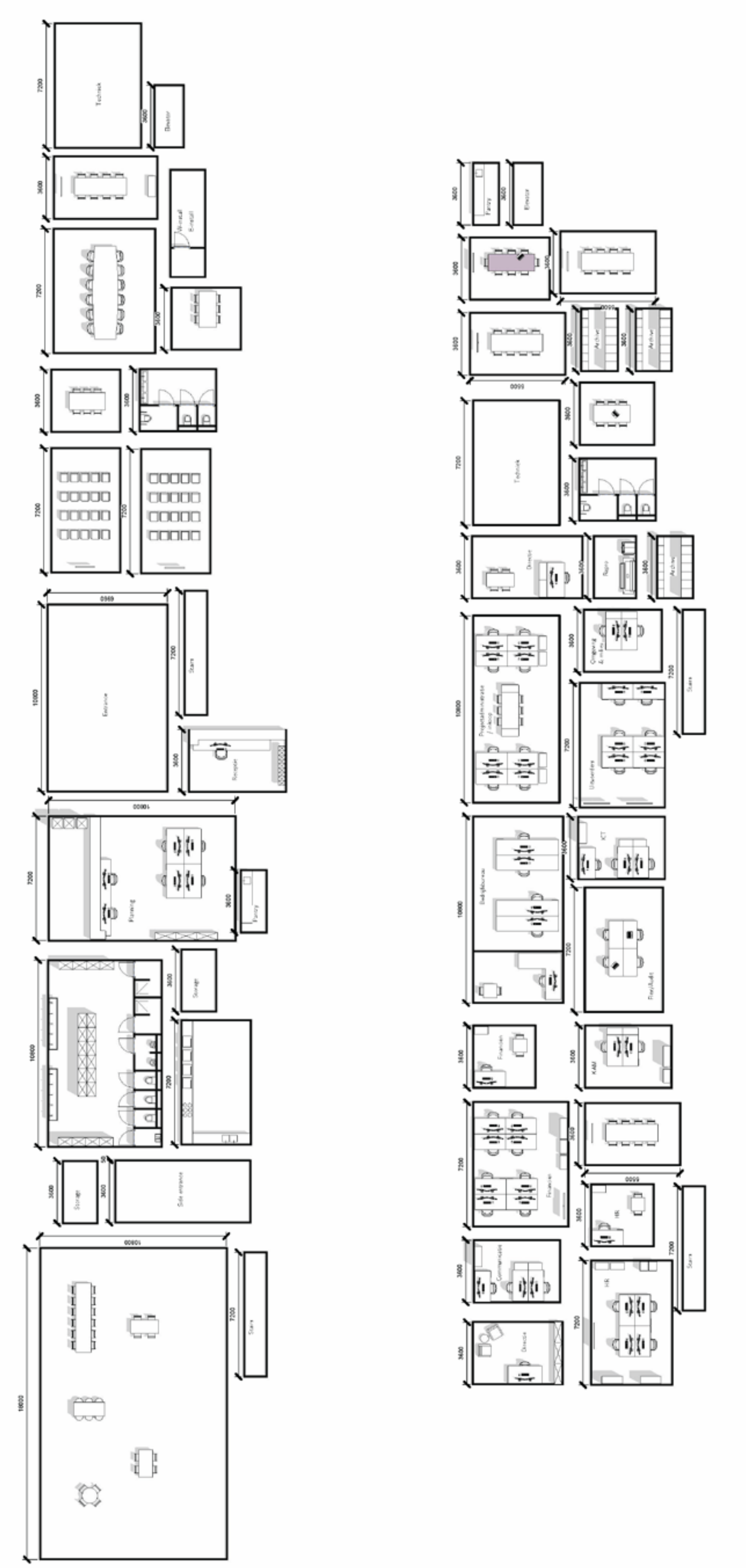
Nr	**Element**	**Quantity**	**L (mm)**	**H (mm)**	**W (mm)**	**Concrete**	**Steel**	**min. Mrd (kNm)**	**min. Vrd (kN)**	**min. Nrd (kN)**
1	Beam	20	4960	450	720	B60	Feb 500	189	282.2	-
2	Beam	4	3160	450	720	B60	Feb 500	189	282.2	-
3	Beam	4	5270	450	720	B60	Feb 500	189	282.2	-
4	Beam	4	5230	450	720	B60	Feb 500	189	282.2	-
5	Beam	4	6990	450	720	B60	Fep 1860	517.0	340.0	-
6	Beam	5	5380	450	720	B60	Feb 500	189	282.2	-
7	Beam	2	5480	450	720	B60	Feb 500	189	282.2	-
8	Beam	1	5170	450	720	B60	Feb 500	189	282.2	-
9	Beam	1	7100	450	720	B60	Feb 500	189	282.2	-
		45								
10	Column	38	400	2860	400	B45	Feb 500	-	-	2789.7
		72								
33	Wall	5	6180	3370	180	B45	Feb 500	-	-	5314.2
34	Wall	5	3490	3370	180	B45	Feb 500	-	-	2600.0
35	Wall	5	3460	3370	180	B45	Feb 500	-	-	4000.0
36	Wall	5	3930	3370	180	B45	Feb 500	-	-	2600.0
38	Wall	5	3800	3370	180	B45	Feb 500	-	-	2500.0
40	Wall	5	4160	3370	180	B45	Feb 500	-	-	2255.9
41	Wall	5	2480	3370	180	B45	Feb 500	-	-	4000.0
42	Wall	5	2480	3370	180	B45	Feb 500	-	-	4000.0
44	Wall	5	3980	3370	180	B45	Feb 500	-	-	4000.0
45	Wall	5	5270	3370	180	B45	Feb 500	-	-	2657.1
		50								
46	Façade element	20	4960	3370	130	B45	Feb 500	-	-	1100.0
47	Façade element	12	4960	3370	130	B45	Feb 500	-	-	1500.0
48	Façade element	16	4960	3370	130	B45	Feb 500	-	-	1000.0
49	Façade element	8	6760	3370	130	B45	Feb 500	-	-	800.0
50	Façade element	4	5540	3370	130	B45	Feb 500	-	-	1100.0
51	Façade element	4	5540	3370	130	B45	Feb 500	-	-	1000.0
52	Façade element	4	7336	3370	130	B45	Feb 500	-	-	1100.0

