Compute - Demount - Adapt

Developing a computational workflow to aid in the design of adaptability with demountable components or oversizing.

Design for Change

Master thesis
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Summary

At the moment there is an increasing shortage of raw materials, which are needed to create new building components. The approach of a circular economy can be used to reduce the need for new materials. Many different methods are part of the circular economy, including design for adaptability and design for demountability. During this project interviews were held with architecture and structural design companies, to determine the approaches taken in practice. By doing these interviews, it was found that architects generally focus more on creating adaptability. Demountability is generally seen as a tool for adaptability and reuse of materials, instead of being seen as a goal.

During the interviews and literature review, many methods that are currently used to increase adaptability were determined, including oversizing elements and demountable connections. Oversizing elements does lead to an initial increase of material use, but removes the need to make changes to the structure during the building's lifespan. On the other hand, demountable connections don't increase the material use, but do lead to a need for changes being made to the structure. The method of scenario-based design can also be used to increase adaptability, by anticipating how the building could change to meet the user's needs over time. But this method is not often applied yet. Scenario-based design can be combined with a computation workflow, which makes it possible to easily test many scenarios.

There are still difficulties related to creating adaptable buildings. These include technical difficulties, for instance it's more difficult to reach technical requirements such as acoustic requirements and air tightness with adaptable buildings. But the main reason why there are still limited adaptable buildings being constructed is the higher construction costs of these buildings. For instance due to the higher material use of over-sizing or the demountable connection, which are more expensive than traditional connections. To lower the costs it is possible to only apply adaptability measures where they are needed.

During this project a computational workflow is created to determine where the measures are required, by applying scenarios to a preliminary design. The workflow can also be used to compare multiple grid-sizes, as span was determined to be an important aspect relating to both adaptability and material use. The workflow uses an optimization process to determine the minimal amount of changes that are required for the structure to adapt the initial design to the different scenarios. Another optimization approach was also used to determine the minimal mass of the structure, after the structure has been adapted. However, this second approach was unsuccessful.

The process that determines the minimal amount of changes results in the minimal amount of elements that need to be demountable or over-sized. The workflow creates a list of which elements need to be replaced with a larger cross-section for each of the scenarios. By combining these lists, all elements that might have to be replaced can be determined per design variant. The most suitable design variant depends on the method for creating adaptability in the design. If demountable connections are used, the design variant with the lowest initial mass and lowest amount of demountable elements is preferred. If over-sizing is used, the design variant with the lowest mass after over-sizing the structures is preferred.

A test-case is used to determine whether this approach is beneficial for material use of the structure. In this test-case, three structures are created for the same preliminary design. The first is based on a traditional structural design, the other two were created with the workflow by, one using demountable elements and the other using over-sizing. The structures are compared using life-cycles, one with anticipated scenarios, the other with

unanticipated scenarios. From this test-case it was found that the structures optimized bythe workflow can result in less material being used over the building's life span, if the scenarios are correctly anticipated. In case the scenarios from the workflow don't match with the scenarios that will actually take place, the structures from the workflow offer no benefit over the traditional structure. The functionality of the workflow therefore depends on the scenarios that are determined during the design process.

As the workflow can be used to decrease the material use of the structure, this can also lead to a decrease in costs. Furthermore, less demountable connections or over-sized elements are needed, when compared with current practice of creating adaptable buildings. The structure can therefore also be less expensive than it would currently be to create adaptable buildings. However, the workflow does increase the complexity of the structure, which can increase the costs. This is especially the case for the method of demountable connections. This method requires the elements to be replaceable without having to disassemble the rest of the structure. More research is required to create connections and a process capable of making these changes without much effort.

There are also still multiple ways in which the workflow can be expanded, for instance including more building systems and more scenario types. In combination withthis further research the workflow could be useful in practice to reduce material use. Especially, since this workflow brings separate approaches which are already used in practice together in one workflow.

Contents

1. Introduction

The current building industry is based on an unsustainable linear "take-make-dispose" idea. About 40 % of all raw material use and about 40 % of all waste generation is caused by the building industry (Askar, Bragança & Gervásio, 2022). In contrast with this, the concept of circular economy (CE) focuses on minimizing waste and promoting material reuse (Smitha & Thomas, 2021). Thereby the amount of "waste" can be used as new material for other buildings. Due to the material scarcity it becomes increasingly necessary to realize a building process that is circular.

There are many different aspects that can be connected to CE. Smitha and Thomas (2021) discuss an overview of many of these dimensions by categorizing them into eight aspects. One of the aspects they mention is "The 'R's of circularity". These 'R's refer to "Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover". This framework is an extension of the founding principle of CE, being just "Reduce, Reuse and Recycle".

To be able to achieve these goals Smitha and Thomas (2021) also mention CE strategies as another aspect. Among these strategies are Design for Disassembly (DfD), Design for Adaptability (DfA) and Design for Reuse (DfR). These strategies all focus on lengthening the lifespan of either components or buildings, thereby lowering their environmental impact.

These three strategies can be achieved by creating a demountable structure. This allows the building to be taken apart easier, components to be replaced or removed, and for the components to be put together again after the first use. Another method related to circular economy is the oversizing of elements, which focuses on design for adaptability. However, not a lot of buildings are built to be demountable or adaptable. Therefore, this research will focus on creating a computational workflow to aid the process of designing adaptable buildings, with demountable components or oversizing.

In this report the overall structure of the research will be presented first. This includes the problem statement, research structure and the methodology. These create an overview of the research approach taken during the project. In the methodology the different methods of research will be explained in more detail. This includes the approach used during the literature review, the semi-structured interviews as well as the development of the computational workflow.

After that, the results from the preliminary research will be reported. First the results from the literature will be discussed. Literature research has been done on the topics of demountable structures and scenario based design as well as the use of computational tools for the design of structures. Secondly, the results of the semi-structured interviews will be shared. An overview of the mentioned aspects relating to designing demountable buildings will be given.

Following the preliminary design stage, the results of the development stage will be shared. During this stage a computational workflow to better inform designers in relation to the adaptability of a design will be developed. First the general goal and how it would be used in the design process is described. Then the different steps in the workflow are explained in more detail.

Subsequently, the developed computational workflow is tested. The workflow is applied to a test case. The results of which are compared to a design of the same test case where the computational workflow is not applied.

Finally, the research question will be answered in the conclusion. Furthermore, the limitations of this research and recommendations for further research will be shared. This conclusion will also include a reflection on the research itself.

1.1 Problem statement

As mentioned, 40% of raw material is used by the construction sector. This material use goes hand in hand with CO_2 emissions, as a lot of energy is needed to manufacture new components. About 33% of greenhouse emissions are caused by the construction sector (Rahla, Mateus & Bragança, 2021).

As part of a circular economy, adaptability can be introduced to reduce the environmental impact of a building. By enabling a building to change according to changing needs, the lifespan of a building can be increased. This reduces the need for new materials and spreads the emissions of the material that is used over a longer time period.

Currently, adaptability is often created by oversizing components, as this allows for a larger force to be applied on the structure at a later moment. However, this also means that more material is being used in the present, even though we are already experiencing a material shortage. Therefore the focus should also be on designing a building that uses a minimal amount of material now, while still offering the possibility to be adapted other needs in the future.

In a demountable structure, components can be removed and replaced by stronger components, if the need arises. Therefore, demountable structures could be used to increase the adaptability of a building, while minimizing the material use of the initial design. However, rather than just enabling a structure to be disassembled, the structure needs to be designed in a way that these changes to the structure are easy to make.

Scenarios can be used to assess how adaptable a structure is. After applying possible future scenarios to a structure, the amount of changes that are required to adapt the structure can be determined. The number of required changes can be used to compare the different structures to each other.

A computational workflow could be used to aid in the process of designing an adaptable building, by being able to test many possible future scenarios with relative ease. Furthermore it can be used to simultaneously assess different design options, and compare the results.

The main research question of this project is thus: **"How can a computational workflow be used to increase the amount of adaptability in the design of a building's structure, while minimizing material use?"**. In order to answer this question several sub-questions have been formulated.

1. *"How are buildings currently being designed to be demountable and adaptable?"*

The goal is to find out the strategies that are being applied, as well as the difficulties that are still present in the design process. This creates a base knowledge to work from, as well as creating a better understanding of what is needed to improve the design process.

2. *"How are computational tools currently used to design reconfigurable structures?"*

Similar to the first sub-question, the findings to this question should create a base knowledge. By understanding how computational tools currently function, this can be used as inspiration to create a computational workflow.

3. *"How can a computational workflow be designed to increase the adaptability of a design?"*

This question will be the focus of this research project and is therefore further separated into steps. These steps relate to how to minimize material use, how to apply multiple scenarios, how to create multiple design options and finally how to evaluate these design options on adaptability and material use.

4. *"How can a computational workflow be used to inform the design process? "*

Having a computational workflow does not guarantee adaptability. This question focuses on the different ways in which a computational workflow could be used and which decisions it might provide information for.

5. *"How can the functionality of a computational workflow be evaluated?"*

As the final part of the research it is important to be able to justify the result from the computational workflow. Therefore the developed workflow will be evaluated. The result of this evaluation should show the difference between a case where the offered solutions are and are not applied, thereby showing potential advantages and disadvantages.

1.2 Research structure

To answer the research questions multiple methods are used, which will be described with more detail in section 1.3. This section will give an overview of the research structure and how the different methods relate to the research questions and to each other. The project is separated into three broad phases, as can be seen in image 1 on the next page. These three phases are: research, development and testing. It is important to note that all of these activities will be present during each phase, the names of the phases relate to the main focus of each of the phases.

The project starts with the research phase. During this initial phase, the state of the art of both demountable buildings as well as relating computational design is reviewed. The two first sub-questions will be answered in this phase. This is done partly by doing a literature review on both topics. This will give insight into the newest developments in both areas as well as what aspects haven't been researched in full yet.

The other part of the research phases consists of having interviews with companies that have experience with designing demountable buildings. This will offer an opportunity to understand how theory relates to practice, and to what extent current developments are being applied. This also gives more insight into what challenges exist in practice, and what would be most helpful to increase the amount of demountable buildings being constructed.

This phase will also inform the direction of the next phase. It provides information about what could be improved in regards to demountable structures as well as what computational tools would be helpful.

The next phase is the development phase. During this phase the third and the fourth sub-question will be answered. The development of the computational workflow will be partly based on further literature review, as well as research by design. The literature review will lead to more information about the method for creating such a workflow. With research by design the actual workflow is created. This will follow an iterative process of development and testing of the workflow.

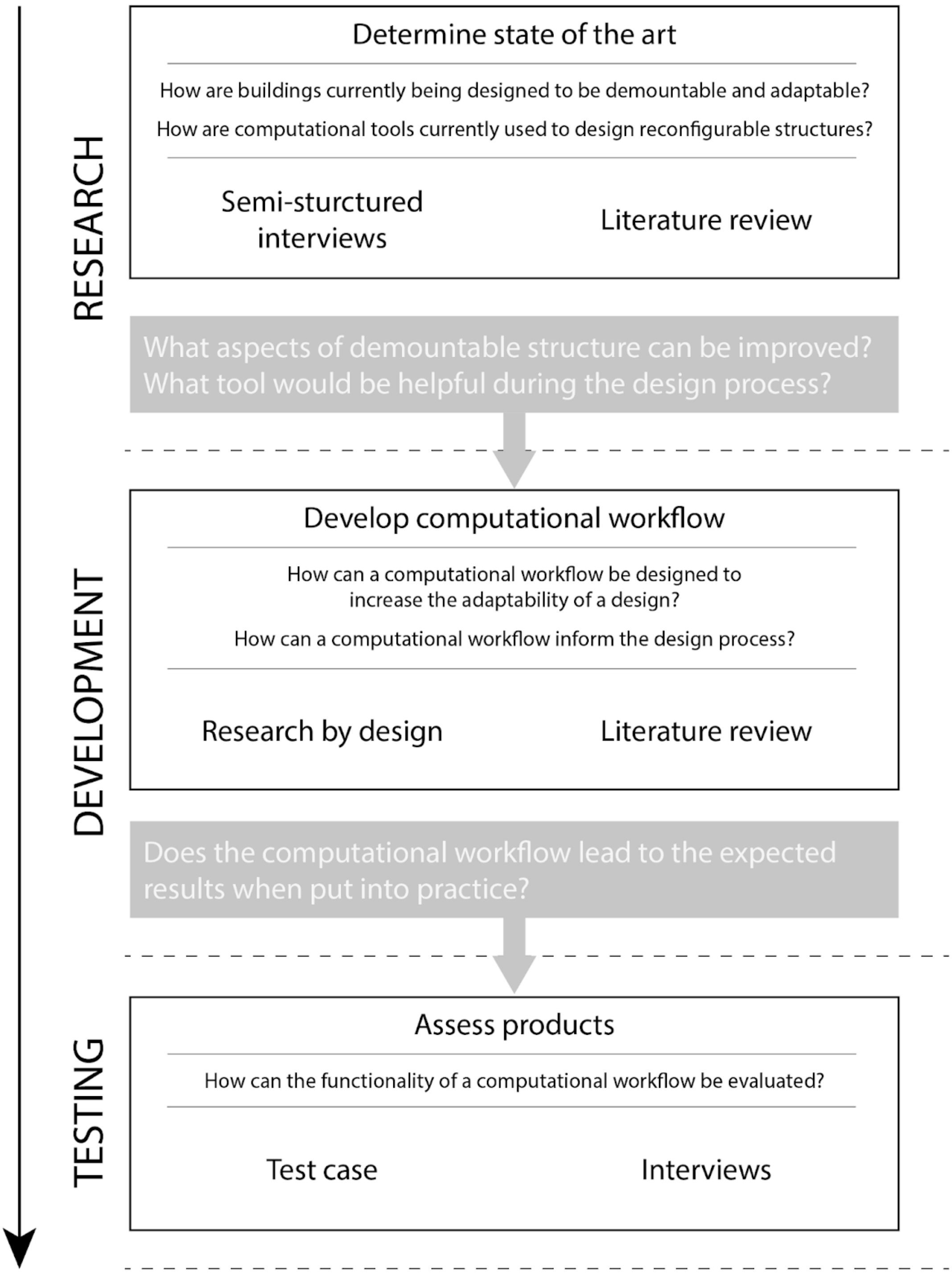


Image 1: Research structure (author)

During the last phase of the project, the last sub-question will be answered. This is the testing phase and will focus on evaluating the workflow that has been created during this project. This evaluation will partly be done with a test case. Due to this evaluation the products can be compared to the "current standard" of building. Therefore, it is possible to determine whether the workflow suggested during this research could be beneficial in designing demountable buildings or not. Furthermore, some additional interviews will be held, to determine whether this is a workflow that would be useful in practice as well.

1.3 Methodology

In this section the methods that are used during this project, as mentioned in the previous section, will be explained in more detail. The used methods can be divided into two groups. On the one hand methods are used to gather and analyze existing information, being a literature review and semi-structured interviews. On the other hand research by design is used to develop new products using the previously gathered information. The development of new products then leads to new insights.

1.3.1 Literature review

A literature review is conducted at the start of the research to create a base knowledge on the topic and to determine the current state of the art. For the literature review scientific papers are selected using the scopus database. Firstly, sets of keywords are created relating to the main questions of this research project. The results found with these keywords are first filtered to only find papers relating to the topic of engineering. Of the resulting papers the title and abstracts are scanned to determine whether these papers do indeed relate to the topic.

In some cases, if the found papers relate very well to the main topics and are very helpful in the research, connected papers are found by looking at the sources or by using the website connectedpapers.com (Connected Papers, z.d.). The suitability of these papers is then also checked by reading the title and abstract.

1.3.2 Semi-structured interviews

A set of semi-structured interviews is conducted to gain insight in some of the current practices in regard to designing demountable and adaptable buildings. Semi-structured interviews follow a set of predetermined questions, but also offer flexibility to veer off these questions to gain the required information. The list of standard questions used for these interviews can be found in Appendix A.

The selection of companies to contact depends on four aspects. Firstly, to allow for the possibility to conduct an in-person interview, only companies that are based in the Netherlands are selected. Furthermore, by limiting the research to one country the external factors, such as policies and demand for demountable products, will remain consistent. As a result, the research focuses on differences in method, such as chosen structural material, instead of location bound differences. Secondly, all companies have experience designing at least one demountable building. The companies are also selected to have experience with different structural materials and buildings systems, to get an overview of different methods. Furthermore, companies with different roles in the design process are selected, to gain a better understanding of the entire process.

In the end, ten companies are contacted to determine whether they would be willing to take part in this research. The six companies that responded positively include one structural engineering firm, one building system factory and four architectural firms.

Because of the small sample size, it is possible this does not accurately reflect the overall views from the building industry in regards to demountable buildings. Nevertheless, these interviews do offer an insight into methods that are currently being applied to design demountable buildings.

1.3.3 Research by design

The development of the computational workflow will be achieved by research by design. Through the act of developing or designing these products, knowledge is gathered. The information that is gathered about the design process can be used to design a similar type of product.

This research will follow an iterative process of design and testing phases. The design of the computational workflow will focus on programming, through the use of Grasshopper and Python. The product will be tested based on requirements set at the start of the process. This testing will focus on the functionality of separate parts of the workflow. Especially since the workflow will consist of multiple steps that will have to work together.

The design phase can follow different processes. It is possible to broaden the options by designing multiple variants and choosing one or multiple of these variants. But it is also possible to follow a linear process and work on just one design variant. The actual design process will probably consist of a mix of these processes, with phases where just one option is developed further, and phases where multiple options are considered simultaneously.

I Research Phase

2. Literature Review

During the literature review the research is divided into three main topics, being design for adaptability, scenario-based design and computational workflow for reconfiguring structures.

On the first topic a lot of information is already available, as the idea of creating demountable and adaptable buildings stems from the introduction of prefabrication methods (Ferreira Silva et al., 2020). Research has been done on how to make connections demountable and how to assess the demountability. However, for now this research will focus on the strategies that can be applied to create more adaptability and the current difficulties and opportunities in regards to demountable buildings.

Scenario-based design is a strategy that has been used in several engineering design fields, to better understand the performance of a design over time. However, this technique is not often applied in architecture yet (Eilouti, 2018).

The use of computational tools in designing is a more recent development in architecture (Cantrell & Mekies, 2018). Therefore, less research has been done on the creation of computational methods for reconfiguring structures. Nonetheless, there are some projects which can be used as reference for this research.

2.1 Design for adaptability

As mentioned, demountable buildings follow from the introduction of prefabricated processes in the 1800s. Originally, prefabrication was mainly applied for a quick assembly process. Nowadays the application of demountable buildings is mainly focused on reducing material use and increasing reuse possibilities (Ferreira Silva et al., 2020). In this section common strategies for designing adaptable buildings and common difficulties and opportunities will be discussed.