53	Façade element	4	7336	3370	130	B45	Feb 500	-	-	800.0
54	Façade element	4	2963	3370	130	B45	Feb 500	-	-	1500.0
55	Façade element	4	3090	3370	130	B45	Feb 500	-	-	1000.0
56	Façade element	4	6100	3370	130	B45	Feb 500	-	-	1100.0
57	Façade element	4	6980	3370	130	B45	Feb 500	-	-	800.0
58	Façade element	4	4290	3370	130	B45	Feb 500	-	-	1000.0
59	Façade element	2	5380	3370	130	B45	Feb 500	-	-	1100.0
		115								
79	H.C.S.	160	6960	200	1200	B60	-	39.90	14.70	-
80	H.C.S.	200	5000	200	1200	B60	-	39.90	14.70	-
		430								

A.5. Geometries of the walls and façade elements



A.6. Standardized room designs



A.7. Structural calculations of design by hand

Check 1: floors

Floor length	M_{ed} (kNm)	M_{rd} (kNm)	V_{ed} (kN)	V_{rd} (kN)
6960 mm	32.51	39.9	18.7	19.7

Floor 5000mm will have a lower moment, it has the same resistance, so no check is needed.

Check 2: beams

Beam	Floor A	Floor B	M_{ed} (kNm)	M_{rd} (kNm)	V_{ed} (kN)	V_{rd} (kN)
7100 mm	6960 mm	6960 mm	442.3	189	249.2	282.2
5480 mm			263.5	189		282.2
5380 mm			253.9	189		282.2
5270 mm			243.7	189		282.2
5230 mm			240	189		282.2
5170 mm			234.5	189		282.2
4960 mm			215.9	189		282.2
3160 mm			87.6	189		282.2
6990 mm			428.7	517	235.3	340
7100 mm	6960 mm	5000 mm	368.7	189		282.2
5480 mm			230.3	189		282.2
5380 mm			222.0	189		282.2
5270 mm			213.0	189		282.2
5230 mm			209.8	189		282.2
5170 mm			205.0	189		282.2
4960 mm			188.7	189		282.2
7100 mm	5000 mm	5000 mm	331.0	189		282.2
5480 mm			197.2	189		282.2
5380 mm			190.0	189		282.2
5270 mm			182.4	189		282.2

Check 3: columns

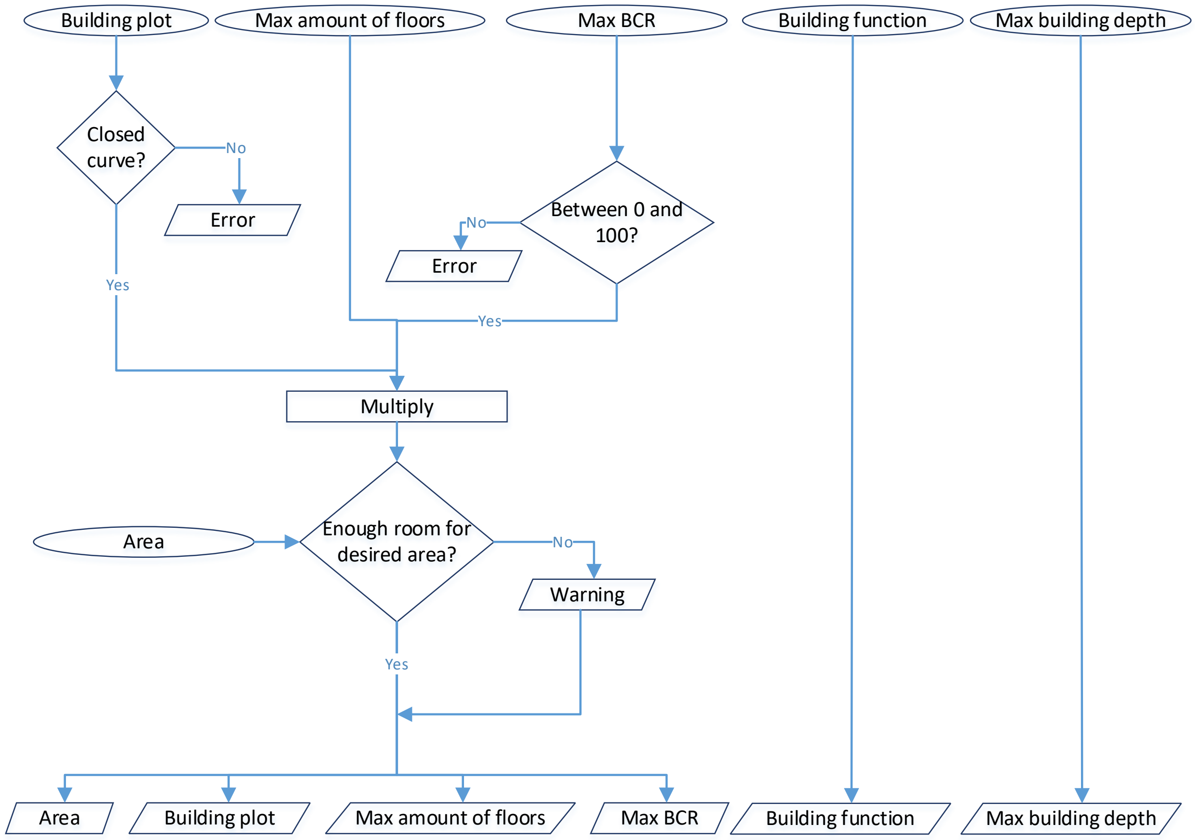
Column (mm)	Beam A (mm)	Beam B (mm)	Floor A (mm)	Floor B (mm)	$N_{ed\ roof}$ (kN)	$N_{ed\ floor}$ (kN)	N_{rd} (kN)	Max Floors
2860	6990	6990	6960	6960	685.97	1667.3	2789.7	2

A.8. Used elements from stock

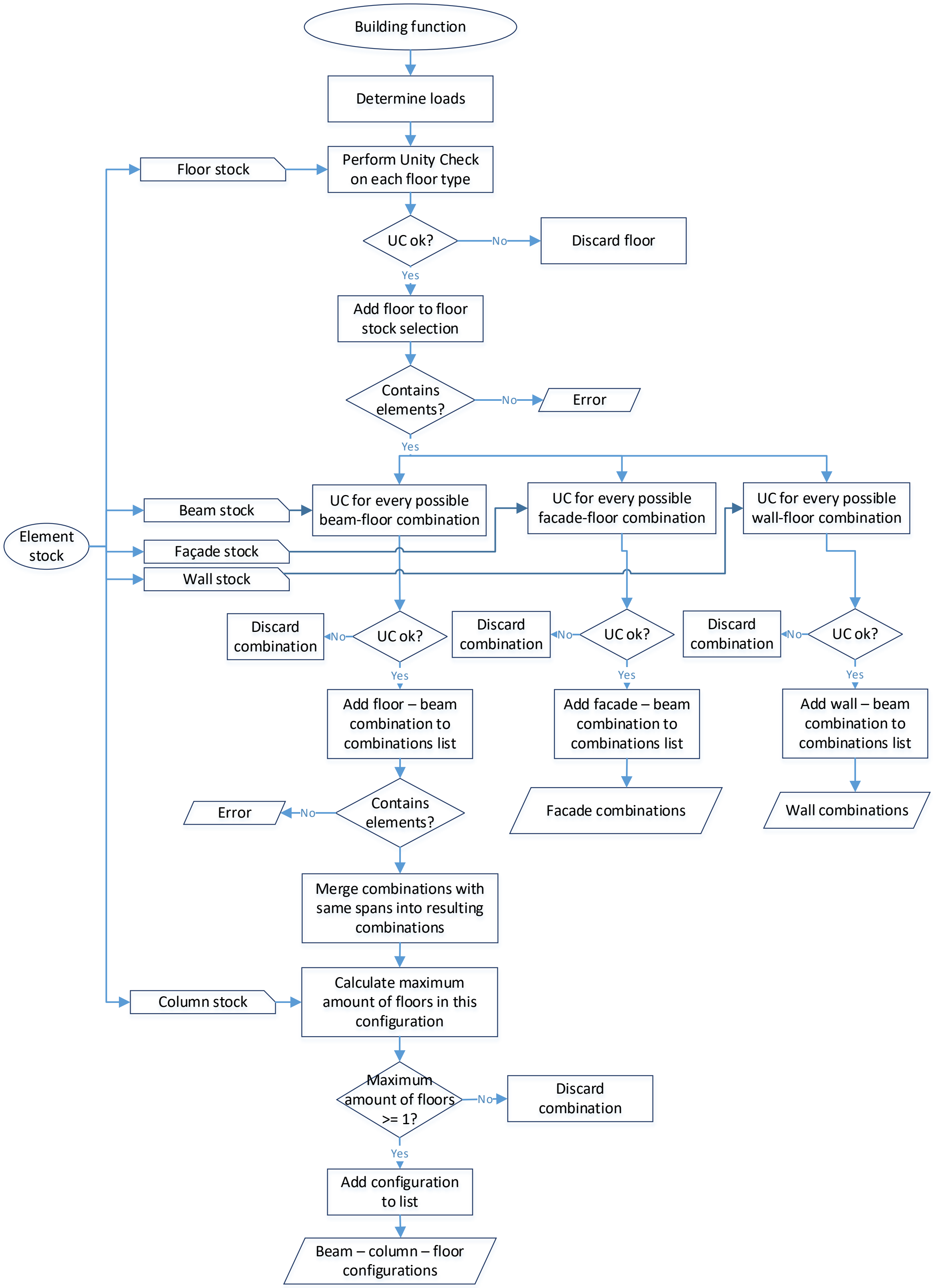
Stock nr.	**Element**	**Length**	**Amount**
79	HCS	6960	144
80	HCS	5000	150
1	Beam	4960	22
2	Beam	3160	2
46	Façade	4960	4
47	Façade	4960	7
48	Façade	4960	8
49	Façade	6760	4
50	Façade	5540	4
51	Façade	5540	2
52	Façade	7336	4
53	Façade	7336	4
54	Façade	2963	3
55	Façade	3090	4
57	Façade	6980	4
58	Façade	4290	3
59	Façade	5380	2
10	Column	2860	24
New	Wall	3434	1
New	Wall	3440	1
New	Wall	5224	2
New	Wall	5240	3
New	Wall	5250	1
New	Wall	5420	1
New	Wall	5620	1
New	Wall	5810	2