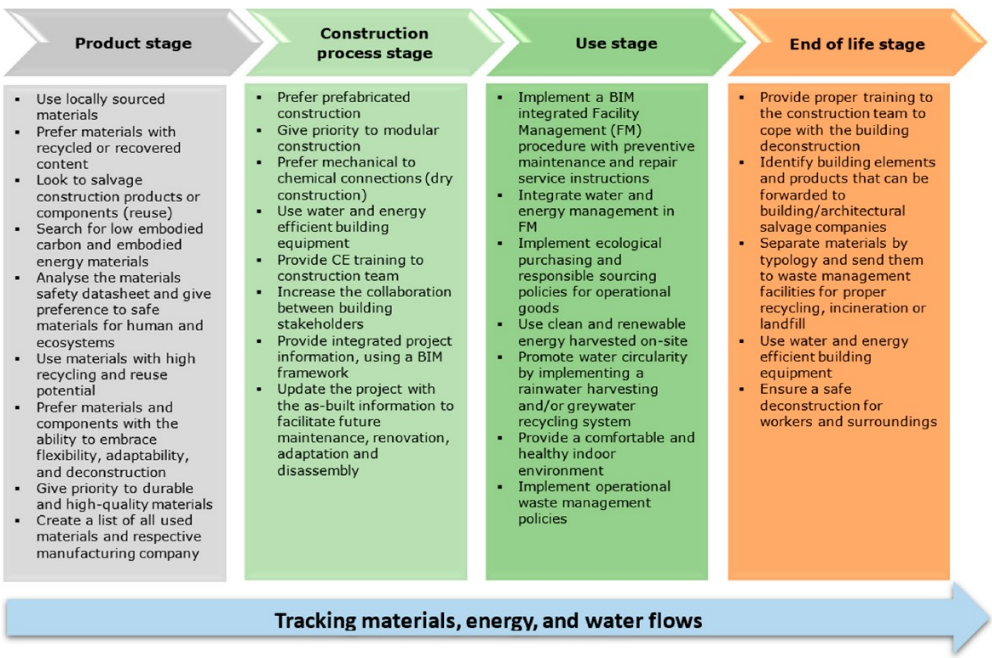


Image 2: A framework for CE implementation throughout the building’s life stages (from Rahla et al., 2021).

There are many strategies available that can be applied to create a more circular building method (see image 2)(Rahla et al., 2021). Some of these relate to demountability, while others relate to other aspects such as the environmental footprint of material. In this research the focus will be on strategies relating to demountability and adaptability, that are applied during the design stage.

Even though there is already quite some research on demountability and many of these strategies have been explored, there are still difficulties relating to demountability. These difficulties lead to possibilities to improve the process of creating demountable buildings.

2.1.1 Strategies

Over time many strategies for increasing adaptability have been developed. A few commonly applied strategies will be discussed in this section (see image 3).

Separating Layers

A common strategy to increase the demountability of a building is to separate the materials into layers. The components used in a building have different lifespans, therefore they need to be replaced at different moments in time (Fatourou-Sipsi & Symeonidou, 2021). Different interpretations of these layers exist. Duffy first introduced the concept of separating layers, identifying four layers with different lifespans, being shell, services, scenery, and set (Askar et al., 2021). Brand builds on this concept, mentioning six layers, being stuff, space plan, services, structure, skin and site. Each of these has a different lifespan, site having the longest being eternal and stuff the shortest being daily. By being able to replace one of these layers without damaging the others, the adaptability of a building is increased (Salama, 2017).

In order to be able to do so easily, the connections should preferably be mechanical. Connections that are chemically bonded are often difficult to remove and require a lot of force. This leads to the components being damaged during the disassembly (O'Grady et al., 2021) . Mechanical connections on the other hand are easier to disassemble.

Open Building

Habraken also proposes to separate the building components from each other, however he only mentions two groups, being supports and infill (Salama, 2017). The supports is any aspect of the building that is fixed, while the infill are the aspects that can more easily be changed (Khosravi et al., 2019). Often, the structure and installation channels in a building are considered to be the supports, while the interior walls are considered infill.

This method was a reaction to the mass production of uniform houses (Askar et al., 2021). By separating these groups the infill can more easily be changed, allowing the users to change their dwelling to their needs. This in turn leads to more diverse housings. At the same time the buildings can adapt along with the changing needs (Khosravi et al., 2019).

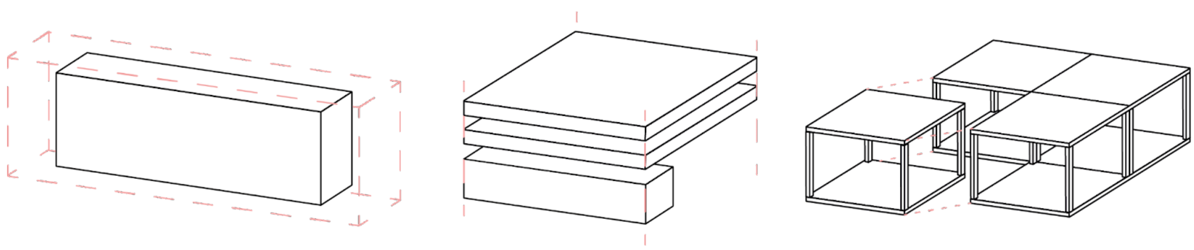


Image 3: Strategies for designing adaptable buildings (author).

Modular Design

Another strategy is to create a modular design with standardized components. Many modular buildings are designed to be adapted during their lifecycle. Due to the rationalization of the building into modules, the disassembly and reconfiguration possibilities are optimized (Ferreira Silva et al., 2020). Because the components are modular they can more easily be interchanged, creating flexibility and increasing the reuse potential (Arisya & Suryantini, 2021). Furthermore, due to the standardization of components, less unique components will be created. As a result the disassembly becomes simpler and more efficient (Arisya & Suryantini, 2021).

Modularity often goes together with prefabrication. The elements are produced off site in a factory, creating a better working environment. In these factories a higher level of accuracy can be achieved, leading to a better quality and reduced waste (Ferreira Silva et al., 2020).

2.1.2 Difficulties and opportunities

Even though the interest in demountable and adaptable buildings is increasing, there are still many disadvantages, which keep people from designing and building adaptable structures. Some of these difficulties will be shared in this section, along with opportunities to improve upon these difficulties.

Cost

One of the main reasons for the lack of demountable buildings is the associated cost. Demountable buildings currently are still more expensive compared to traditional construction (Salama, 2017). Even though the demountable buildings can lead to more residual value, the client can often not afford the risk of the higher building costs. Along with the generally uncooperative nature of the construction industry, this leads to an unwillingness to build demountable buildings (Torgautov et al., 2021).

There are many aspects that relate to the higher cost of demountable buildings, such as increased complexity (see image 4 and 5), the storage of materials, increased labor costs, training expenses and transportation costs. However, there are also many aspects that could reduce the cost such as resale value, partnerships to raise funds, financial incentive by governments and savings due to less equipment being needed (Rios et al., 2015).

The cost also relates to the time needed to disassemble a building. Considerably more time is needed to disassemble a building compared to the demolition of a building (Salama,

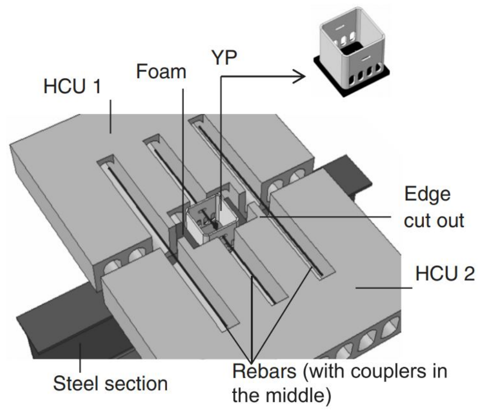


Image 4: Demountable shear connection hollow core slab floor (from Feidaki et al., 2019).

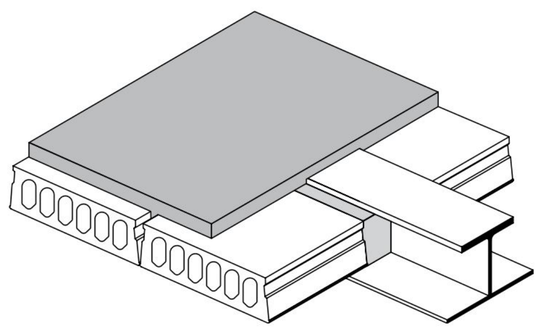


Image 5: Traditional hollow core slab floor (from Bouwen met Staal, 2013).

2017). However, this time can be reduced by providing training to the construction team, thereby increasing their productivity, as well as planning the deconstruction and keeping track of the materials and components (Rios et al., 2015). Furthermore, by developing demountable connections further, simplifying the connections, the time needed to disassemble these structures could be further reduced.

Lack of information

Another aspect which hinders the reuse of material is the lack of available information of the components. This is partly due to a lack of collaboration from material suppliers, hindering the collection of information (Rahla et al., 2021). But another reason is the uncertainty over the quality of the components, due to the difference in quality offered by suppliers (Salama, 2017). The components could also have a lower quality due to damages that occurred during the building's life, for instance due to rusting, cracking, or rotting (see image 6). Furthermore changes could be made to the building, which can affect the building's components (Anastasiades et al., 2021). This can include replacing elements as well as altering the elements themselves, by for instance cutting or drilling holes in them.

Image 6: Rotten woorden rafters (Mosoarca & Gioncu, 2013).

To counter this lack of information during the disassembly phase, all information about the building's components should be tracked, with so-called material passports (Fatourou-Sipsi & Symeonidou, 2021). BIM software can be used to gather and store this kind of information (O'Grady et al., 2021). By gathering all information at the start and keeping track of changes, the quality of the components can more easily be determined.

Lack of standardization

Lastly, there is a lack of standardization. Even though standardization of products is offered as a strategy to increase the amount of reuse in ISO 20887, there are currently no such standards (Anastasiades, 2021). This is partly due to standardization being seen as a threat to the current building industry. Manufacturers want to protect the way they are currently creating building components and contractors see it as a threat against the uniqueness of their projects.

However, standardization would increase reuse, as components could more easily be applied in another building. Furthermore, as mentioned, standardization could increase the ease of constructing and disassembling buildings, as the components will be more familiar (Arisya & Suryantini, 2021).

2.2 Scenario-based design

As mentioned, scenario-based design is not often applied yet in architecture. When it is applied it is mostly done to assess the robustness of a building's performance, as has been done by Walker et al. (2022) and Kotireddy et al. (2019). However, this tool could also be used in combination with adaptable buildings, to understand how they could change over time

(Eilouti, 2018). Especially as designers have mentioned that there is a lack of tools to help make future-oriented design choices (Galle et al., 2017). In this section some of the advantages will be discussed, along with some methods taken to use scenarios in the design process.

2.2.1 Advantages

There are multiple reasons someone might use scenarios during the design process. Mainly, the scenarios help gain knowledge about the possible results from design decisions, therefore they can be used to make better informed decisions during the design process (Kotireddy et al, 2019). As the future can not be predicted with certainty, and the needs of users continuously change (Eilouti, 2018) scenarios can be used to test different design options and to gain more knowledge about the possibilities.

According to Kotireddy et al (2019), scenarios are necessary to ensure the performance of a building across its lifetime. As the needs change over time, the building will have to adapt along with the changing needs. This is especially the case for buildings that are deemed to be future-proof (Galle et al., 2017). By testing different design options with scenarios, the options that are most resilient or most adaptable to changes can be chosen.

Scenarios can be used to assess how a transformation will impact the users. Thereby it can be used to reduce the gap between the expected performance of a building and the actual performance the building will have (Kotireddy et al., 2019). As the designer will better understand which needs might arise, but also which needs will probably not arise, unnecessary oversizing can be prevented. Furthermore, it could also be used to beforehand negate issues that might arise, thereby reducing future costs as well as reducing additional negative environmental impacts (Galle et al., 2017).

2.2.2 Approach

Multiple approaches have been suggested for the use of scenario-based design for architecture. These are mainly based on methods used for other fields. The best approach can depend on which goal the user wants to achieve with the scenarios. During this literature review a few different approaches have been researched. Even though the exact approach might differ, there are similarities between the approaches. The overall steps that these approaches seem to share are discussed in this section (see image 7).

1. It is important to understand that scenarios are not necessarily predictions of what will happen. During the process of scenario-based design, the designer is exploring possibilities and “what-if”s (Eilouti, 2018). However, the scenarios do have to be deliberate (Galle et al., 2017). Therefore the goal of what one wants to research with a scenario needs to be clear.
2. After determining the goal and boundary conditions, the next step is often to determine what uncertainties might lie in the future. Some of these uncertainties can be reduced by doing research into these topics, such as how an user might interact with its surroundings (Kotireddy et al., 2019).
3. The next step is to determine the design alternatives that will be tested with the scenarios. During this step one should look at which aspects of the design are fixed, and which can be influenced (Walker et al., 2022). The different design options could be all different combinations in which the changeable aspects can be combined.
4. Some of the approaches include the step to determine the “driving forces” based on the uncertainties and the design options. This can be done to find the scenarios that

are most relevant. The driving forces are the aspects that could lead to different future possibilities. After finding these forces the importance and uncertainty of each is considered, to determine which driving forces to use in the scenarios (Galle et al., 2017).

5. Subsequently the scenarios are developed in more detail. Based on the goal different types of scenarios could be created. If the goal is to verify a predetermined plan, a predictive scenario is used to test it. However, if the goal is to compare the resilience of multiple design options, more surprising scenarios are used (Galle et al., 2017).
6. As the needs of users change continuously, many scenarios could be developed. To focus effort, the number of scenarios is reduced to a few key scenarios. These scenarios contain the bigger and more important changes in needs. These are also the scenarios which will result in the current design not being suitable anymore, requiring the building to be adapted to the new needs (Eilouti, 2018).
7. Finally all design options are tested with all determined scenarios. The results of these scenarios will have to be looked at individually, as the results might cancel each other out if the average is taken (Kotireddy et al., 2019). How to interpret these findings depends on the goal of using the scenarios.

In their paper Eilouti (2018) mentions that a next step within scenario-based design could be to automate part of the process using computational tools. This would ease the process of using scenario-based design.

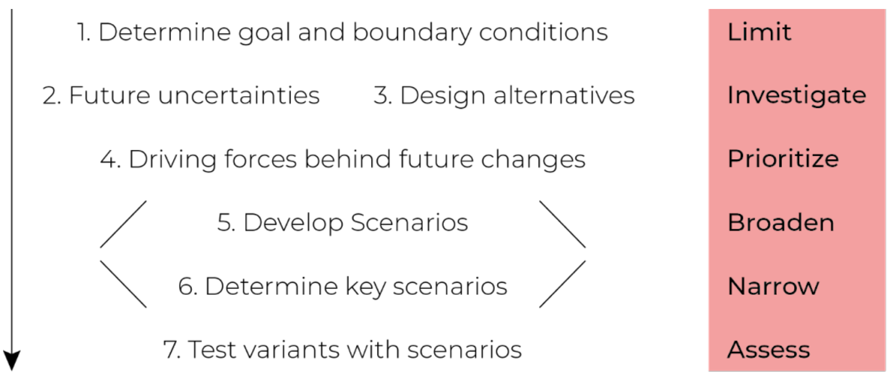


Image 7: Approach scenario-based design (author).

2.3 Computational workflow

Computational methods are often not applied to increase the adaptability of a structure. However, a few examples of research into this topic do exist, which will be discussed in this section.

Reconfigurable truss-beam

Currently, if computational methods are used in the design process of a structure, they are commonly used to create a custom design based on predetermined load cases (Nadir et al., 2004). These designs are often not easily adaptable to other load cases. To create more adaptable structures, load cases of multiple scenarios are sometimes applied to a single design. As the same configuration will have to suffice for different load cases, the components of these structures are often oversized. Nadir et al. (2004) instead propose a method to reconfigure a kit of parts for a truss beam. Different configurations suffice for different load cases. These three different methods are visualized in image 8 below (Nadir et al, 2004).

The method proposed by Nadir et al. consists of two loops. The outer loop minimizes the total sectional area of the set of components to minimize the material use. The inner loops, of which there are as many as there are load cases, check whether the set of components can be used to satisfy the requirements for each load case. The flowchart of this method can be seen in image 9 (Nadir et al., 2004).

This method effectively reduces the manufacturing costs of the structure compared to the two more common methods, which was the goal. However, it can still lead to the oversizing of elements, as some load cases could require less material than others. Because the method only allows for the reconfiguration with the current set of components, the structure can not be adapted to use less material. By allowing some of the components to be replaced, oversizing of the components could be reduced.

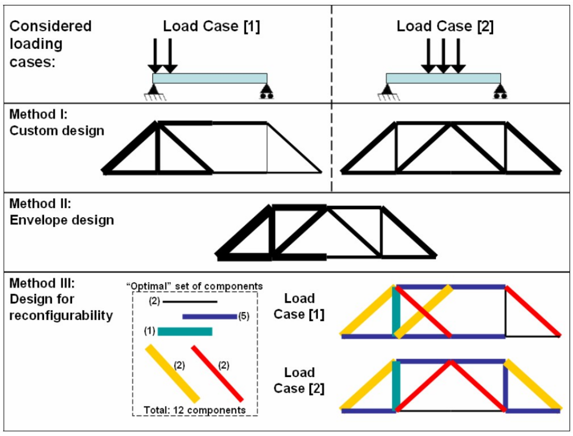


Image 8: Three structural design optimization methods considering different loading conditions (from Nadir et al, 2004).

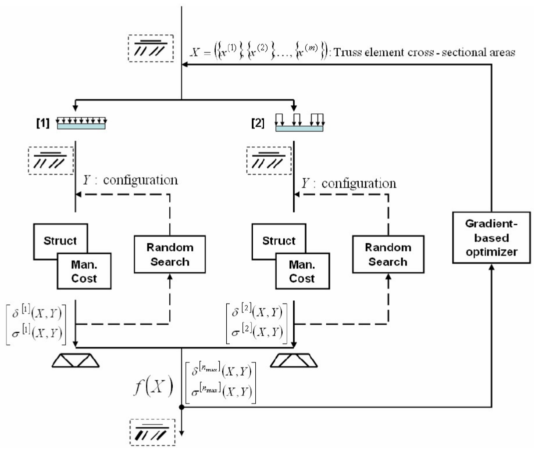


Image 9: Method III optimization flow chart (from Nadir et al., 2004).