A.9. Algorithm flowcharts

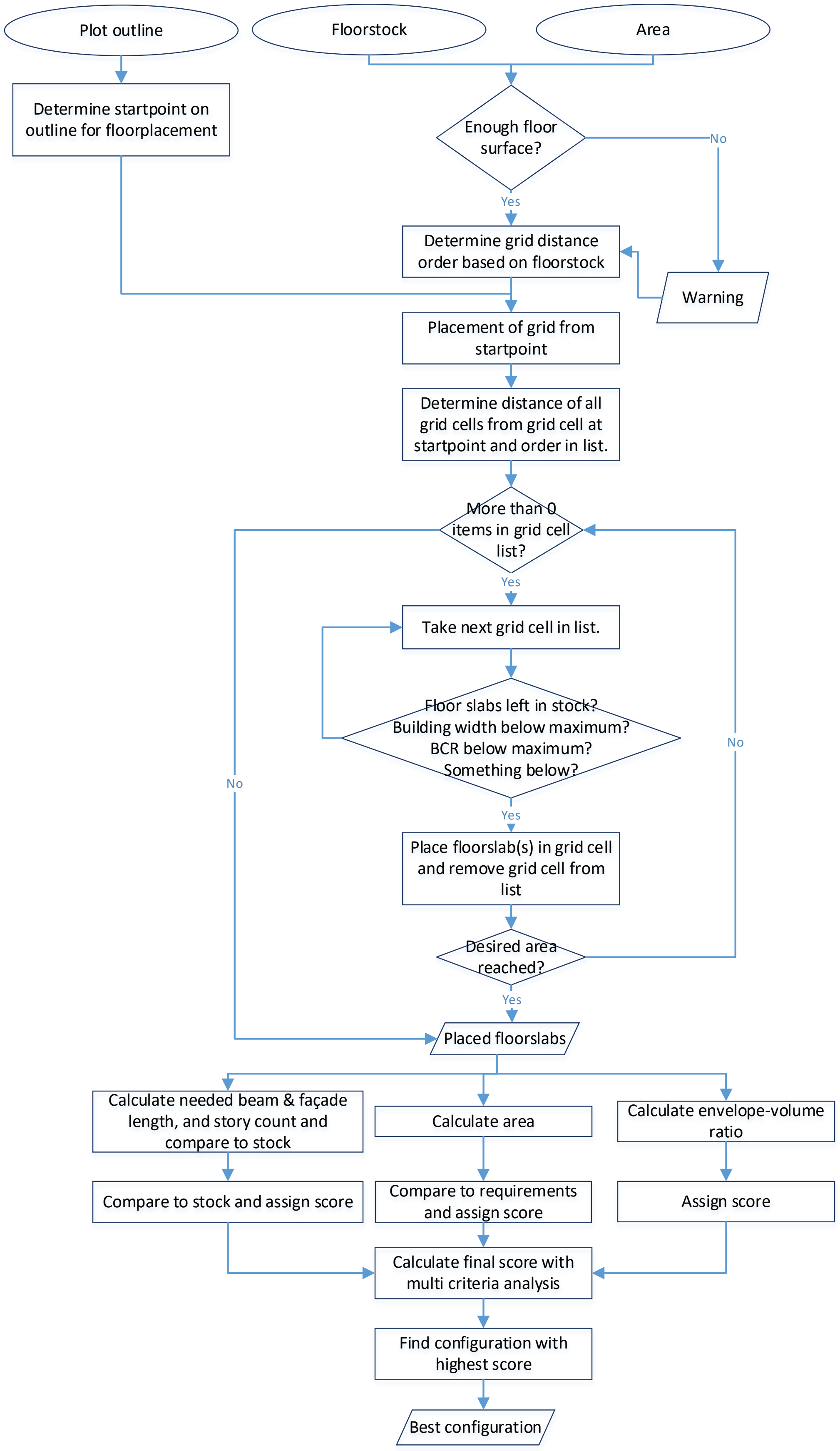
A.9.1. Requirements



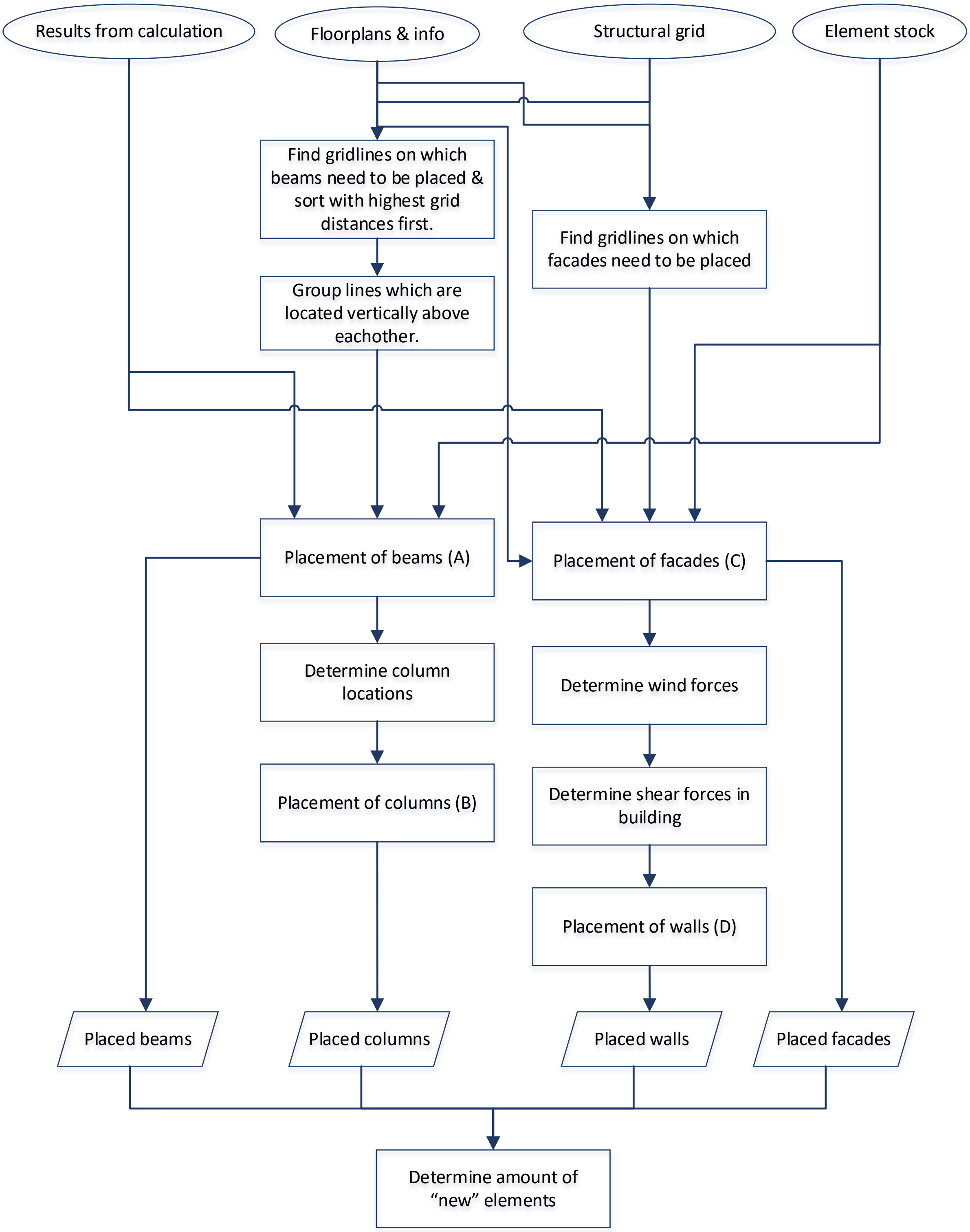