Optimal reuse of components

More recently similar research has been conducted by Brütting et al. (2018; 2021; 2022). In these papers, multiple approaches are tested, with the focus on reusing components from a set of stock. As the supply of stock is limited to sets with certain cross sections, discrete sizing is used for these computational methods instead of continuous sizing (Brütting et al., 2022).

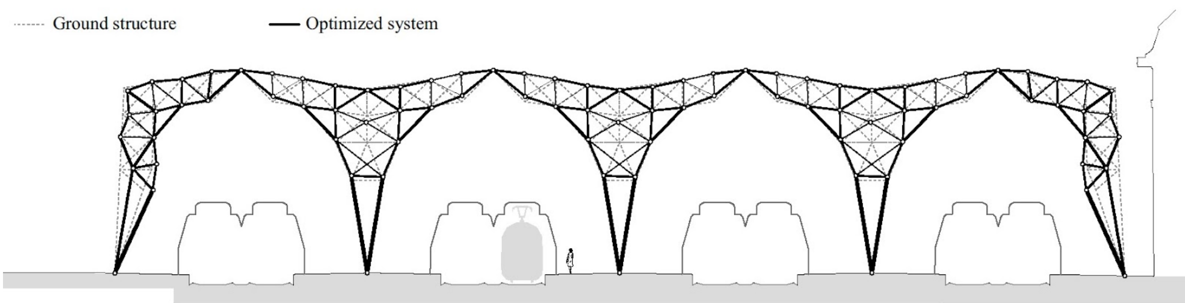


Image 10: Optimal transversal section layout (from Brütting et al., 2018).

For most of the approaches a structure is calculated to make the best use out of a predetermined stock of reclaimed elements. For instance, a preliminary design is made for the structure for a train station roof, along with determining which forces would be present on this structure. Through topology and discrete sizing optimization, the design is changed to enable the use of elements reclaimed from electric pylons (see image 10) (Brütting et al., 2018). This design, however, does not take future need for adaptation into consideration.

Reconfigurable kit of parts

Another research by Brütting et al. (2021) does take reconfiguration possibilities into consideration. A kit of parts is created that can be used for three different structures. The preliminary design of these structures are changed through form finding in order to reduce the amount of components needed in the kit of parts to create all three structures. Furthermore, the cross sections of the components are minimized in order to reduce the material use. In the end, the kit of parts can be reduced from 208 components to 170 components to create the three structures, consisting of 108, 111 or 132 components.

Even though the amount of components in the kit of parts is reduced, there are still many components which remain unused. And even though the reuse potential of the structure is increased by optimizing for three different structures, these structures need to be designed beforehand.

3. Interviews

Semi-structured interviews were conducted with six different companies, all of whom had at least some experience with designing demountable buildings. Summaries of the interviews can be found in Appendix B. Among the companies were one structural engineering office, one building system factory and four architectural firms. Combining the information from all interviews resulted in the following findings. The results have been grouped by topic. First, the largest scale will be discussed, being adaptable buildings as a whole. Following this, the scale becomes increasingly smaller, first building systems, then connections and finally material will be discussed.

3.1 Adaptable buildings

Multiple strategies for creating adaptable buildings have been mentioned during the interviews, as well as the difficulties that still prevent adaptable buildings from being built. These strategies will be discussed in this section, but first the reasons for building adaptable or demountable buildings are discussed.

Advantages

As a response to being asked why they designed a building to be demountable, multiple interviewees posed the question “When is it beneficial to build demountable structures?”. They often continued with saying that temporary buildings would benefit a lot from being demountable. However, buildings in general, especially dwellings, have a long lifespan. For these cases it would be more beneficial to ensure that the buildings can adapt rather than necessarily being demountable. They argued that this would increase the lifespan of the building, thereby making it more sustainable.

Another priority over creating demountable buildings would be to minimize the material use of buildings, thereby focussing on the material shortages now rather than the shortages in the future.

However, these interviewees also stated that even though not all buildings have to be demountable, there are a lot of associated benefits to demountability. One interviewee mentioned the demountable connections being a result of prefabrication rather than being an aim. Prefabrication leads to an increase in quality and more precise components. It also increases the speed of production and creates more production possibilities, such as being able to apply pretension in concrete elements.

Multiple interviewees pointed out the other benefits of demountability, such as a higher amount of flexibility and the possibility to better recycle materials at the end of the building’s lifespan (Image 11).

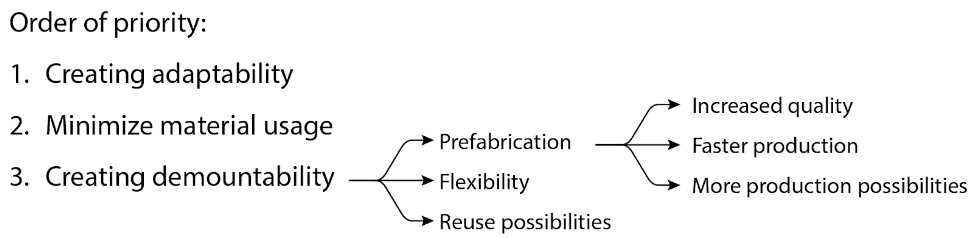


Image 11: Order of priority and advantages demountable buildings (author).

Difficulties

Despite the advantages, not a lot of buildings are designed with demountability and adaptability in mind. Most interviewees mentioned what currently keeps people from creating demountable buildings is the higher costs compared to traditional building systems. An option would be to only make the building partially demountable, where more flexibility is needed. Or to make a building remountable, meaning a bit more effort will have to go in disassembling the building, but reuse is still possible. Such a strategy has been used by Strackee, focussing the demountability where it is required the most.

The mindset of other actors in the building process has also been described as a hindrance in the design process. The interviewees elaborate that the other actors are often unaware of the possibilities of demountable buildings, and prefer to keep building in a traditional way. Surprisingly this has been mentioned by interviewees from some of the architecture firms, as well as an interviewee from the structural engineering firm.

Strategies

When it is possible to create an adaptable building, multiple strategies could be applied. One of the strategies to increase adaptability, that was mentioned often, is to use the construction as a frame. The rest of the building is considered an infill in this frame.

This strategy works well together with another often mentioned strategy of separating different materials into individual layers. For instance to not embed pipes into a concrete floor. By separating the layers, it becomes easier to replace a material and to recycle the materials at the end of life.

Other mentioned strategies include standardization and oversizing. Both of these are used to increase the lifespan of the components. By standardization the component can be more easily reused as is. By oversizing, the material can be trimmed down and reused.

3.2 Building systems

According to the majority of the interviewees one of the most important choices, and often one of the first choices, when designing a demountable building is the choice for a building system. Each system comes with its own restriction, mainly in size, which will have to be taken into consideration during the design process. After a building system is chosen, a lot of changes can still be made within the restrictions of the system, but certain dimensions are set and can not be altered anymore. Both the interviewee from the building system factory and an interviewed architect state that it is beneficial for the architect to know the building system well. When an architect knows the restrictions of a system, they also know what the possibilities are within that system.

All interviews mention that due to the decision for a building system being made so early, it is also difficult to introduce demountability later on in the process. This would be nearly impossible due to the amount of changes needed to fit the design within the restrictions of the demountable building system.

One of the limiting factors of the building systems is the span. Some of the architects, the structural engineer and the building system designer, advocate for using small spans, as this generally limits the amount of material needed. On the other hand the other architects advocate for larger spans. as this is beneficial for the flexibility of a space, and can thereby increase the lifespan of a building.

During the interviews it also became clear that even if a building is designed to be demountable, the reconfiguration possibilities are often still limited. Often the building can only be rebuilt in the same or a similar way as the original building. According to the interviewees it can also be very challenging to change the function of a building, due to the different regulations for the functions. This becomes easier if this has been taken into account during the design process.

3.3 Connections

All interviewees point to the importance of using dry connections, as these can be disassembled. This does however impact aspects such as the airtightness of a building as the regulations for this are often achieved with wet connections.

Most interviewees also emphasized that the connections should be as simple as possible to facilitate the disassembly process. This process should be taken into account during the entire design process. One of the aspects to consider is the reachability of the connections. However one architect noted that even if the connections are simple in theory, it might still be more difficult to disassemble in practice due to rusting for instance.

As the connections should be as simple as possible, some architects and the structural engineer also mention to mainly use hinge connections, as these are simpler than fixed connections. However, this in turn influences the stability design of the building, as stability can not be created by the fixed connections.

The use of simple connections also impacts the building system as a whole. According to some interviewees stacking the components is preferred, this is however not always possible since this takes up more space. Furthermore, because of the hinge connections certain components need to be designed in a different way, for instance balconies need to be supported at two sides and can not cantilever from the building.

The difficulties with these mechanical connections led to some interviewees wondering how much of a building needs to be demountable, in order for the building as a whole to be considered demountable. They mention that often a bit of sealant is applied for the air tightness, but if this connection can also be cut easily, it should not affect the overall demountability of the building. Furthermore, one architect pointed out that not every small part of a building needs to be demountable, as long as the larger component is demountable and reusable.

4. Discussion Research Phase

Following the results of the literature review and the semi-structured interviews, many similarities between theory and practice were found. The mentioned strategies in particular corresponded a lot with each other. These strategies included separating layers, working with a frame and infill, modular design and open building.

However, some of the offered solutions, such as oversizing and standardization, lead to an increase in material use. Due to the existing material shortage, it would be preferable if the adaptability can be increased, without increasing the material use of the initial design.

Both researches also determined that the higher costs of demountable buildings were the main reason for not building such structures. However, where the literature pointed to ways to profit from demountable buildings, the interviews focused on introducing as much adaptability as possible in the budget.

Even though it is possible to further develop demountable building systems to be cheaper and to meet these standards, some interviewees remarked that not every element of a building has to be demountable. This is due to the interviewees not regarding demountability as the main goal to be achieved. Instead in their design processes they mainly focus on other aspects, such as prefabrication and adaptability, which can work well together with demountable structures.

This can lead to partially demountable buildings, where some chemical connections are still present, even though mechanical connections are preferred. Chemical connections are also still used to be able to meet certain standards, such as air tightness.

An aspect that was mentioned during the interviews, but did not come up in the literature review is the importance of deciding on a building system. There is a wide range of demountable systems on the market, but deciding on the right material and grid can have a big consequence on the adaptation options.

At the same time buildings that are currently being built to be demountable, often don't have a lot of reconfiguration possibilities. This limits the reuse possibilities. The literature review led to possible solutions for this problem.

Scenario-based design can be used to test whether a design can adapt to the future needs. On some occasions a design is made with a specific possible scenario in mind, but this can be incorporated into the design process more.

Computational design tools can also be used to increase the reconfiguration possibilities. This can be combined with scenario-based design, where the computational methods are used to check whether the structure suffices for the scenarios.

II Development Phase

5. Functionality

Before developing the computational workflow, it is important to understand how this would fit within the design process of a building. This chapter will explain how the workflow could aid in making decisions regarding adaptability and material use. First, the goal of the workflow will be explained. This section includes the problems that the workflow should aid in solving. As well as what could be achieved by using the workflow. Second, the general concept of the workflow will be explained. Both the required input and expected output are described. This section will explain in more detail which decisions should or can be made before, during and after using the workflow.

5.1 Goal

In short the goal of the workflow is to increase the adaptability while minimizing material use. However, from the research phase it became clear the problem is not as simple as that. A few of the results from the research phase stand out, being the higher cost of demountable structures, the priority of adaptability over demountability, and the lack of reconfiguration possibilities.

The cost of a structure can be brought down by not using demountable connections. Adaptability can then be achieved by oversizing components. This allows for the infill of the building to be replaced or changed more easily. However, this would lead to an increase in material use at the start of the building's life-cycle. This is thus in conflict with the goal of minimizing material use. Still oversizing could be beneficial in the long term, as less material will have to be removed and added to allow for adaptations. Therefore, if it's almost certain a scenario will happen, oversizing could be a good method to increase adaptability.

Despite the higher costs, demountable connections could also still be a favorable solution, by limiting the amount of demountable connections that is applied. To allow for different structure configurations a limited amount of components could be demountable, while other components are not demountable. Thereby reducing the cost. But this raises the question, which elements should be demountable?

Based on the given input, the workflow should generate a few different design alternatives for the structure. More importantly, the workflow should show how these design options can be adapted based on provided future scenarios. As a result the workflow will be able to give feedback about how to make a building more adaptable. At the same time the workflow should be able to give information about the material use. Therefore, this information should allow for a designer to make a better informed design decision.

5.2 General concept

The interviewees have made it clear that designing for adaptability needs to be done from the start of the design process. Therefore, the computational workflow will focus on the preliminary design phase.

However, some decisions need to be made in advance of using the workflow, due to the limitations of the workflow. At the same time, the results of the workflow should aid the designer to make better informed decisions. Image 12 shows an overview of which decisions take place at what moment in the general design process.

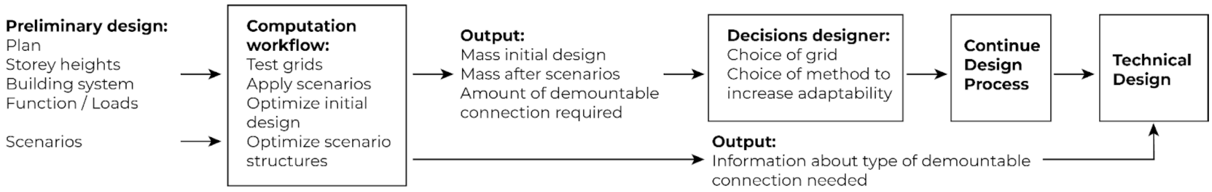


Image 12: Design process when using computational workflow (author).

5.2.1 Input

The main input required for the workflow is the preliminary design. This includes the outline of the building, interior walls and the height of the building. This will be used to find appropriate locations for the load bearing elements.

Furthermore, the designer should provide the scenarios they want to take into account during the design process. These scenarios could include a change in floor plan, a change in function or adding one or more floors on top of the building. The designer could put in an altered model to function as a scenario on their own, however the possibility is provided to quickly generate a few scenarios based on common adaptations. Currently the workflow incorporates two common adaptation scenarios, but this could be expanded with further research and development.

The input of certain load cases is optional, as the workflow includes a preset of common load cases. Nonetheless, these load cases can be adjusted to better fit with the design problem. It would also be possible to adjust the load cases of the scenarios, to indicate a change in functions.

The final input that is required in advance is the choice of building system. This is due to the limitations of the scope of this research. For now only one type of building system is taken into account, however in the future this could be expanded. This would allow for an even more well informed design process, as the environmental impact of different materials could be taken into account as well. The structure with the lowest material use, does not have to result in the structure with the lowest environmental footprint. Furthermore, during the preliminary research the interviewees stated that the choice of building system also has a big impact on the adaptability of a building.

At the moment the workflow functions for steel frame structures with concrete hollow core slab floors. This type of structure is currently most common for demountable and adaptable buildings. Furthermore, there is more information about demountable connections for steel structures than for other building systems. Therefore incorporating this building system into the workflow would be most useful when put into practice at this time.

5.2.2. Workflow

Before explaining the separate steps of the workflow in more detail in the next chapters, this section creates an overview of how the workflow will function. Image 13 and 14 illustrate said workflow briefly, for a complete overview of the workflow see appendix C.

As span has a big impact on adaptability, multiple grids with differing spans will be tested with the workflow. As a first step grids will be selected from a predetermined list. This selection is based on how well the grids align with the preliminary design. From the different grids follow separate structural designs, which will be the design variants.

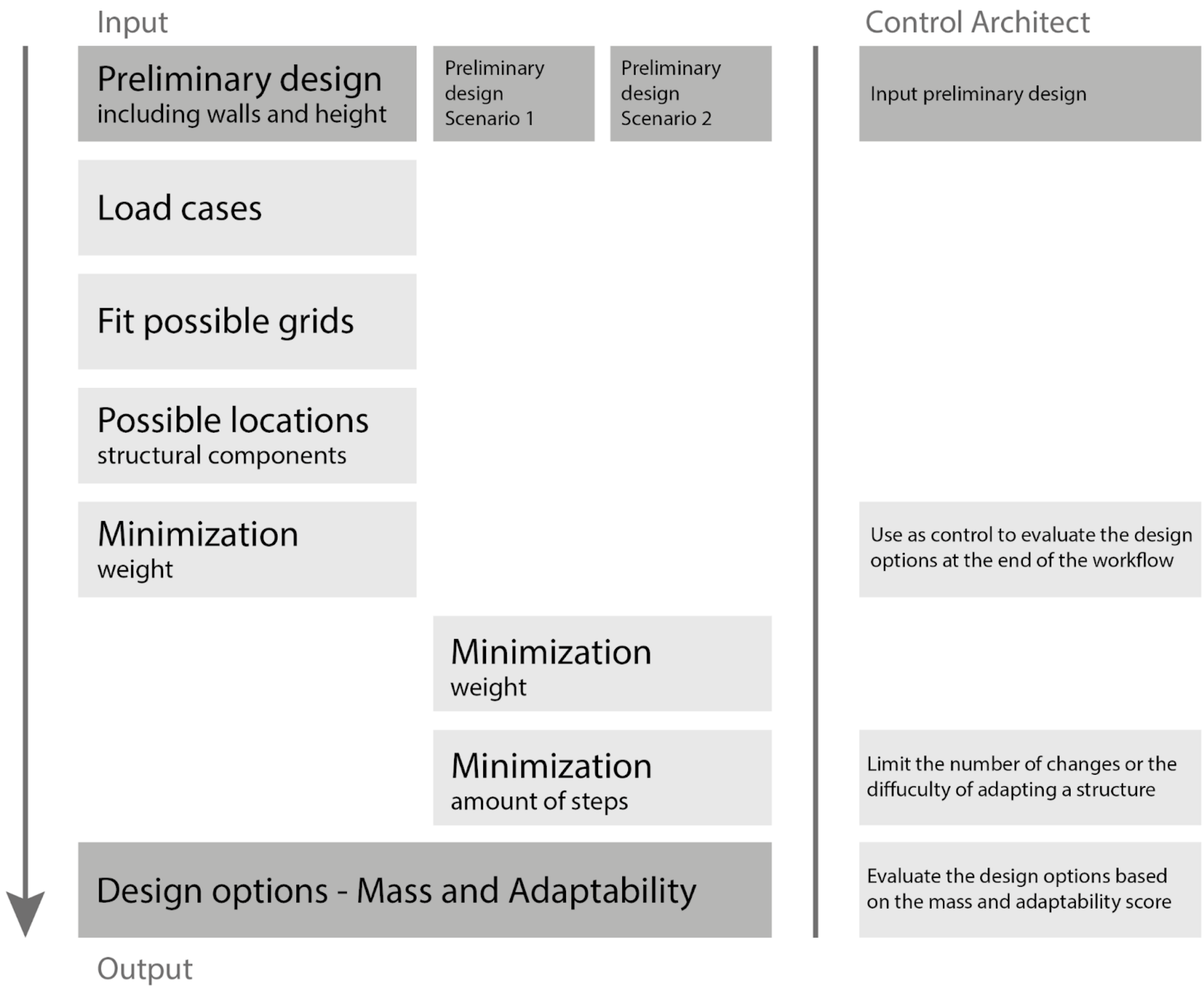


Image 13: General steps computational workflow (author).

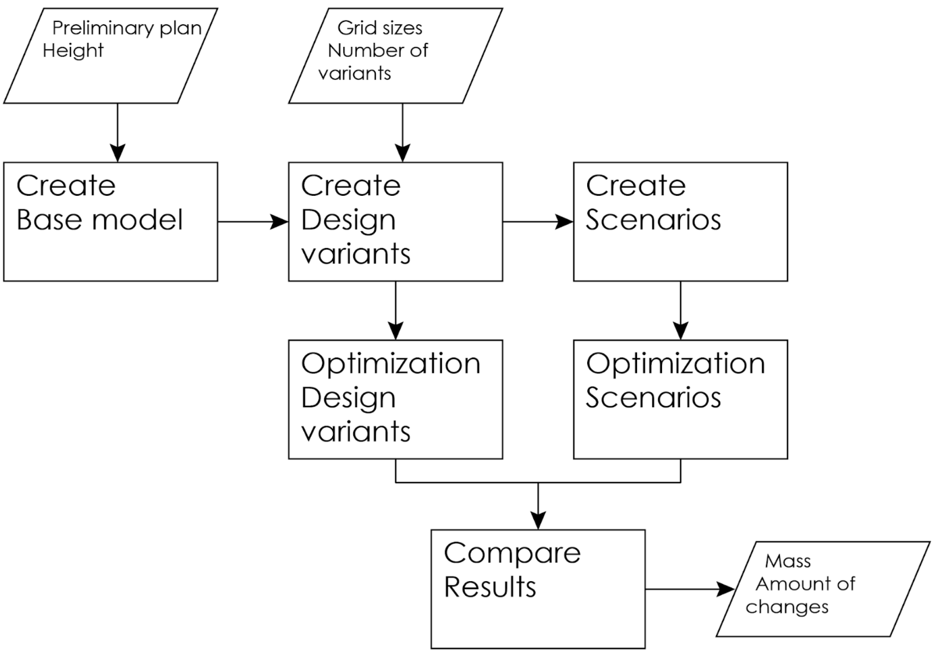


Image 14: Overall computational workflow (author).

The structure of these design variants are then optimized for the least mass. This allows the user of the workflow to reflect on the final results by comparing them to the optimized situation without any scenarios.

Only after this optimization will the different scenarios be taken into account. Two different approaches for this optimization are tested during this research. In the first approach the scenario models are optimized similarly as the initial models. Afterwards the differences between these models are counted. The second approach uses the initial models as a base. From this base it adjusts the structural model, until it meets the requirements for the scenarios. Again the amount of differences are counted. The amount of changes will be used as an indication for how adaptable the structure is. The different design options along with their adaptability score and total mass will be presented to the architect.

5.2.3 Output

The workflow provides a lot of information about the structural models. This can be used to inform the design process in a few different ways. There are two ways the adaptability of the building can be increased: applying demountable connections, and oversizing elements. By using demountable connections, changes to the structure are easier to make. On the other hand, oversizing elements removes the need to change the structure in order to adapt to the scenarios. Both methods are already used in practice to increase the adaptability of buildings, but without considering which elements would benefit most from these measures. The project Building D(emountable) by cepezed (see image 15) can be completely disassembled. Oversized structural elements have been applied in the design of Circl by de Architekten Cie (see image 16).

For each of these methods the workflow also provides information about the different design variants. This information can be used to choose the most suitable variant. This approach has also been used in practice already. The structure of the National Military Museum by Claus van Wageningen architects (see image 17) has been optimized for minimal weight using parametric tools. However, this building can not be easily adapted.

Demountable connections

The workflow can be used to determine which elements would need to be replaced when the building is adapted to a certain scenario. As a result, this information can be used to determine whether it would be beneficial to use a permanent or a demountable connection. The elements that would have to be replaced for multiple scenarios would benefit the most from being demountable. Similarly, elements that don’t have to be replaced for any scenario benefit less from being demountable. This way the workflow can be used to determine which connections don’t have to be demountable to reduce costs, while still providing adaptability.

Image 15: Building D(emountable); building designed to be disassembled (cepezed, 2019)

Oversizing specific elements

The workflow also offers information about which elements need to be adapted. Specifically, for which elements the cross section needs to be increased. It gives this information for each of the different scenarios. In case a certain element would have to be replaced to achieve all of the offered scenarios, it would be possible to use this larger element in the initial design. This would result in less changes being required to adapt the building, but would also result in a higher material use. However, as the workflow determines where the oversizing is most beneficial, not all elements will have to be oversized. In turn this leads to less material being used, compared to the current practice of oversizing. .

Image 16: Circl; Building designed with oversized structural elements (de Architekten Cie, 2017).

Compare design variants

As the workflow optimizes all scenarios for a few different design variants, it is possible to compare these variants to each other. For each variant the adaptability and material use of each scenario is documented. For each design variant the workflow provides both the mass and the amount of changes that are required to adapt the design variant to the scenarios. One variant can have a higher mass than the other, but also need less changes to adapt. The designer can weigh these options and use this information to make better informed design decisions.

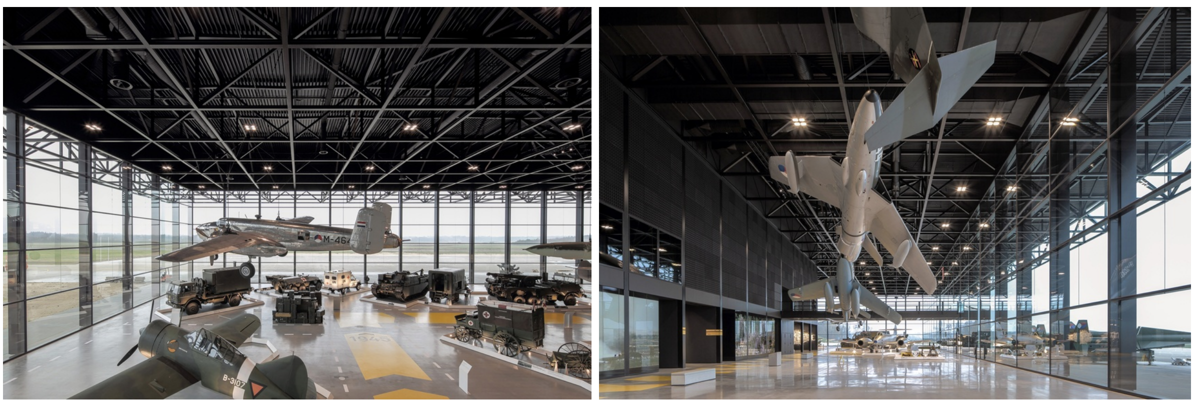


Image 17: Nationaal Militair Museum; parametrically designed to have a low structural mass (Claus van Wageningen architecten, 2014).

6. Variants and Scenarios

The first part of the computational workflow focuses on creating line-models based on the preliminary design that is offered as input. Based on the preliminary design, design variants are created (see image 18). The design variants are then used to create models for the different scenarios.

The computational workflow is created with the software Rhino, specifically with the Grasshopper software that is included in Rhino. Grasshopper can be used to quickly generate many scenarios based on predetermined parameters. To create the models the Pufferfish plugin is used.

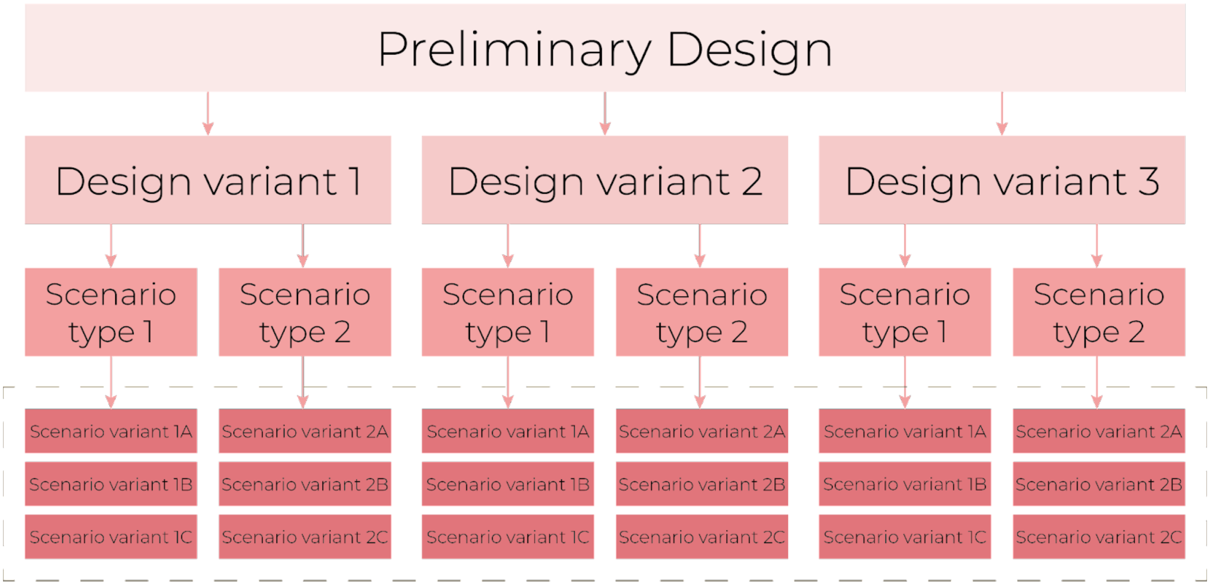


Image 18: Data-structure of the variant and scenario models (author).

6.1 Design variants

As the proposed design process is meant to be used to increase adaptability of a building, it is expected that the preliminary design will align with common methods to create more adaptability. The structural models will be generated with these methods in mind. In particular, separating layers and incorporating a modular grid. As a result the structural elements can be replaced more easily.

Currently, the workflow only incorporates one building system, being steel frame structure with pretensioned concrete hollow-core slab floors. In future research this could be expanded upon by adding other building systems. As a result, design variants could also include different types of material and structures.

The design variants are based on different sizes of modular grids (see image 19 and 20). The grid-size directly impacts the two main aspects for which the design options are tested, being mass and adaptability. A larger grid is generally considered to be more adaptable, as there will be less structural components to consider during an adaptation. However, a smaller grid is generally considered to result in less material use, due to the shorter spans which have to be

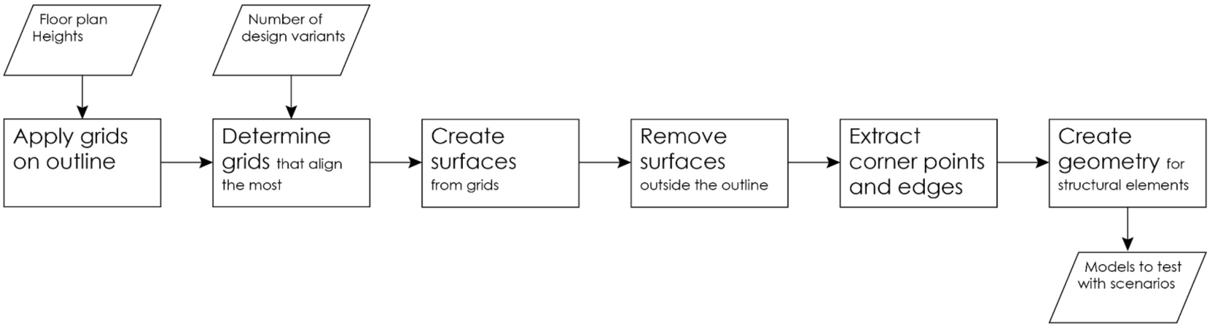


Image 19: Workflowr - Creating design variant models (author).

achieved. As a proof of concept the grid size will be constant over the entire structure, it might however be possible to allow for different grids in separate areas of the building.

As the designer will provide the preliminary design, the design variants can not deviate too much from this design. Therefore the grids that align the most with the preliminary design are chosen for further calculations (see step 1 of the workflow in appendix C).

First all grids, from a list of predetermined grid sizes, are applied onto the preliminary design. The distance from the grid points to the walls, both exterior and interior, of the design are then determined. The grids with the lowest distance are then used to generate the models. It could be possible to let the architect decide how much the structure is allowed to differ from the preliminary design. However, for now a number is set for how many design variants are to be tested.

Based on the grids and the height the locations of the structural elements are determined. Elements that lie outside of the boundary of the preliminary design are removed. Bracing elements are also added to all possible locations, later on in the process part of these elements are removed. This allows for the placement of bracing elements to also be part of the optimization, rather than being predetermined.

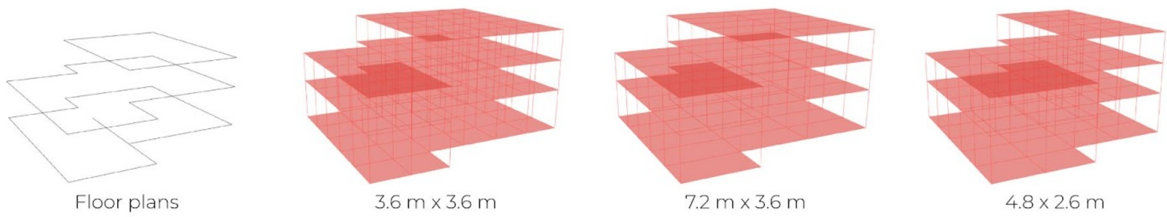


Image 20: Preliminary designs (floor plans) and related design variants (author).

6.2 Scenarios

As explained scenario-based design can aid to increase adaptability in a building. In this case scenarios are used to determine which elements will likely need to be replaced during adaptations to a building. This section will first explain which scenario types are currently incorporated into the workflow. Afterwards, the steps to implement these scenarios in the workflow are described.

6.2.1 Scenario types

It is important to carefully consider the scenarios that are tested during scenario-based design. They shouldn't be too predictable, in which case it would be unnecessary to investigate the scenario, but they also shouldn't be so unpredictable, that the scenario is unlikely to ever happen (Galle et al., 2017). To determine which scenarios would be relevant, the different types of building adaptations that are currently being done are investigated. This gives insight into the needs, possibilities and limitations of these adaptations.

Adding floors

A common adaptation to a building is to increase the floor area of said building. This is especially common to create more space for dwellings with the current housing shortage. Moreover, in Dutch cities there is often not much space to build new buildings, by adding floors the floor area can be increased, without increasing the building's footprint. When adding floors to expand a building generally one of two approaches is taken.

Image 21: VIPP Chimney House (Studio David Thulstrup)

Image 22: Fenix I (Mei architects and planners, 2019)

Either the existing building structure is slightly overdimensioned, so additional floors can be added without having to reinforce the building's structure (see image 21). This over dimensioning could be caused by a change in requirements for the calculations of sufficient load bearing capacity. Often the area that can be added in this way is limited, as the load-bearing capacity is not so overdimensioned to allow for a lot of additional floors.

If the structure of a building is not overdimensioned, the structure of the building has to be reinforced in order to allow for the load of the extra storeys. In this case often a large amount of floors is added, as the required adaptation is already quite invasive (see image 22).

In both cases the mass of the added structure is kept as light as possible. This is done so as much area as possible is added, while requiring the minimum amount of change.

Changed floorplan

When a building loses its original function, it is sometimes transformed to be used for another function. In light of the material shortage and circular economy, this is preferred over demolishing a building and creating a new one, due to the lower amount of material use. When transforming a building, the floorplan often has to be changed, to allow for the new function of the building. The possibilities for such an adaptation are dependent on the grid size. Again there are generally two approaches..

Either the grid for the original purpose can also be used for the new purpose. In this case the new layout of the building is designed around the pre-existing grid. This limits the design possibilities. This option is therefore not always feasible.

Another possibility is that the structure has a relatively large grid size. As a result it is possible to subdivide this grid as needed. This generally leads to more adaptation possibilities, but this might also lead to more material use, as a larger grid size is used.

However, for either of these options the transformation of the building has to be designed around the existing grid (see image 23). This limits the design possibilities for the architect.

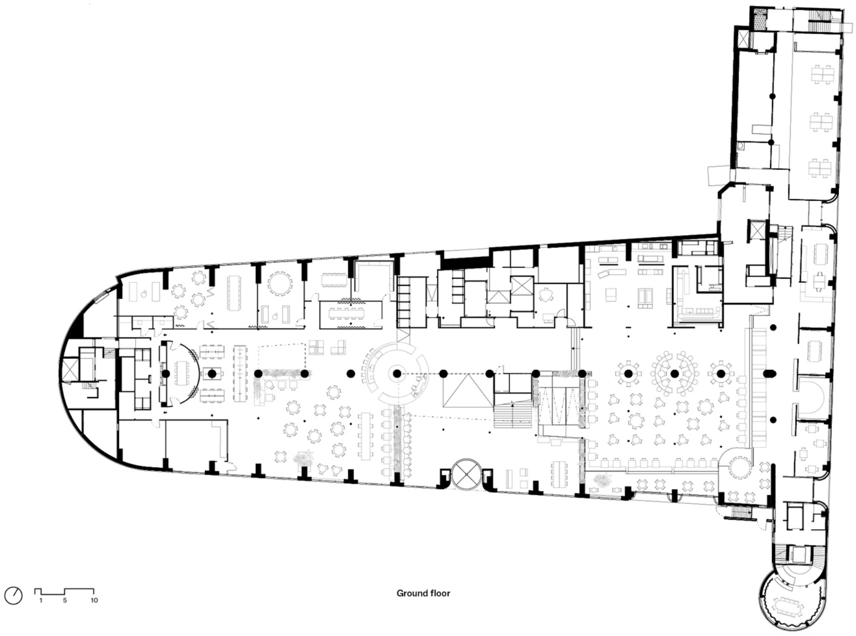


Image 23: Ground floor Stationspostgebouw Den Haag(KCAP, 2022)

Changed Loads

During the lifespan of a building, the loads that are applied to the structure can also change, some examples:

1. Change in function - Different functions result in different permanent and variable loads. Some functions lead to loads that are relatively similar, such as offices and dwellings. However, some functions lead to much higher loads, such as industrial and storage functions.
2. Change in environment - Some loads are dependent on the climate of the building's surroundings, such as wind loads. It is possible that in the future the climate will change, resulting in stronger winds, and thereby higher loads on the building.This is however difficult to predict.
3. Change in the building's self weight - During a building's lifespan many adaptations can be made to a building, this includes transformations or renovations. During these adaptations to a building, elements can be replaced, such as the facade and interior walls. If these elements are replaced for heavier elements, the permanent load on the structure changes.