A.9.2. Stock calculation

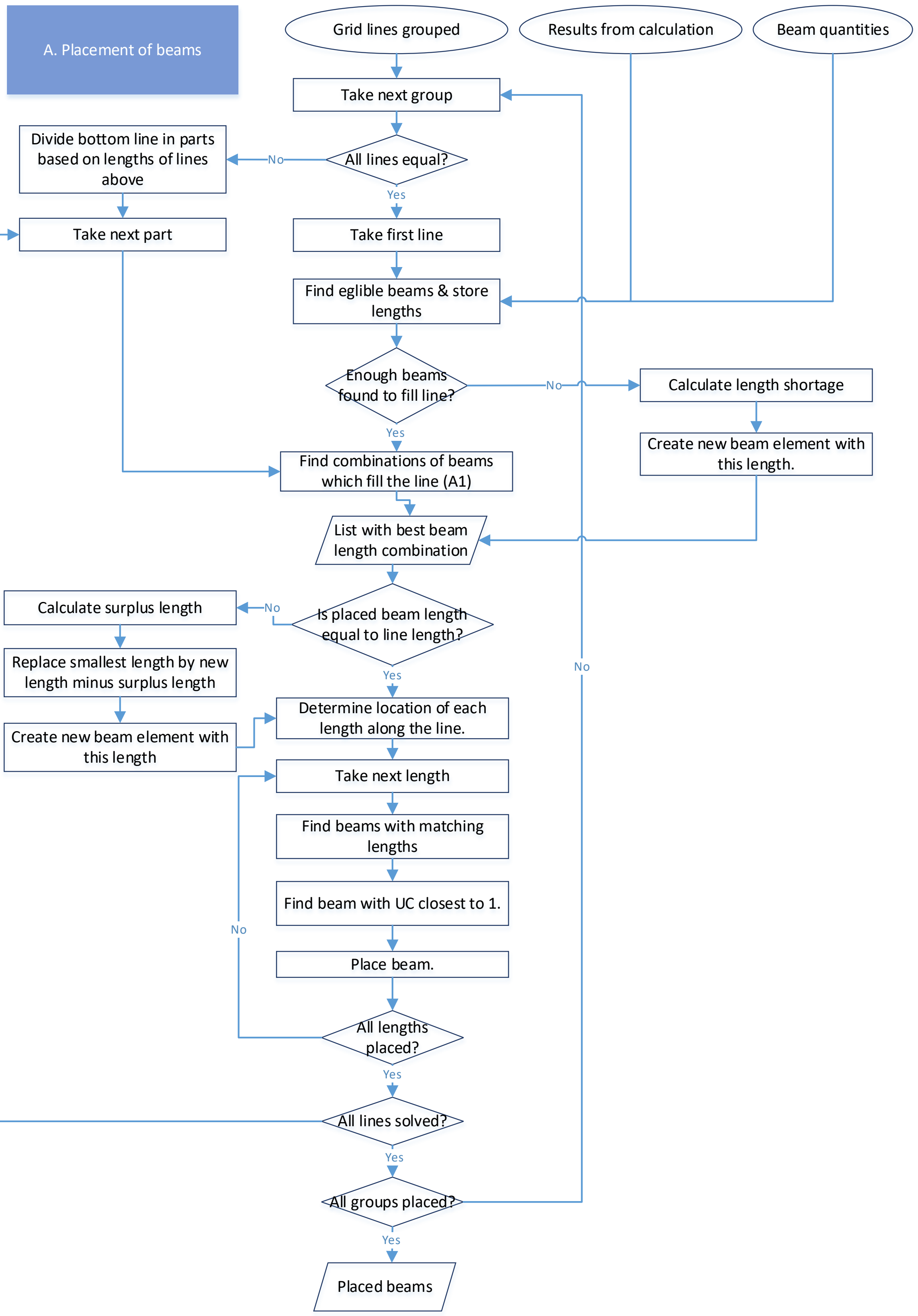


A.9.3. Grid generation and floor placement