When the adaptations are made to a building, the loads of the new scenario should preferably be similar or lower than the original loads. Else, the structure will need to be adapted to bear the increased loads.

Conclusion

The discussed adaptations can be divided into two groups. Firstly, adaptations that directly impact the structural elements, being adding floors and changing the floorplan. These result in elements being added or removed. Secondly, adaptations that indirectly impact the structural elements, being changed loads. This adaptation affects the stress in the structural elements, which does not necessarily result in a change of the structure. For this project only the adaptations that directly change the structure will be taken into account. These also lead to new configuration possibilities, which are currently often limited. In future research other scenarios can also be added to the computational workflow.

The possibilities of the adaptations are limited by the current structure of a building. Either the adaptation must stay within the boundaries of the structure's load-bearing capacity and grid, or an additional structure needs to be created, which is often a large and expensive intervention. Based on the adaptations the following scenarios are formulated, which deviate from these limitations:

1. Adding floors without limiting to the existing load-bearing capacity or adding a second structure. This is done by replacing part of the structural elements, so that the load-bearing capacity of the structure can be increased.
2. Removing structural elements, so that the building can be more easily adapted to the new floorplan. This might for instance be necessary in case a large gathering space is required. Other structural elements are replaced with stronger components, to compensate for the loss of structural elements.

By using these two scenarios, the workflow could lead to new options that were not possible before. It also creates the possibility to compare the workflow with conventional methods of adaptation.

6.2.2 Models

After the different design variants are created, the scenarios are applied to these variants (see step 2 of the workflow in appendix C). For each type of scenario, multiple options are created, thereby allowing to test multiple possible designs for future adaptations. The structural models for the scenarios are created by adapting the structural models of the design variants. Either elements are added or removed from these models.

Adding floors

This scenario is created similarly as the design variant models (see step 2A of the workflow in appendix C). The grids of the different variants are used, but they are applied on different floor plans (see image 24). The exterior and interior walls of the design variants are used as a base, but they can be replaced by a different design for each of the floors.

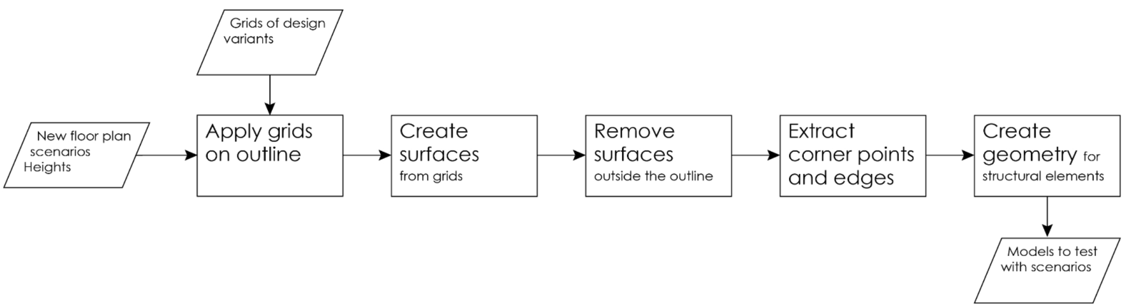


Image 24: Workflow - Scenarios adding floors (author).

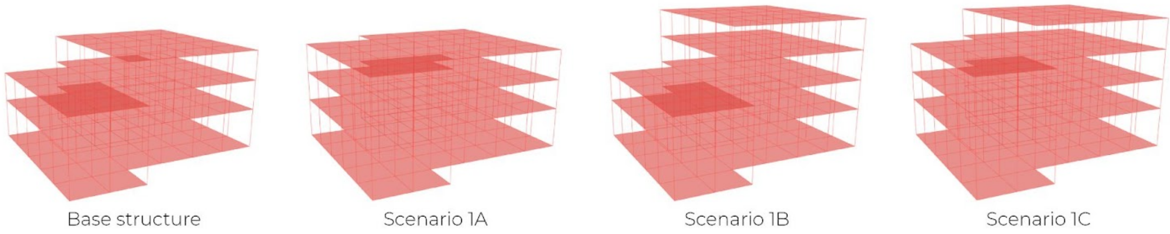


Image 25: Scenarios adding floors (author).

It is also possible to add a new floor (see image 25). However, it is important that all models have the same amount of input, due to the way the data is managed later in the workflow. So in case one scenario has fewer floors than the other, a null placeholder should be used for the non-existing floor.

Removing structural elements

The process of creating the models for this scenario type differs (see step 2B of the workflow in appendix C). The finished models for the design variants are used as a base, from which the elements are removed (see image 26). The designer creates a three dimensional shape, which indicates a space they want to remain empty (see image 27). The workflow then determines which column, bracing and floor elements are within this area, before removing said elements.

As a result it is possible to remove as many elements as desired. From creating a slightly larger space by removing a single column, to creating an open space across multiple storeys by removing columns, beams and floor elements.

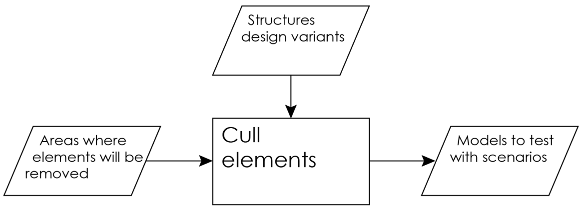


Image 26: Workflow - Scenarios removing elements (author).

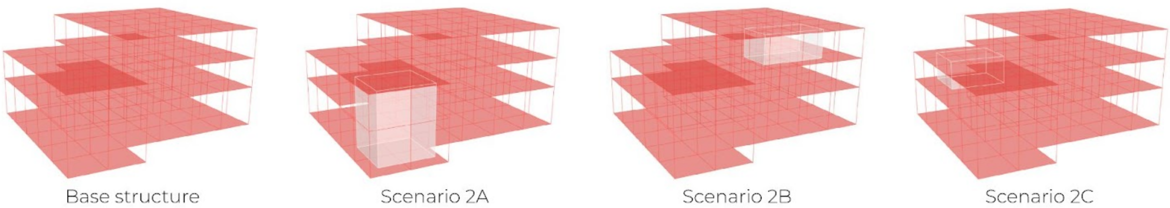


Image 27: Scenarios removing elements, elements within white boxes are removed (author).

7. Optimization

After creating the required models, the models can be optimized (see step 4 of the workflow in appendix C). For this process the plug-in Karamba developed by Clemens Preisinger (2013) and the plug-in Anemone are used in Grasshopper. This research uses two separate approaches for the optimization of the scenarios.

The aim of the first approach is to achieve models for the scenarios with minimal mass. When a model has the minimal allowable mass, the model also uses the least amount of material. Thus this approach is used to determine the least amount of material that could be used for each of the design variants and the scenarios.

The aim of the second approach is to achieve models which deviate the least from the base design. The amount of changes that are needed will be used as a measure of adaptability. The lower the amount of changes, the easier the structure can be adapted. In reality the adaptability would also depend on other aspects, as some elements can be replaced more easily than others. However, as the goal is to oversize these elements or to make them demountable, it is assumed for the optimization that the same amount of effort is required to replace any element. This optimization approach is used to determine the easiest ways to adapt the design variants to the different scenarios.

7.1 Set-up structural models

In chapter six the set-up of the variants and scenarios is explained. The line models that are created in this process are now used to create the required structural models. To create these models the parametric finite element analysis plug-in Karamba is used. This section will go into more detail about the set-up of the structural models. The values and load-cases that were used for the calculations can be found in appendix D.

First the structural elements are created from the elements in the line-models. The workflow currently only includes a steel frame structure building system. The structural elements therefore include columns, beams and bracing elements. When constructing these elements, a unique ID is given to each of the elements, corresponding to their location in the model. This allows for the comparison of the cross-section of each element across the different models, as the index of the elements might differ.

The bracing elements are all given the same cross-section, which will not be changed by the optimization process later on. This is done to ensure that they will not be dimensioned for compression instead of solely tension. The columns and beams are given the smallest cross-section of the list of cross-sections that will be used during the optimization.

The elements are then connected by adding joints at the end of all the elements. The intention was to use hinged joints, as this type of connection was advised by the interviewees due to its relative simplicity. However, this was not possible due to the way the scenario models are constructed. If a column is removed in a scenario, the beams that connect to each other above said column will only be connected with a hinge and therefore will not have enough support. As a result, all connections are currently set to be fixed. In future research an alternative way for constructing the scenario models might solve this problem. As a result of these fixed elements, the bracing elements are not required. However, it is assumed that the building will be changed over time. The bracing elements facilitate these adaptations, by providing stability when elements are replaced.

At the bottom of all columns of the ground floor supports are added. These act as the foundation. The supports are fixed in translational movement, but released in rotation. Subsequently, loads are applied on the structures. These loads include the self-weight of the structure, live-loads, and wind perpendicular to the four sides of the building. The loads are determined in accordance with Eurocode standards and include the safety factors for ULS (Ultimate Limit State) calculations. In order to apply these loads meshes are created from the floor, roof, and facade surfaces.

The weight of the concrete floor slabs can vary, due to larger grid-sizes requiring a thicker floor. However, the optimal floor thickness will remain the same over the scenarios, as the grid-size and load on the floors are not changed. However, the optimal thickness might be different for the separate design variants. Therefore, the most suitable thickness needs to be determined for each of the variants, to find the weight of the floors. For both approaches the floor thickness is optimized for minimal thickness before the rest of the model (see step 3 of the workflow in appendix C). This simplifies the optimization process. First one floor element is taken for each of the different grids. Supports are placed alongside the edges, to simulate the beams that bear the floor. Then the same load cases are applied to the floor that are applied to the rest of the model. Finally the floor thickness is optimized using the 'Optimize Cross Section' component from Karamba. The mass of the floor is divided by the area to obtain the weight per square meter. The resulting weight is applied as a force on the beams of the complete models.

During the optimizations two criteria are used to determine whether the structure suffices or not. These criteria are maximum allowed deformation and maximum allowed utilization. Since the safety factors are already incorporated in the loads, the maximum utilization is set to be 100%. The maximum deformation on the other hand does not have to meet these safety factors. Therefore, for the deformation a maximum of L/200 is used, instead of L/250. This will counterbalance the safety factors in the loads.

7.2 Minimal mass

The goal of this first optimization approach is to reach the minimal mass for a structure to be sufficient. Both the base models of the design variants, and the models of the scenarios are optimized using this approach. The design variants are optimized to determine the minimal mass for each of the initial design options. The scenarios are optimized to research the minimal mass that can be achieved after changes. The approach is illustrated in image 28. The optimization process consists of two steps; removing bracing elements and cross-section optimization.

During the creation of the models, bracing elements were placed at all possible locations, as a result, many more bracing elements were placed then needed. The first step is therefore to remove some of these elements. With the 'BESO for Beams' component from Karamba, the elements that carry the least load are inactivated. To ensure that all levels have some bracing, this step is performed per storey, after which the lists of inactive elements are combined.

The elements that are inactivated for the design variants are then also inactivated for the related scenario models. As a result the placement of the bracing elements is the same for each scenario. Were this not done a lot of changes would possibly be required to go from the initial design to the scenarios, solely for the bracing.

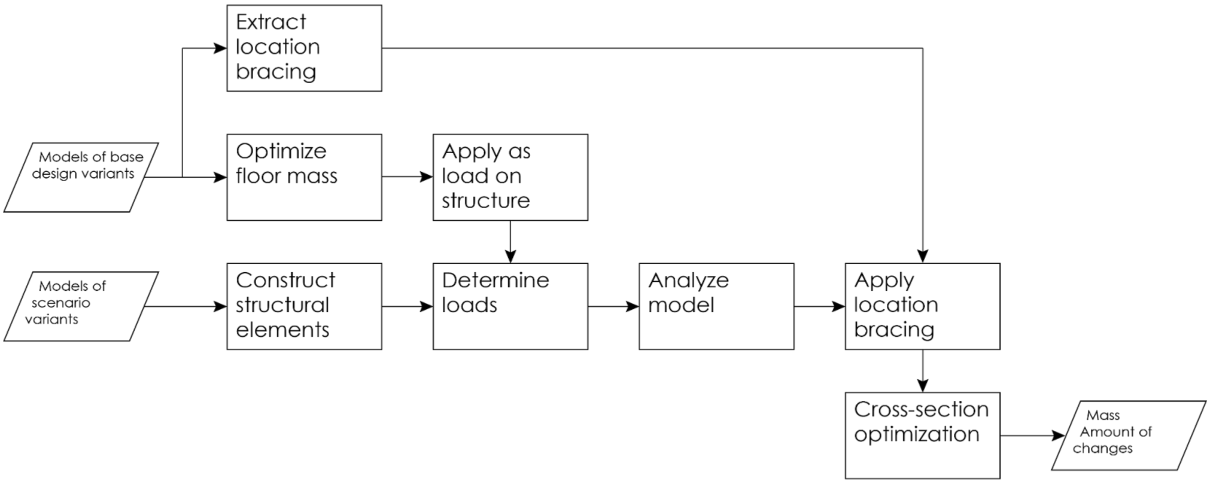


Image 28: Workflow - Minimal mass approach (author).

Finally, the cross-sections of the beams and columns are optimized using the 'Optimize Cross Section' component of Karamba. This component functions as an "Automatic selection of the most appropriate cross sections for beams and shells" (Preisinger, 2021). This component takes cross sections from a predetermined list, thereby making this a discrete optimization. For each element it takes the first cross-section in the list that suffices the boundary conditions (see image 29). These boundary conditions consist of a maximum displacement and a maximum utilization.

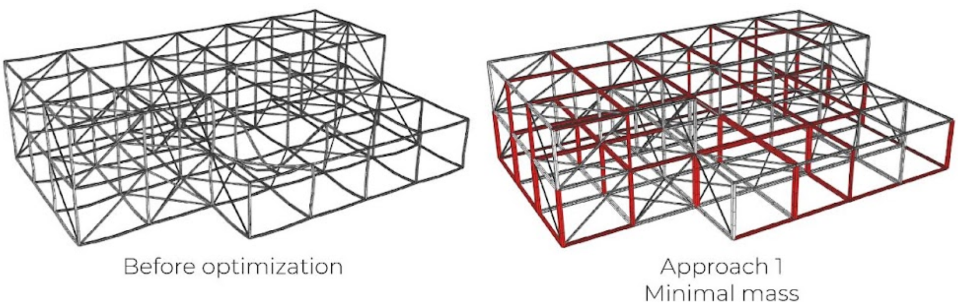


Image 29: Changed elements - Minimal mass approach (author).

7.3 Minimal changes

While the minimal mass optimization approach was applied on both the design variant models and the scenario models, this approach is only applied to the scenario models. The approach is meant to result in the lowest amount of changes to adapt the design variants into the different scenario configurations. The approach differs from the previous approach in two ways, as can be seen in image 30.

Firstly, the cross-sections from the elements of the optimized design variant models are extracted and applied to the elements of the scenario models. So instead of having the smallest possible cross-section, all elements have the cross-section of the initial design stage. This is required as the optimization will start making changes to these cross-section, to arrive at the smallest amount of changes needed.

Secondly the 'Optimize Cross Section' component is not used, as this would recalculate all the elements in the model. Instead the structural elements are changed one by one. To achieve this the Anemone plug-in is used to create a loop. First the cross-section of just one element is increased, and the model is analyzed to check whether it meets the requirements. If it does not meet the requirements, the cross-section is increased again. This continues until either the requirements are met, or until the cross-section is increased a predetermined amount of times. If the requirements are still not met, the cross-section of another element is also increased. Which elements are chosen to be increased is determined on the utilization of the elements. When a new element needs to be added, the utilization of all elements is calculated. The element with the largest utilization, that has not been adapted yet, is added to the list of elements to increase the cross-section of. This cycle continues until the requirements are met (see image 31). These requirements are the same as with the previous approach, being the maximum displacement and the maximum utilization. By adding one element to the group of changed elements at a time, the minimum amount of changes can be determined.

In case of the second scenario type however, the cross-section optimization component is used for the added structure to save time. The elements are optimized before the step by step change optimization, otherwise the optimization could focus too much on the added structure. This way the cross-sections of the added elements can be increased beforehand, as this would not alter the amount of modifications needed. By determining which elements are added, their IDs can be given as input to the cross-section optimization, which will only optimize these elements.

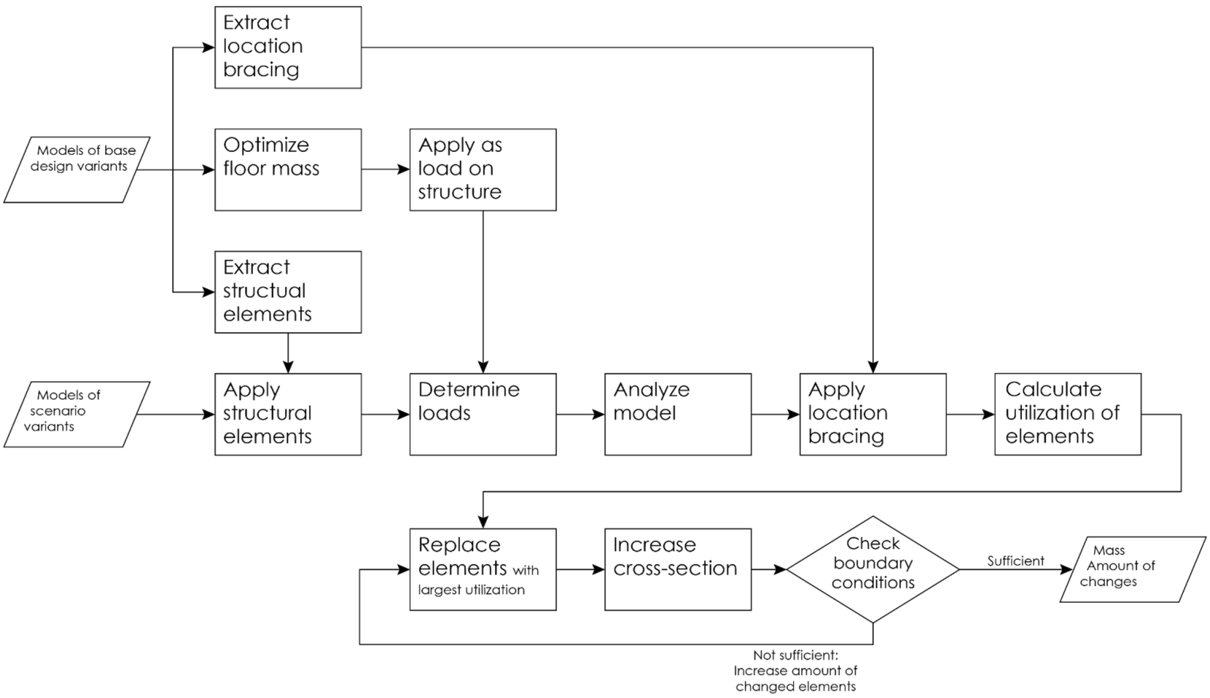


Image 30: Workflow - Minimal changes approach (author).