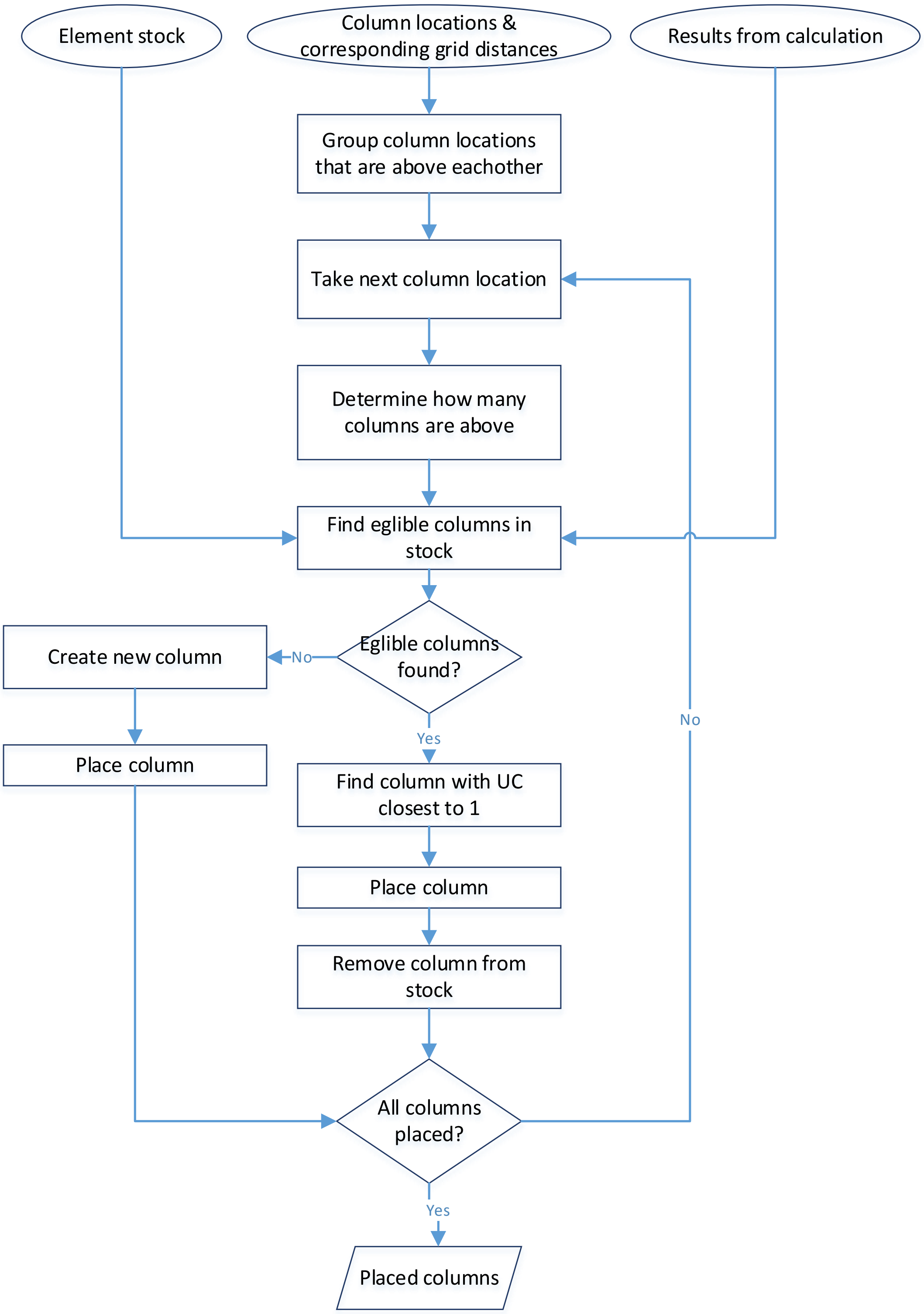


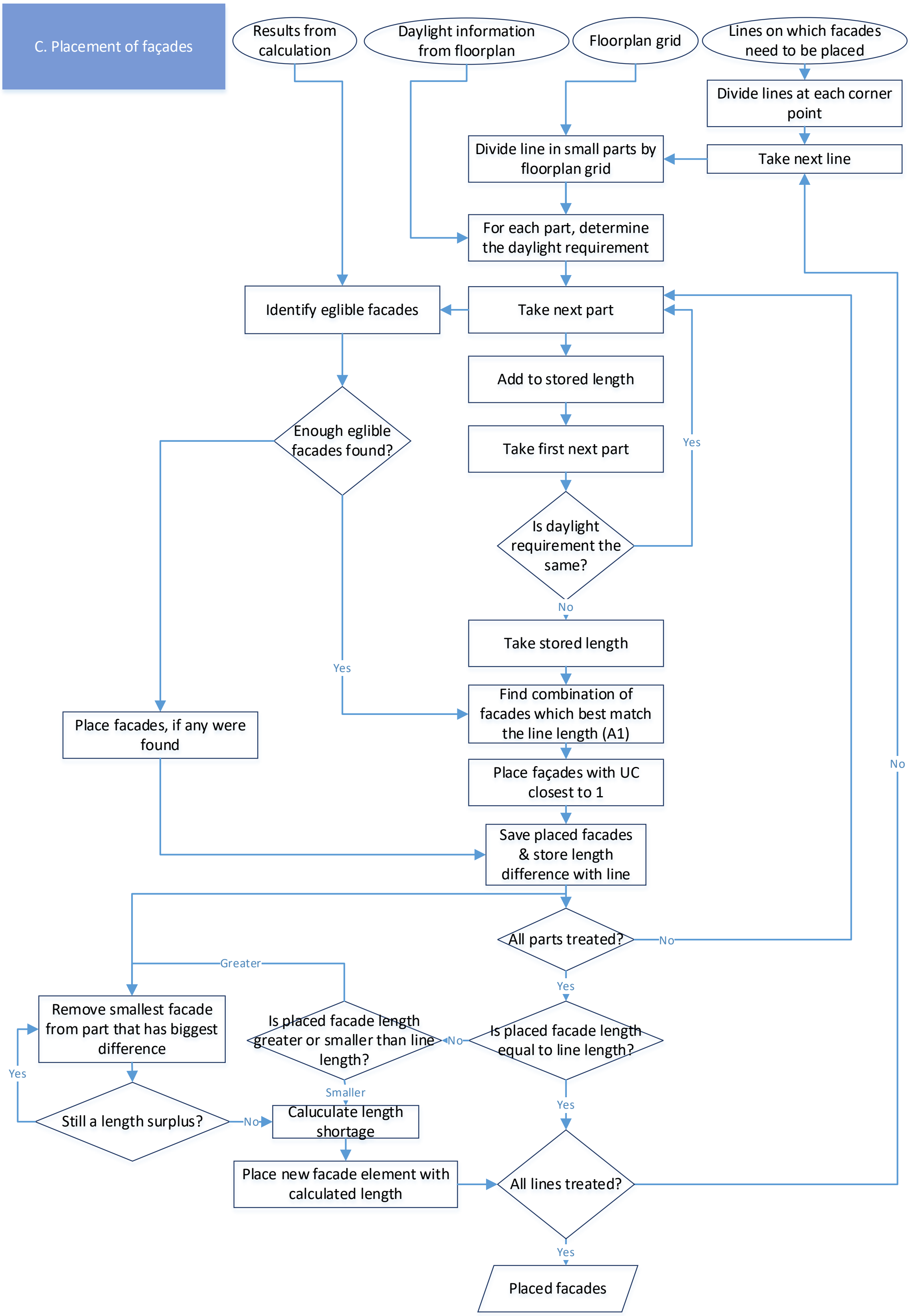
A.9.4. Placement of beams, columns, and façades



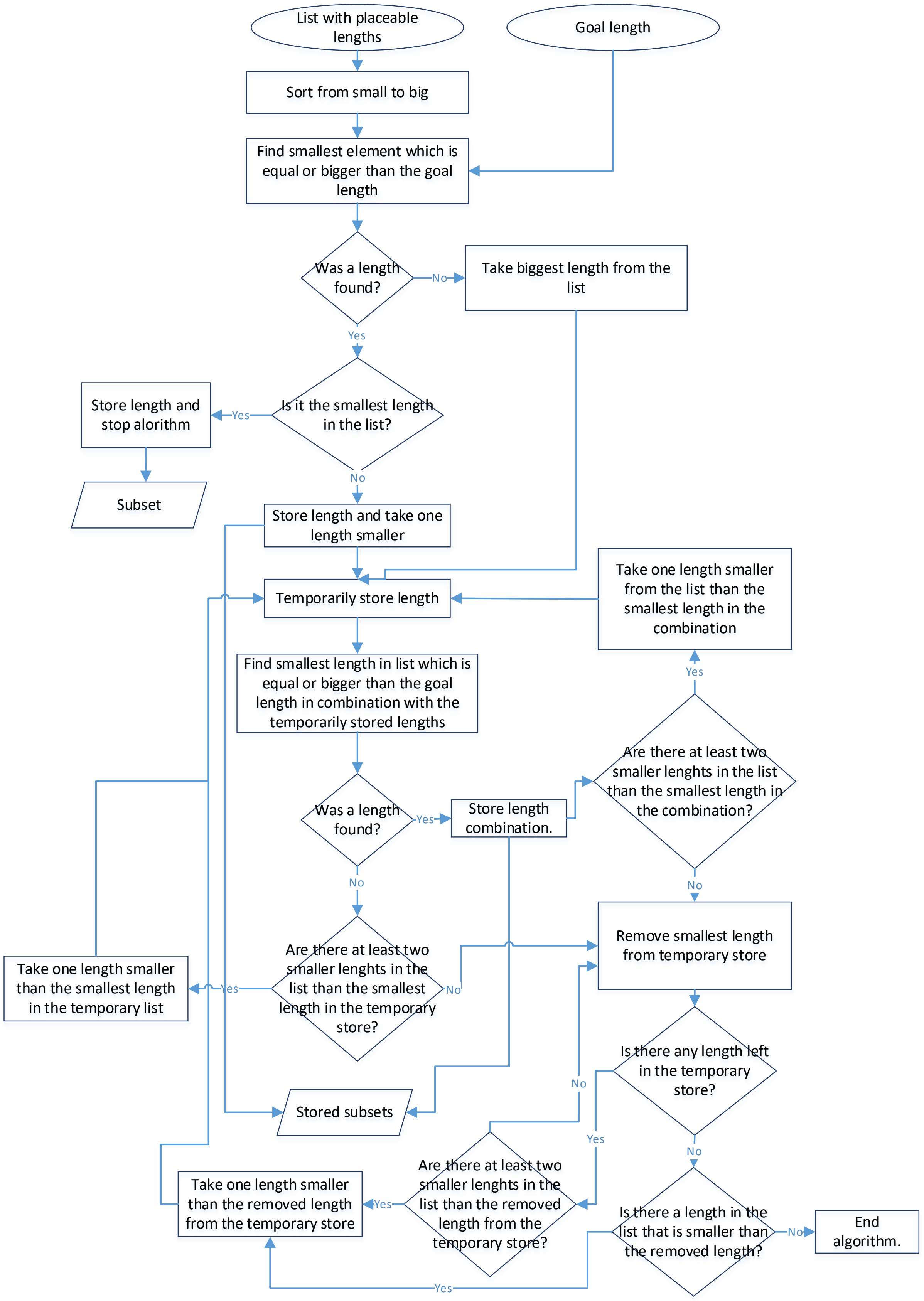

A. Placement of beams
Grid lines grouped
Results from calculation
Beam quantities
Take next group
All lines equal?
No
Yes
Divide bottom line in parts based on lengths of lines above
Take next part
Take first line
Find eglible beams & store lengths
Enough beams found to fill line?
No
Yes
Calculate length shortage
Create new beam element with this length.
Find combinations of beams which fill the line (A1)
List with best beam length combination
Is placed beam length equal to line length?
No
Yes
Calculate surplus length
Replace smallest length by new length minus surplus length
Create new beam element with this length
Determine location of each length along the line.
Take next length
Find beams with matching lengths
Find beam with UC closest to 1.
Place beam.
All lengths placed?
No
Yes
All lines solved?
No
Yes
All groups placed?
No
Yes
Placed beams

B. Placement of columns

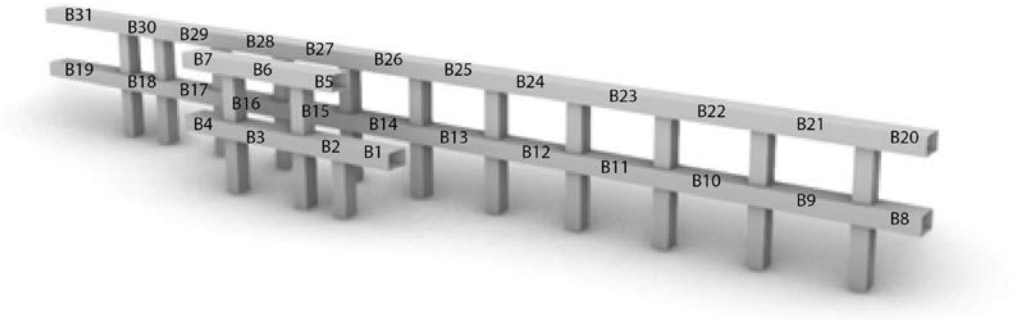



C. Placement of façades
Results from calculation
Daylight information from floorplan
Floorplan grid
Lines on which facades need to be placed
Divide lines at each corner point
Take next line
Divide line in small parts by floorplan grid
For each part, determine the daylight requirement
Identify eglible facades
Take next part
Add to stored length
Take first next part
Yes
Is daylight requirement the same?
No
Enough eglible facades found?
Take stored length
Yes
Find combination of facades which best match the line length (A1)
Place facades, if any were found
Place façades with UC closest to 1
No
Save placed facades & store length difference with line
All parts treated?
No
Greater
Yes
Remove smallest facade from part that has biggest difference
Is placed facade length greater or smaller than line length?
No
Is placed facade length equal to line length?
Yes
Smaller
Yes
Still a length surplus?
No
Caluculate length shortage
Place new facade element with calculated length
All lines treated?
Yes
Placed facades

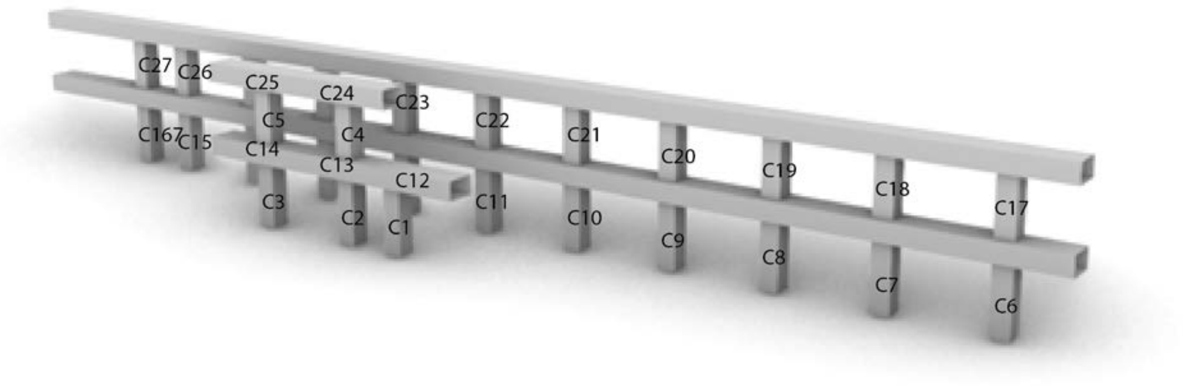
A.9.5. Subset sum problem



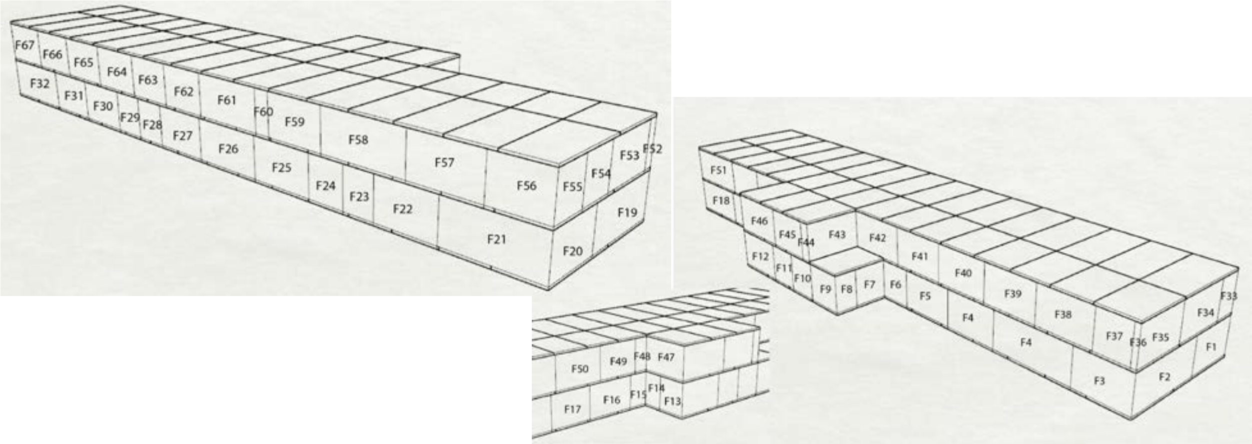
A.10. Structural verification of digital study case