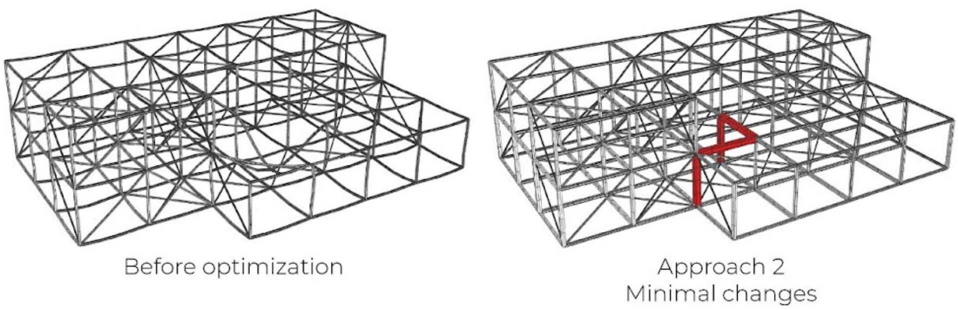


Image 31: Changed elements - Minimal changes approach (author).

7.4 Discussion

Both of the approaches described above have their advantages and disadvantages, the most important of which will be discussed in this section.

Firstly, optimizations of test models demonstrated that the process used for the "minimal mass" approach does not always deliver the lowest mass. On occasion the "minimal changes" approach delivered models with a lower mass. After doing more literature research it became clear that the lowest mass is not always achieved by the 'Optimize Cross Section' component.

"Behind the scenes Karamba3D iteratively adapts temporarily the strength of the materials. This may lead to uneconomic results in case of structures where the maximum displacement occurs in a small region, whereas the rest of the structure shows a much smaller deformation." (Preisinger, 2021)

In the scenarios that are incorporated in the workflow it is indeed possible that the maximum displacement occurs in a small region. This is especially the case for the removing elements scenario. When a column is removed, the beams above it deform much more than the other elements in the structure, as can be seen in image 32.

Nonetheless the minimal changes approach also does not result in the lowest mass, as this was not the goal of the approach. This approach also has other disadvantages. Firstly, the approach is a lot slower than the other, due to the large amount of calculations needed to be done one after the other. The speed is also dependent on the amount of elements that will need to be changed; the more elements need to be changed, the longer the process remains running. However, the number of changed elements can be limited, to limit the run time. But this results in another disadvantage, being that the model might not meet the requirements. In this case the minimal amount of changes remains unknown.

Another disadvantage that impacted both approaches was the displacement of the bracing elements. The displacement output from Karamba considers all elements. As a result of the weight, length and small cross-section of the bracing elements, these elements tended to result in the highest displacement in the models. However, in contrast to other structural elements, bracing elements are allowed to have a relatively high displacement. To counteract this displacement, the specific weight of the bracing elements was set to zero. Subsequently, the weight of the bracing elements is not taken into consideration for the total mass of the structure either. Nonetheless, as the weight of the bracing elements does not change between the different scenarios, this does not impact the comparison between the different variants and scenarios.

All of these disadvantages might not occur when another program is used for these approaches. Further research would be required to test this, however this falls outside of the scope of this project.

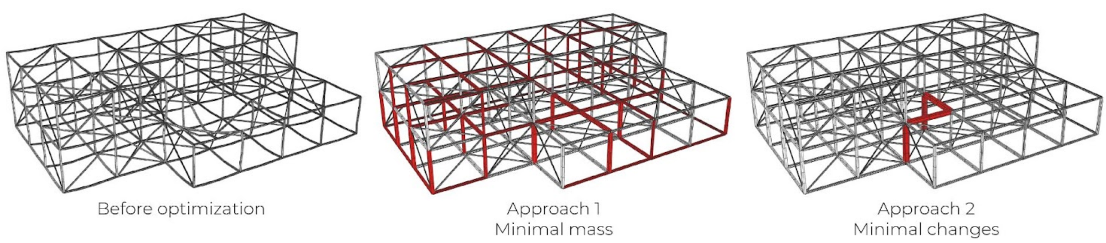


Image 32: Changed elements - Optimization approaches (author).

From this point on, the “minimal changes” approach will be used for optimization of the scenarios. This is due to the “minimal mass” approach not reaching its goal of always providing the lowest mass, instead giving on average similar masses as the “minimal changes” approach. At the same time the amount of changes that would be required for the “minimal mass” approach often far exceeds the amount needed for the “minimal changes” approach. This is probably due to the entire model being recalculated in the optimization.

8. Output Workflow

There are multiple ways to use the information that is provided by the computational workflow. This chapter will focus on how the output of the workflow is structured and how this can be used to inform design decisions. As discussed in chapter 5 there are two methods to increase the adaptability of a design. These are applying demountable connections and oversizing elements. Furthermore the workflow can be used to determine the most suitable design variant for these methods.

In the previous chapters the setup of the different models and their optimization was discussed. So now the optimized models of the scenarios are available. However, these models need to be compared to the design variant to gain the needed information to inform the design process. This is possible due to the element IDs referring to the location of the elements. By linking these IDs to the cross-sections, the cross-section of each element in all of the scenarios can be compared to the design variant (see step 5 of the workflow in appendix C). If the cross-section is not the same as it was in the original design variant, then the element would have to be changed. This way all required information to compare the design variants can be gathered.The information that is most useful for the comparison depends on which method is taken to design the structure.

8.1 Demountable connection

The best design variant for this approach is based on the mass before changes and the amount of changes needed. The mass of the design variants before changes can be determined without the scenarios, as this is the result of the cross-section optimization of the design variants. For the list of all elements that might have to be changed, the scenarios do have to be compared to the design variant. For each scenario all elements are compared to the design variant (see image 33). Each time the cross-section does not match, this element ID is added to a list. However, the information about these scenarios need to be combined in one model, as the goal is to be able to adapt to any of the scenarios. These lists of element IDs are therefore combined, at the same time removing any duplicates. The element IDs are used to determine the location of the elements that need to be demountable. Meanwhile, the length of the list determines the amount of demountable elements needed for each design variant. As both the mass and the amount of demountable elements are determined for each of the variants, this can be used to decide on the choice of grid (see table 1 and image 34). A design variant having the lowest mass and lowest number of demountable elements is preferred. If one variant has the lowest mass and another the lowest amount of demountable elements, the designer should consider which aspect is more important for their project.

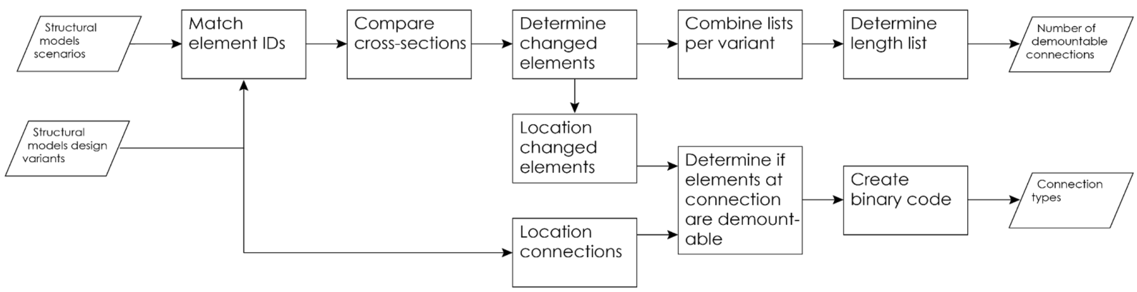


Image 33: Workflow - Demountable connections (author).

Table 1: Design variants for demountable connections method (author).

	Steel Mass design variants (kg)	Concrete Mass design variants (kg)	Amount of demountable elements
Grid 1	16.867	168.780	25
Grid 2	18.144	170.720	51
Grid 3	23.701	198.220	32

At the same time this information can be used to inform the choice of connection type. A lot of demountable connections already exist for steel structures, as bolted connections are quite common for these structures. However welded connections, or continuous elements are also still common. These two aspects remove the ability to disassemble certain elements. For the proposed workflow it is required that some elements can be replaced without changing the entire building. The list of demountable elements can be used to determine which connections need to be demountable.

For each element surrounding the node it is assessed whether the element is within the list of elements that need to be demountable. Each node is given a binary code consisting of six numbers, one for each of the surrounding elements. This code can be used to determine what connection might be needed (see appendix E). An overview of which type of connection is required at each node is then created (see image 35). A catalog of connections could be created to aid the decision for a certain connection. For instance, if just a beam needs to be demountable the node could be a standard bolted connection. But if all six surrounding elements need to be demountable, a more complex connection is needed.

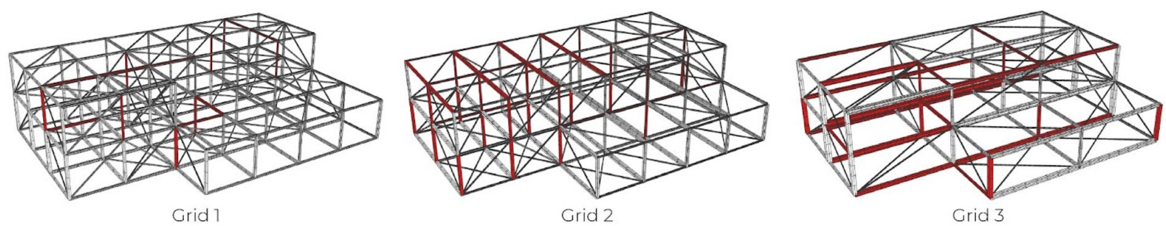
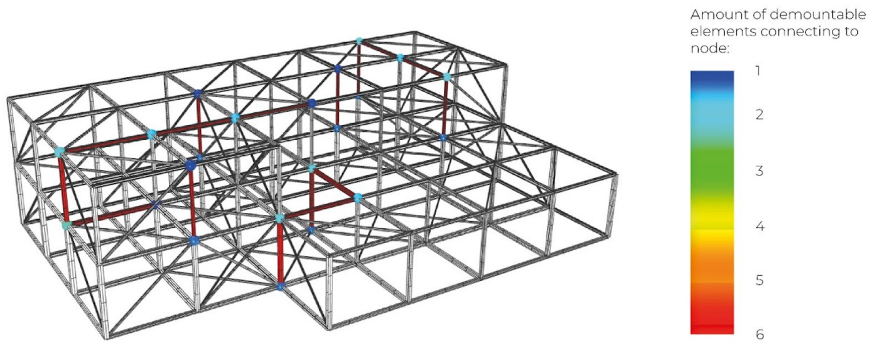


Image 34: Design variants for demountable connections method (author).



Connection type	Nodes count
1	68
2	2
3	3
4	7
5	4
7	5
8	1

Image 35: Demountable connections grid 1 (author).

Exactly these connections with six demountable elements form the biggest challenge. The elements need to be able to be replaced while the rest of the structure stays intact. Therefore the connection needs to be reachable, without having to disassemble the whole building. This type of connection does not exist yet, but inspiration could be gathered from modular connections. In their research Rajanayagam et al. (2021) describe multiple newly developed modular building connections. Most of these connections contain some type of extra part to connect the structural elements to each other (see image 36). Whether this be a plate bolted to the side of the other elements, or a box that is put into two hollow elements to connect them. Often these parts have openings to ensure the reachability of the connection.

However, these connections are designed for modular buildings. The connections join modules together, and as a result, they cannot be immediately translated into connections for non-modular buildings. Nonetheless, some of these connections could be adapted to be used for non-modular buildings as well.

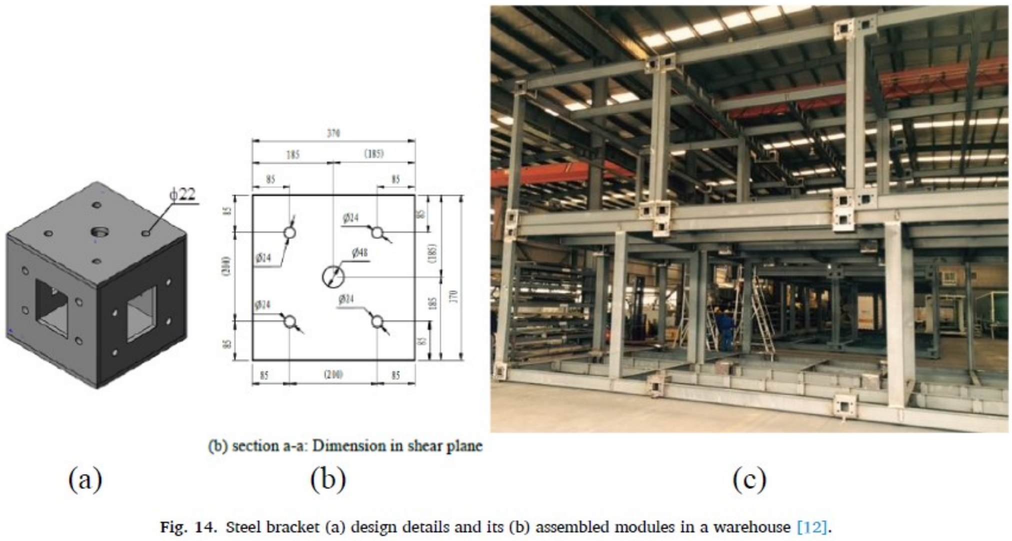


Image 36: Steel bracket, design details, and its assembled modules in a warehouse (Rajanayagam et al, 2021, p.1914)

8.2 Oversizing specific elements

The other method to increase the adaptability of a building would be to oversize elements beforehand. This would increase the material use at the beginning, which is undesired. But by determining where this oversizing would be needed, the material use can be limited.

To determine which design variant would fit best for this method, the mass of the structure after the elements are oversized is required (see table 2). Therefore, for each of the design variants a structure needs to be made where the needed elements are oversized (see image 37). These structures are created by using the element IDs to compare the cross-sections of all the scenarios to the design variant.

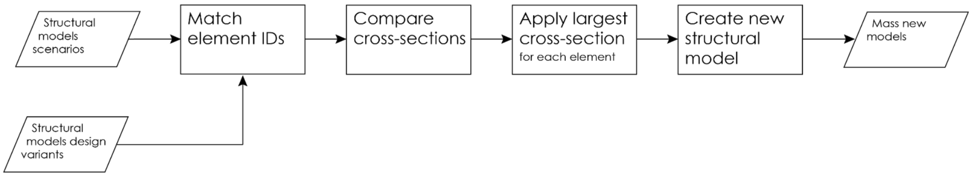


Image 37: Workflow - oversizing elements (author).

The cross-sections are compared element by element. For each element the biggest cross-section is taken from the list of cross-sections across the different scenarios. A new structure is assembled with the largest found cross-section for each of the elements (see image 38). This is repeated for each of the design variants. By determining the mass of these structures a design variant can be chosen. The design variant with the lowest mass is preferred.

Table 2: Design variants for oversizing (author).

	Concrete Mass after oversizing (kg)	Steel Mass after oversizing (kg)
Grid 1	232.800	19.921
Grid 2	232.800	21.761
Grid 3	270.300	29.650

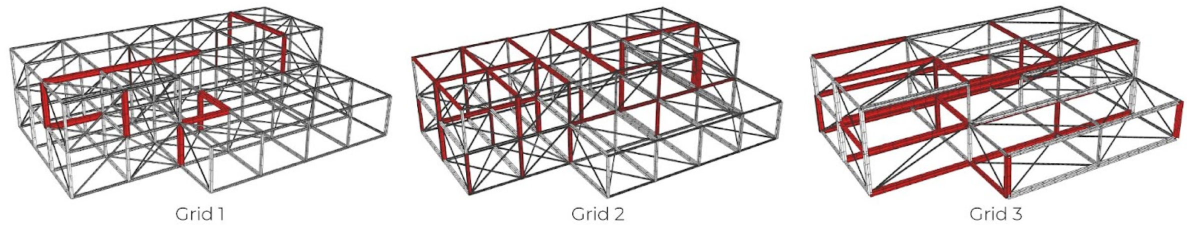


Image 38: Design variants for oversizing (author).

III Testing Phase

9. Assessment

The final stage of this research is to test how the workflow performs when put into practice. To achieve this a test case is created, on which the workflow will be applied. Furthermore a workshop with one of the previous interviewees is conducted, to test whether the workflow would be usable in practice.

9.1 Test case

A test case is used to compare the impact of the workflow on the way a building would adapt over time. For the same initial design, two structures will be created with the workflow, following the two different proposed methods, and one structure will be created without the workflow. The results of these models will be compared by applying possible life-cycles to the models. This will give insight into the adaptability of the three structures.

9.1.1 Methodology

For the test-case a small office building will be taken as the subject, as office buildings are more likely to be subjected to changes compared to for instance residential buildings. The size of the building will be limited, since the time required to optimize is related to the amount of elements in the structure. To limit the time required for the optimizations, the size of the building is limited to two stories and a footprint of roughly 22 by 15 meters.

Six load cases are applied to the models. These consist of one for weight, one for use, and four for wind from all different directions. The load cases have been multiplied with a safety factor. The optimization is set to meet a utilization requirement of maximum 100 %. Furthermore the optimization is set to meet a maximum deformation. This deformation should be 1/250 of the span, but has been adjusted to 1/200 of the span, to account for the safety factor that is incorporated in the load cases.

Six scenarios are taken into account in the workflow, three of each scenario type. The scenarios are chosen based on what would be probable from an architectural standpoint. Furthermore, when determining the scenarios a variety of scenarios is ensured, such as difference in size and location of the changes.

The workflow is used to design two different structures, using the methods discussed in chapter 8. These methods are “demountable connections” and “oversizing specific elements”. These structures will be compared with a third structure, which is based on more traditional building methods. This structure will also be optimized to have a minimal mass, but will not be designed to be adaptable. This optimization approach is similar to the design process of the structure for the Nationaal Militair Museum in Soesterberg (see image 17 in chapter 5). The structure will have continuous columns, with beams bolted in between. As a result, beams could be replaced, but to replace a column a lot of other elements will have to be replaced as well. This structure will act as a baseline to compare the other methods to.

The three structures are then subjected to the same changes, to test the adaptability and material use of the designs. Three life cycles are applied to the structures.

1. No changes required
   It is possible that during the lifespan of the building no structural changes are required at all. This life cycle will be used as a baseline for the other life cycles.
2. A series of anticipated scenarios
   The structural models are created to be adaptable to any of the possible scenarios that were taken into account in the workflow. A combination of these scenarios has not been taken into account. However, over a longer period of time it is likely that multiple changes would be necessary. This life cycle will investigate the impact this has on the functionality of the workflow.
3. Unanticipated scenarios
   The workflow only takes into account some predetermined scenarios. However it is impossible to predict what will happen in the future, and what changes might be required. This life cycle will therefore test how well the structure can adapt to scenarios that were not taken into account in the workflow.

To test these life cycles a change is made to the base model of the structure. Then the base model is given as input for the "minimal changes" approach. However, the approach extracts the cross-sections from the three structures designed with the workflow, instead of extracting those of the design variants. This allows for the simulation of how these structures could be altered to adapt to the changes.

For each change the following information is gathered: does the structure need to be adapted, which elements need to be changed to allow for this scenario, how much weight is added and removed from the structure, and how big is the load that is applied on the foundation piles. With this information the amount of needed alterations as well as the total mass of used materials after each scenario can be determined.

The amount of alteration is used to indicate the adaptability of the structure, less required changes signifies a better adaptability. This amount includes both the elements that the workflow indicates as having to be replaced as well as any elements that would also have to be disassembled to enable this replacement (see image 39). For instance if the element that needs to be replaced is part of a column that continues over multiple storeys, the other parts of said column would also need to be replaced. On the other hand, if the element has demountable connections on either side, the element can be replaced without removing any other elements.

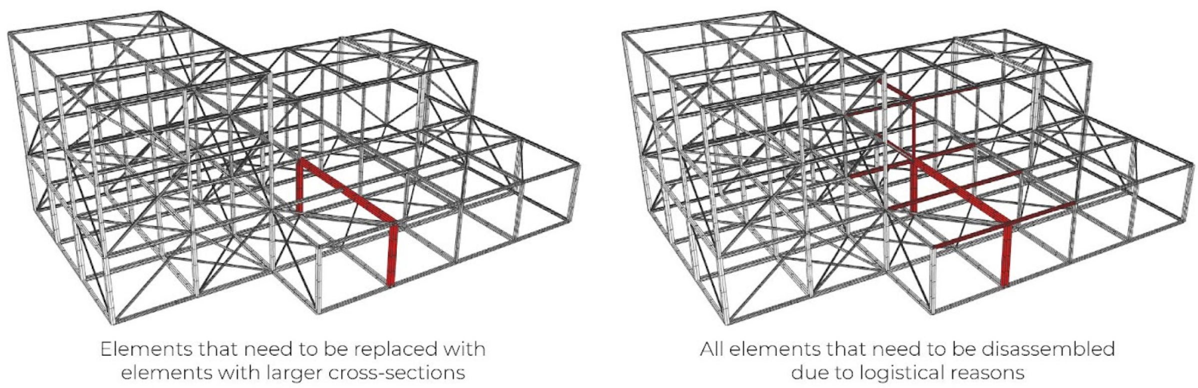


Image 39: Elements that need to be replaced

Mass is used to determine the material use, to compare the environmental impact of the different structures. This is possible as only one type of building structure is taken into account in the workflow. Therefore the environmental impact per kg remains the same. However, as two materials are used in the structure, steel and concrete, the mass of these will be determined separately.

The load on the foundation piles gives an indication about whether the foundation would be strong enough to carry the extra load that is applied. The foundation lies outside the scope of this project, but it is an important aspect to keep in mind.

9.1.2 Creating adaptable structures

As input the floorplan of the building and height of the storeys is required, as can be seen in image 40. This input is used to create the different design variants, with differing grids. These are chosen from a predetermined set of grid sizes (see appendix D). The grids that align the best with the floor plans are 3.6 by 3.6, 4.8 by 3,6 and 7.2 by 4.8 (see image 41). The smaller grids usually align better with the floorplan and therefore are more likely to be chosen for the design variants.

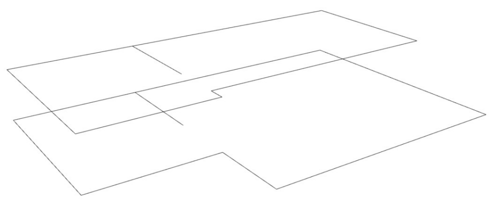


Image 40: Line drawing floor plans (author).

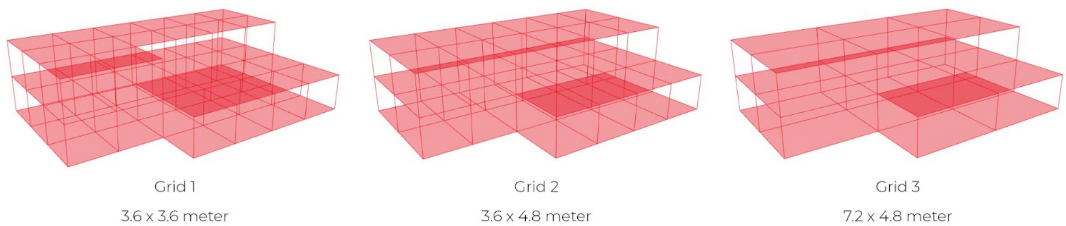


Image 41: Grids that align best with the floor plans (author).

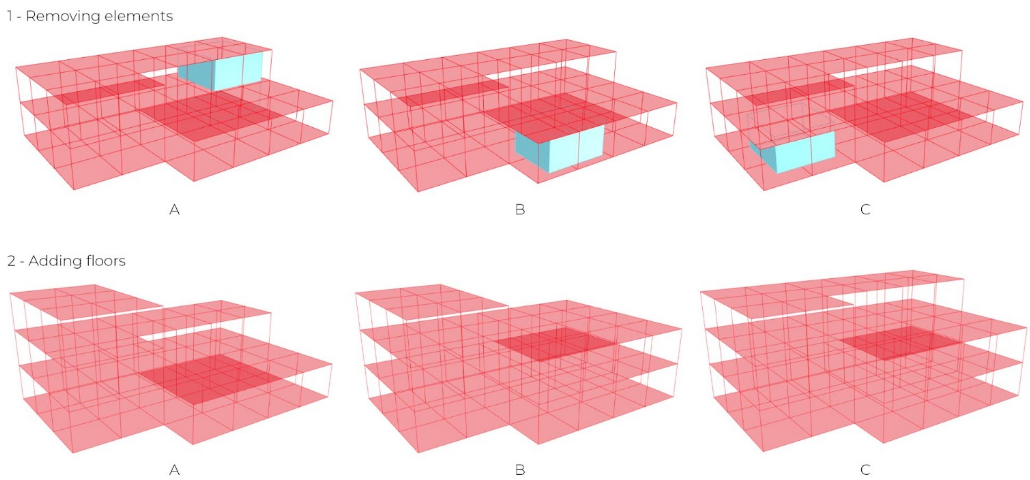


Image 42: Scenarios that have been taken into account in the optimization (author).

Table 3: Information about the design variants (author).

	Steel Mass design variants (kg)	Concrete Mass design variants (kg)	Amount of demountable elements	Concrete Mass combined scenarios (kg)	Steel Mass combined scenarios (kg)
Grid 1	16.867	168.780	25	232.800	19.921
Grid 2	18.144	170.720	51	232.800	21.761
Grid 3	23.701	198.220	32	270.300	29.650

With these grids the models for the design variants are made. The scenarios (as shown in image 42) are applied to these design variants. The "minimal changes" approach is used to determine the mass for each scenario structure, and the amount of changes required to enable this adaptation. The resulting mass and number of changes can be compared over the different grids, to better inform the decision for a grid size (see table 3). With this information the three structural models are made to test during this test-case (see image 43). For each of these approaches different criteria are used to determine which grid is most suitable, as described below:

1. Baseline
   This model does not take adaptations into account, therefore the structure that is considered most suitable is the design variant with the lowest mass. As shown in table 3, the design variant with the lowest mass, both for steel and concrete, is grid 1.
2. Demountable connections
   The best option for this method has the lowest amount of demountable elements as well as the lowest mass for the initial design. Grid 1 and grid 3 have a similar amount of elements that would have to be demountable, but the mass of grid 1 is considerably lower. Therefore grid 1 is also considered the best design variant for this method.
3. Oversizing specific elements
   For this method all elements that might have to be replaced are already given the bigger cross-section that would be needed. Therefore no demountable elements should be needed. The grid that is most suitable is instead determined by the mass of the models with the oversized elements, which in this case is again grid 1.

The structures that result from these methods are the final output from the computational workflow. The architect or structural engineer can consider these options and decide which would be most suitable for the project they're working on at that moment.

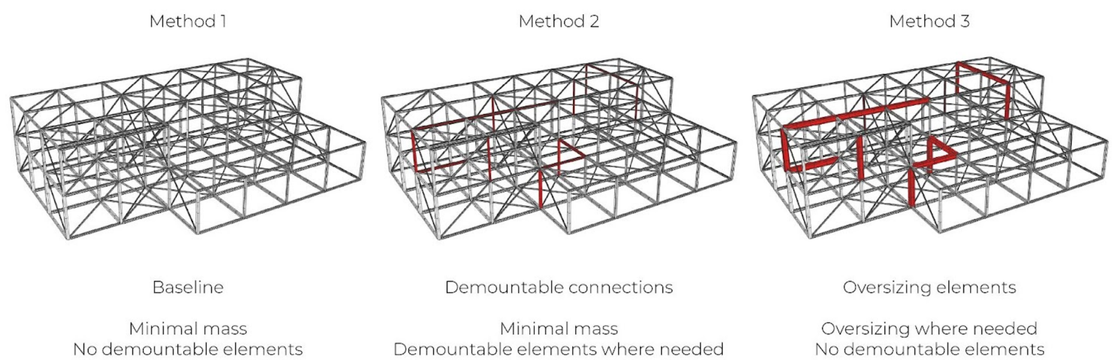


Image 43: Structures created with the computational workflow (author).

9.1.3 Life-cycles

To assess whether the workflow had a positive impact on the adaptability of the structure, the structures are tested by applying different life-cycles on them. After each adaptation the adaptability and material use is determined.

1 - No changes required

The results of the first life-cycle are to be expected, but it is good to keep in mind that it's possible no changes would be required at all. In this case, both the first and second method have the same material use, as they are both based on grid 1 of the design variants (see table 4). However, the second method does have demountable elements, which will likely increase the costs of the structure. Understandably the third method has a higher mass, and is therefore least material efficient when no changes occur.

Table 4: Life-cycle 1 - Results (author).

Life cycle 1

Method 1 - Standard structure			**Method 2- Demountable conncections**			**Method 3 - Oversizing specific elements**		
Steel - Mass	kg	16.847	Steel - Mass	kg	16.847	Steel - Mass	kg	19.912
Concrete - Mass	kg	168.780	Concrete - Mass	kg	168.780	Concrete - Mass	kg	168.780
Force on foundation	kN	153,4	Force on foundation	kN	153,4	Force on foundation	kN	153,5

2 - Series of anticipated scenarios

For the second life-cycle the anticipated scenarios are combined. The scenarios are applied one after the other alternating between the two types starting with the "removing elements" scenario type. The order of scenarios is the same as shown in image 44 .

During the life-cycle it becomes clear that the structures are not able to adapt, the way they were intended to, when too many scenarios were combined, regardless of which method was used (see table 5). For the second method elements that are not demountable had to be changed. And for the third method, changes have to be made, even though the structure was supposed to be sufficient for all scenarios. This is likely due to the added structures not being optimized for the scenarios of removing elements, thereby adding weight without redistributing the force.

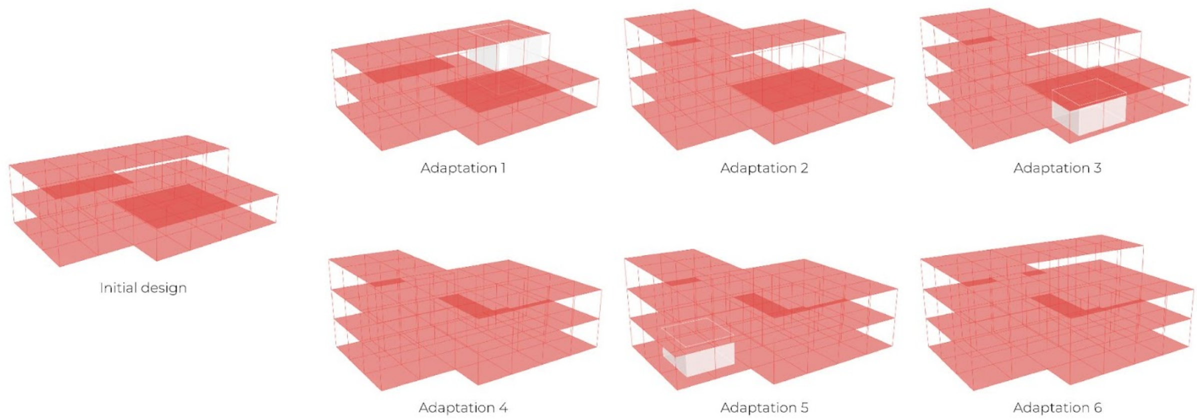


Image 44: Life-cycle 2 - Adaptations (author).

Table 5: Life-cycle 2 - Results (author).

Life cycle 2		Initial Design	Adaptation 1	Adaptation 2	Adaptation 3	Adaptation 4	Adaptation 5	Adaptation 6
Method 1 - Standard structure								
Sufficient?			No	Yes	No	Yes	No	Not possible
Steel - Mass	kg	16.847	16.888	18.790	19177	22.553	23.667	
Steel - Mass removed	kg	-	1.890	-	1.257	-	2.518	
Steel - Mass added	kg	-	1.931	1.902	1.644	3.376	3.632	
Steel - Total mass used	kg	16.847	18.778	20.680	22.324	25.700	29.332	
Concrete - Mass	kg	168.780	157.140	174.600	174.600	197.880	197.880	
Concrete - Mass removed	kg	-	11.640	-	-	-	-	
Concrete - Mass added	kg	-	-	17.460	-	23.280	-	
Concrete - Total mass used	kg	168.780	168.780	186.240	186.240	209.520	209.520	
Required changes		-	4	-	4	-	5	
Changes due to logistics		-	13	-	11	-	25	
Force on foundation	kN	153,4	150,9	201,1	201,1	201,2	235,7	
Method 2- Demountable connections								
Sufficient?			Yes	Yes	No	Yes	No	Not possible
Steel - Mass	kg	16.847	16.888	18.790	19177	22.553	23.667	
Steel - Mass removed	kg	-	825	-	506	-	983	
Steel - Mass added	kg	-	866	1.902	893	3.376	2.097	
Steel - Total mass used	kg	16.847	17.713	19.615	20.508	23.884	25.981	
Concrete - Mass	kg	168.780	157.140	174.600	174.600	197.880	197.880	
Concrete - Mass removed	kg	-	11.640	-	-	-	-	
Concrete - Mass added	kg	-	-	17.460	-	23.280	-	
Concrete - Total mass used	kg	168.780	168.780	186.240	186.240	209.520	209.520	
Changes demountable		-	4	-	2	-	-	
Changes not demountable		-	-	-	2	-	5	
Changes due to logistics		-	-	-	2		8	
Force on foundation	kN	153,4	150,9	201,1	201,1	201,2	235,7	
Method 3 - Oversizing specific elements								
Sufficient?			Yes	Yes	No	Yes	No	No
Steel - Mass	kg	19.912	19.367	21.223	21.200	23.875	27.167	31.524
Steel - Mass removed	kg	-	516	-	198	-	3.890	2.923
Steel - Mass added	kg	-	-	1.856	175	2.675	7.182	7.280
Steel - Total mass used	kg	19.912	19.912	21.768	21.943	24.618	31.800	39.080
Concrete - Mass	kg	168.780	157.140	174.600	174.600	197.880	197.880	221.160
Concrete - Mass removed	kg	-	11.640	-	-	-	-	-
Concrete - Mass added	kg	-	-	17.460	-	23.280	-	23.280
Concrete - Total mass used	kg	168.780	168.780	186.240	186.240	209.520	209.520	232.800
Required changes		-	-	-	2	-	18	16
Changes due to logistics		-	-	-	-	-	28	25
Force on foundation	kN	153,5	151,0	202,4	202,4	204,7	266,0	279,4

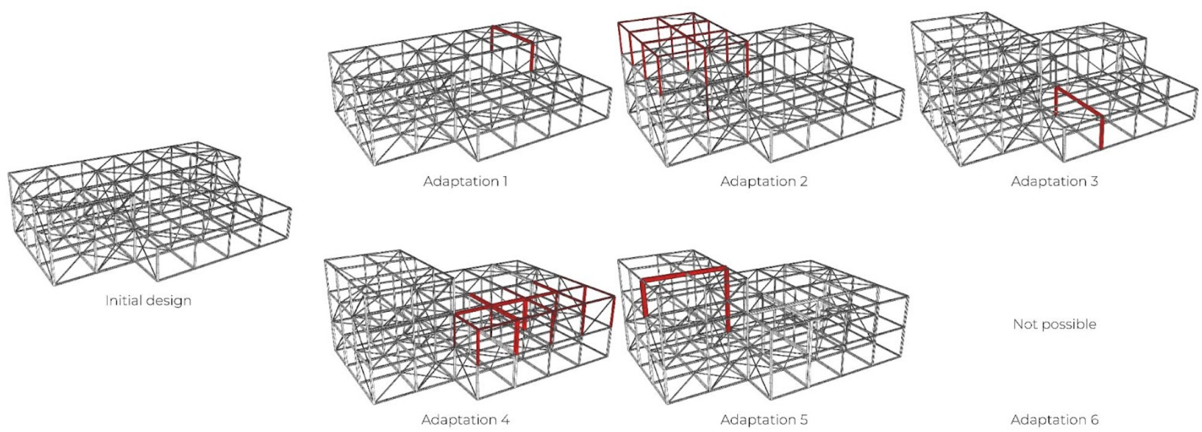


Image 45: Life-cycle 2 - Elements that need to be replaced according to the computational workflow for the method of demountable connections (author).

Surprisingly the second and fourth scenarios, adding floors to the building, can be done without changing anything for all of the methods. This is probably a result of the cross-section optimization of the added elements before the “minimal change” optimization. The restricting requirement for the scenarios is often the displacement. The cross-section optimization already brings the displacement below the maximum, removing the need to make any alterations to the existing structure. For the last adaptation, the optimization beforehand can probably not handle the displacement, which is why for this scenario changes are required. For the first and second method, the optimization could not even finish, as the amount of required changes reached above the set maximum amount of changes.