Element	Length	Stock nr.	M_{ed} (kNm)	M_{rd} (kNm)	V_{ed} (kNm)	V_{rd} (kNm)
B1	3.6	New	62.5	-	63.4	-
B2	2.68	New	34.7	-	51.7	-
B3	4.96	1	118.7	189	95.8	282.2
B4	3.16	2	48.2	189	61.0	282.2
B5	2.68	New	31.6	-	47.2	-
B6	4.96	1	108.4	189	87.4	282.2
B7	3.16	2	44.0	189	55.7	282.2
B8	2.81	New	57.0	-	104.0	-
B9	4.96	1	177.6	189	143.2	282.2
B10	4.96	1	177.6	189	143.2	282.2
B11	4.96	1	177.6	189	143.2	282.2
B12	4.96	1	177.6	189	143.2	282.2
B13	4.96	1	177.6	189	143.2	282.2
B14	4.96	1	177.6	189	143.2	282.2
B15	4.96	1	177.6	189	143.2	282.2
B16	4.96	1	177.6	189	143.2	282.2
B17	4.96	1	177.6	189	143.2	282.2
B18	3.16	2	72.1	189	91.3	282.2
B19	6.99	5	352.8	517	201.9	340
B20	2.81	New	41.6	-	59.2	-
B21	4.96	1	129.6	189	104.5	282.2
B22	4.96	1	129.6	189	104.5	282.2
B23	4.96	1	129.6	189	104.5	282.2
B24	4.96	1	129.6	189	104.5	282.2
B25	4.96	1	129.6	189	104.5	282.2
B26	4.96	1	129.6	189	104.5	282.2
B27	4.96	1	129.6	189	104.5	282.2
B28	4.96	1	129.6	189	104.5	282.2
B29	4.96	1	129.6	189	104.5	282.2
B30	3.16	2	129.6	189	66.6	282.2
B31	6.99	5	257.5	517	147.3	340



Element	Stock nr.	N_{ed}	N_{rd}
C1	10	275.5	2789.7
C2	10	349.6	2789.7
C3	10	371.0	2789.7
C4	10	163.1	2789.7
C5	10	173.4	2789.7
C6	10	479.4	2789.7
C7	10	597.9	2789.7
C8	10	597.9	2789.7
C9	10	597.9	2789.7
C10	10	597.9	2789.7
C11	10	597.9	2789.7
C12	10	597.9	2789.7
C13	10	597.9	2789.7
C14	10	597.9	2789.7
C15	10	476.7	2789.7
C16	10	593.2	2789.7
C17	10	192.7	2789.7
C18	10	246.0	2789.7
C19	10	246.0	2789.7
C20	10	246.0	2789.7
C21	10	246.0	2789.7
C22	10	246.0	2789.7
C23	10	246.0	2789.7
C24	10	246.0	2789.7
C25	10	246.0	2789.7
C26	10	201.4	2789.7
C27	10	251.7	2789.7



Element	Length	Stock nr.	N_{ed}	N_{rd}
F1	4.62	New	48.3	-
F2	7.34	53	76.8	800
F3	4.96	48	235.1	1000
F4	7.34	53	347.8	800
F5	4.96	47	235.1	1500
F6	2.98	New	141.2	-
F7	2.96	54	0	1500
F8	2.04	New	0	-
F9	3.51	New	166.3	-
F10	2.96	54	140.3	1500
F11	2.96	54	140.3	1500
F12	4.96	47	235.1	1500
F13	2.96	54	31.0	1500
F14	2.04	New	21.3	-
F15	1.99	New	94.3	-
F16	4.96	47	235.1	1500
F17	4.29	58	203.3	1000
F18	6.76	49	320.4	800
F19	7.00	New	73.3	-
F20	4.96	46	51.9	1100
F21	7.34	52	539.2	1100
F22	4.96	48	364.3	1000
F23	2.59	New	190.2	-
F24	3.09	55	227.0	1000
F25	5.38	59	395.2	1100
F26	6.10	56	448.1	1100
F27	4.96	46	364.3	1100
F28	2.96	54	217.4	1500
F29	2.96	54	217.4	1500
F30	4.96	47	364.3	1500
F31	4.96	47	364.3	1500
F32	7.34	53	539.2	800
F33	2.04	New	0	-
F34	4.96	47	0	1500
F35	4.96	47	0	1500
F36	0.46	New	8.1	-
F37	2.96	54	52.2	1500
F38	4.96	47	87.4	1500
F39	4.96	47	87.4	1500
F40	4.96	48	87.4	1000
F41	4.96	48	87.4	1000
F42	5.54	51	97.6	1000
F43	5.00	New	0	-
F44	0.97	New	17.1	-
F45	4.29	58	75.6	1000
F46	5.54	51	97.6	1000
F47	5.00	New	0	-
F48	1.41	New	24.9	-
F49	4.29	58	75.6	1000
F50	4.96	48	87.4	1000
F51	7.34	53	129.4	800
F52	0.82	New	0	-
F53	4.96	48	0	1000
F54	3.09	55	0	1000
F55	3.09	55	0	1000
F56	4.29	58	105.3	1000
F57	5.54	51	135.9	1000
F58	6.98	57	171.3	800
F59	4.96	47	121.7	1500
F60	1.31	New	32.1	-
F61	6.10	56	149.7	1100
F62	4.29	58	105.3	1000
F63	4.29	58	105.3	1000
F64	4.96	47	121.7	1500
F65	4.96	47	121.7	1500
F66	4.96	47	121.7	1500
F67	4.96	47	121.7	1500