Even though none of the methods were able to adapt to the combination of all scenarios, the second and third can be adapted to the scenarios easier. Firstly, the structure from the first method already needs to be changed after the first scenario. The other methods first need to be changed for the third scenario. But more importantly the amount of changes and added mass is generally lower for the second and third method. This is largely due to the amount of extra changes that are needed to enable the required changes. For instance, for the third adaptation, both the standard structure and the demountable connections structure require four elements to be replaced by elements with a larger cross-section. As a result a total of eleven other elements need to be disassembled in order for those four elements to be replaced, in the case of the standard structure. For the structure with demountable connections on the other hand, two of the four are demountable, due to the demountable connections. The other two elements can be replaced by just disassembling two more elements.

The standard and demountable connections method both start with the same mass. But as less changes are needed because of the demountable connections, the total mass required to keep adapting the second method is smaller. Similarly the mass of the oversizing method starts off higher than the standard method. But as less material needs to be added, the total mass needed for the standard method is higher from the third scenario. However, due to the large amount of adjustments needed for the fifth scenario of the oversizing method, the total mass of this method surpasses that of the standard method again.

Overall the efficiency of the structures remains similar throughout the entire life-cycle. The average utilization of the elements in all three structures increases slightly from around 31% to around 33% for the oversizing method and 37% for the other methods. This is likely again due to the deformation being the limiting factor to determine when a structure suffices, and not the maximum utilization. Therefore the utilization of the elements is always under 80% even though the actual allowed maximum is 100%. It is interesting to see that the utilization for the oversized elements is lower. Which is likely due to the higher load-bearing capacity of the total structure, due to its oversized elements.

Finally the maximum force that was present at a foundation pile was also gathered. This shows that the load on the foundation can increase significantly. A possible solution would be to oversize the piles, which might lead to unnecessary material use. Another solution might be to add extra piles during adaptations, which would likely take a lot of effort. However, this information is the maximum present load in the foundation, so it might also be possible that the load could be redistributed to other piles to some extent. For this information would have to be gathered about the loads in the entire foundation.

3- Unanticipated scenarios

In the third life-cycle a series of scenarios that were not taken into account in the workflow are applied to the structures. The scenarios are chosen similarly as when designing the scenarios that were taken into account. A mix of four scenarios with different sizes and locations are chosen, two of each scenario type (see image 46).

There are some similarities between this life-cycle and the second life-cycle. Firstly, none of the methods are able to adapt to all of the scenarios (see table 6). In this case, this is to be expected, as these scenarios were not taken into account when designing the structures. Secondly, the structures are able to adapt to one of the scenarios where floors are added. This is likely due to the cross-section optimization of the added elements, which brings the maximum deformation below the maximum allowed limit. Thirdly, the utilization of the elements increases slightly from around 31% to, in this case, 36% for the method of oversizing and 38% for the other two. That the utilization is slightly higher than in life-cycle 2 might be because of adaptation 3, where a large amount of floor space is added. Another reason might be that the structures are not optimized for these scenarios, which results in higher utilization in elements that were not designed for the higher loads. Lastly, the force on the foundation increases considerably, from around a maximum of 150 kN on a foundation pile, to a maximum of 260 kN or even 300 kN.

However, during this life-cycle the difference between the first and the second method is smaller than during the previous life-cycle. The results only deviate from each other in the last adaptation. This is due to the scenarios requiring elements that were not demountable to be changed for all other adaptations. Furthermore some of the elements that were adjacent to the elements that needed to be changed in the last adaptation, were demountable in the second method. This leads to a further decrease of elements which need to be disassembled. As the results of the first two methods are so similar there is not a lot of benefit from the demountable connections in the second approach.

The elements that have to be replaced for the third method are also similar to those of the standard structure. Again with the exception of the last adaptation, in which case more elements had to be disassembled for the method of oversizing elements. The high amount of changes for this method is due to multiple columns needing to be replaced according to the computational workflow. This results in a lot of additional elements needing to be disassembled. As overall more changes are needed for this method, on top of a higher material use in the initial design, the material use is higher during the entire life-cycle. There is therefore no benefit for using this method, in case the actual scenarios don't align with those that were taken into account.

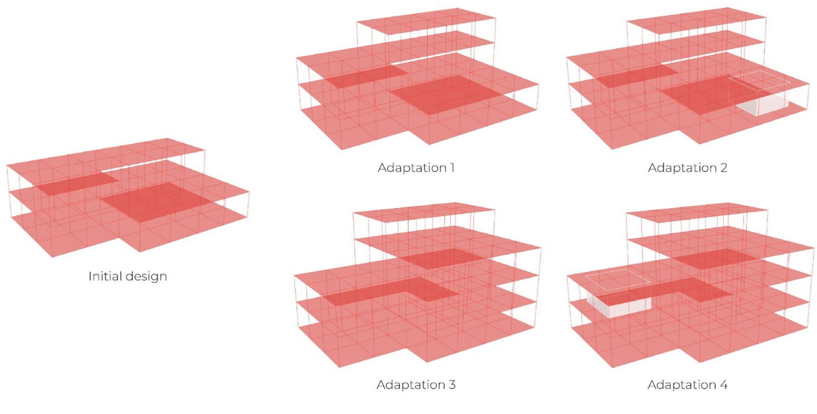


Image 46: Life-cycle 3 - Adaptations (author).

Table 6: Life-cycle 3 - Results (author).

Life cycle 3		Initial Design	Adaptation 1	Adaptation 2	Adaptation 3	Adaptation 4
Method 1 - Standard structure						
Sufficient?			Yes	No	No	No
Steel - Mass	kg	16.847	19.317	19.778	28.945	29.450
Steel - Mass removed	kg	-	-	1.820	942	2.612
Steel - Mass added	kg	-	2.470	2.281	10.109	3.117
Steel - Total mass used	kg	16.847	19.317	21.598	31.707	34.824
Concrete - Mass	kg	168.780	192.060	192.060	261.900	261.900
Concrete - Mass added	kg	-	23.280	-	69.840	-
Concrete - Total mass us	kg	168.780	192.060	192.060	270.630	270.630
Required changes		-	-	5	3	6
Changes due to logistics		-	-	16	7	24
Force on foundation	kN	153,4	202,6	201,6	262.0	264,7

Method 2- Demountable connections						
Sufficient?			Yes	No	No	No
Steel - Mass	kg	16.847	19.317	19.778	28.945	29.450
Steel - Mass removed	kg	-	-	1.820	942	1.399
Steel - Mass added	kg	-	2.470	2.281	10.109	1.904
Steel - Total mass used	kg	16.847	19.317	21.598	31.707	33.611
Concrete - Mass	kg	168.780	192.060	192.060	261.900	261.900
Concrete - Mass added	kg	-	23.280	-	69.840	-
Concrete - Total mass us	kg	168.780	192.060	192.060	270.630	270.630
Changes demountable		-	-	-	-	1
Changes not demountable		-	-	5	3	5
Changes due to logistics		-	-	16	7	11
Force on foundation	kN	153,4	202,6	201,6	262.0	264,7

Method 3 - Oversizing specific elements						
Sufficient?			Yes	No	No	No
Steel - Mass	kg	19.912	22.476	22.952	30.616	31.547
Steel - Mass removed	kg	-	-	2.190	1.113	5.004
Steel - Mass added	kg	-	2.564	2.666	8.777	5.935
Steel - Total mass used	kg	19.912	22.476	25.142	33.919	39.854
Concrete - Mass	kg	168.780	192.060	192.060	261.900	261.900
Concrete - Mass added	kg	-	23.280	-	69.840	-
Concrete - Total mass us	kg	168.780	192.060	192.060	270.630	270.630
Required changes		-	-	5	2	10
Changes due to logistics		-	-	16	7	48
Force on foundation	kN	153,5	201,3	205,1	305,4	300,8

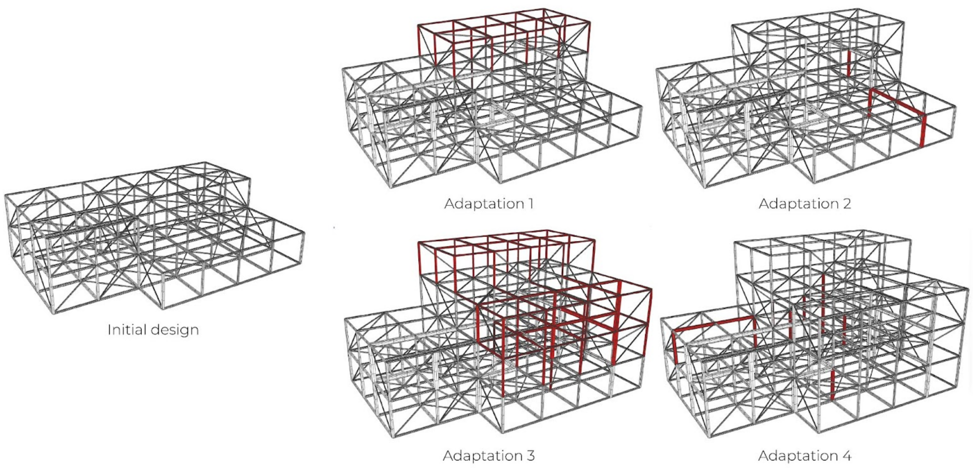


Image 47: Life-cycle 3 - Elements that need to be replaced according to the computational workflow for the method of oversizing elements (author).

9.1.4 Costs

One of the motivations behind the computational workflow was to minimize the costs of creating adaptable buildings. This is done by limiting the locations where the measures for more adaptability are applied. When compared with structures where the measures are applied throughout the entire building, the initial costs of the structures from the workflow can indeed be lower. In the case of the demountable connections method, less of these demountable connections are required, 22 out of a total of 90 connections. All other connections can be standard non-demountable connections. As non-demountable connections are less expensive than demountable connections, this lowers the costs for the structure. In the case of the oversizing method, the initial material use will be lower than if all elements are oversized. Lower material use also results in lower costs.

However, the structures that follow from the workflow do have an increased complexity, compared to other adaptable structures. The use of some oversized elements increases the amount of different types of beams and columns that are used in the building. Furthermore, this could also complicate the connections, as elements with a large difference in size would have to be connected to each other. The use of both demountable and non-demountable connections, leads to an increase of connection types that are used throughout the building. Furthermore, it is possible that very complex and expensive connections are required, when a high number of elements connecting in one node need to be demountable. This would depend on the design and the scenarios, as the structure in the test-case only required relatively simple connections with one or two demountable elements connecting in one node (see image 48).

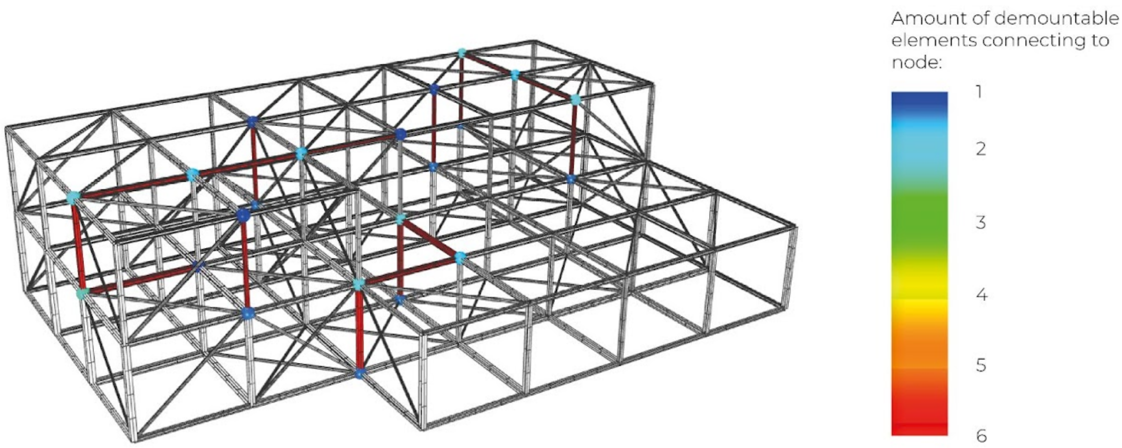


Image 48: Complexity connections (author).

The costs can also vary across the entire lifespan of the building. In the test-case it became clear that the workflow can result in less material being used when the actual changes across the building's life-span match the scenarios that were taken into account in the workflow. This reduction in material use results in a decrease of the costs across the years the building is in use. However, if the reality does not match up with the scenarios that were taken into account, the material use does not decrease significantly. In this case the costs of adaptations remain the same for the structure without adaptability measures and those with adaptability measures.

Lastly, the workflow also depends on the possibility to replace some of the elements within an existing structure. During the life-cycles, it is taken into account that some of the elements next to the elements that need to be replaced would also need to be disassembled.

However, there are also other implications of replacing structural elements. For instance, the structure would need to be temporarily supported during adaptations. The bracing elements are beneficial during this period as they provide stability during these adaptations. When elements are disassembled the fixed connections might not suffice to provide stability. Another difficulty would be the interior finishing of the building. This would make it harder for the structural elements to be reached and replaced.

9.2 Workshop

The usefulness of the computational workflow was also determined with a workshop. This workshop was held with one of the companies that were interviewed during the preliminary research phase of this project. This meeting was focused on establishing whether the workflow and proposed designing strategies could be implemented in practice. During this workshop the workflow was explained in a presentation, including a test-case of how the computational workflow would function in the design process. Afterwards, the computational workflow itself was shown. During the presentation the participant was able to make comments and ask questions about the workflow. Afterwards, the researcher asked the participant some questions about the possibility to use the computational workflow in practice and future improvements.

As a reaction to the presentation, the participant started off by expressing that oversizing of elements requires a sacrifice of materials at the start of the building's life-cycle. Therefore, limiting the amount of elements that are oversized could indeed lead to an improvement in terms of material use. Furthermore, they stated that there is an increase in the use of parametric design tools being used in practice. So a computational workflow could indeed be useful and could be implemented in a current design process.

However, they also stated that determining scenarios to take into account would be a difficult task. In some cases it would be possible to predict which scenarios are likely to occur in the future. But often this is not possible due to the large number of factors this depends on. It might therefore be likely that a scenario that was not anticipated will take place. Furthermore, the amount of scenarios that are taken into account should be limited in some way. When deciding on scenarios it might be tempting to include a large amount of scenarios, so that any future adaptation might be possible. However, this defeats the purpose of the workflow, as a lot of elements would need to be demountable or oversized.

The participant also proposed some ways to improve the workflow. First of all, they recommended expanding the workflow. The workflow could be expanded by adding extra scenario types to be considered. They stated that adding the scenario of increased loads on the structure would be particularly helpful, as the loads to be considered differ per function. Another aspect to expand upon would be the choice of building system. At the moment this is limited to a steel frame structure with concrete floors. If the workflow includes other structural materials and building systems, these could be compared in a similar way as the choice of grid size. Furthermore if multiple materials are considered, the carbon impact of the materials can also be taken into account.

Another proposed improvement relates to the usability of the building. Since the workflow selects larger cross-sections for columns and beams, this impacts the free height below said beams. It is possible that the remaining height is not sufficient for the use of the space. So instead of specifying the floor to floor height, the participant proposed specifying the free height that should be available under the beams. This ensures that the space below the beam remains usable even after adaptations.

Lastly, the participant proposed that the graphic representation could be improved. This would improve the usability of the workflow, as architects are generally visually orientated. An example would be to show the complexity of demountable connections with colors, or showing where the structure could be most improved with a heatmap.

9.3 Discussion

During the test-case it was found that the computational workflow does not ensure that the structure can adapt as intended when multiple changes are made across the life-cycle. As mentioned this is likely because the added structure is not optimized to the other scenarios which remove elements underneath this added structure. To ensure the structure functions for combinations of scenarios as well, it would be possible to expand the workflow to take these combinations into account as separate scenarios as well. However, this could increase the amount of demountable connections required in the structure or the mass of the structure. Both of these would increase the building costs. Furthermore, it might not be likely that a combination of scenarios would actually occur in the building's lifespan. These are aspects that the architect will have to consider to determine which approach is most suitable.

The importance of the architect's consideration is also evident in the life-cycle where unanticipated scenarios occurred. In these cases the structures generated by the computational workflow didn't perform better than the structure without adaptability measures. However, during the workshop it also became clear that it might be very difficult for an architect to determine which scenarios are likely to happen. Following the steps for scenario-based design, as provided in chapter 2.2, might help in this process.

When the scenarios do align with the actual changes during the lifespan of the building, the proposed methods and workflow do offer a benefit compared to a standard structure. Furthermore, the structures don't require as many demountable connections or oversized elements as other adaptable buildings, which would decrease the building costs of the structure.

There are still multiple ways in which the workflow can be improved. These include expanding the workflow to include a greater variety of designs. This can be done by incorporating more scenario types, especially a change in load is interesting to incorporate. A common adaptation to a building is to change its function. As the function changes, the loads on the structure might change as well. Since the current incorporated scenarios directly change the structure, and the scenario of changed loads would indirectly impact the structure, another approach to incorporating the scenario to the workflow would be required. The base structure would only be changed, after the structural elements are already created.

The workflow can also be expanded by incorporating other materials and building systems. Since building systems can differ a lot from each other, the way the line models are set-up will differ. As the first step of the computational workflow will already be different, it is best to create a new workflow for the different building systems and make sure these have the same type of output as the original workflow. This can then be used to compare across the building materials and systems. As different materials have different environmental impacts, this can also be included in the comparison. As a result the building system with the least impact now and in the future can be chosen.

Another improvement might be to combine the two proposed methods for creating more adaptability. At the moment the architect would have to decide for either one or the other. As a result any element that might be changed is oversized in the “oversizing” method. It would be possible to only oversize an element if this benefits the majority of the scenarios and use demountable connections for the other elements. This could reduce the material use and/or the amount of demountable connections required. However, more research would be required to incorporate these changes into the workflow.

An important aspect to mention in relation to the methods is the high amount of different elements in all of the structures. During the preliminary research it was established that both a modular approach and standardization could increase adaptability (see chapter 2.1). This high amount of different elements doesn’t align with these approaches. However, using these approaches would likely lead to an increase of material use. At the same time the methods proposed during this process do increase the complexity of the building, when compared to a modular building. This could also increase the cost of the building, as a result of which these methods are less likely to be used to construct buildings.

Furthermore, to make the adaptations to the building some elements will have to be removed, without disassembling the rest of the structure. This also increases the complexity of these adaptations. This can result in more elements needing to be removed than the elements that need to be replaced with elements with a larger cross-section. Ideally, these elements would be demountable. However, more research into this topic is required as it is still difficult to be able to disassemble individual elements from a structure.

IV Conclusion

10. Conclusion

Because of the increasing material shortage, structures built conforming to a circular economy are becoming increasingly important. One way to achieve a more circular economy is to increase the adaptability of the buildings, decreasing the amount of material needed in the future. Currently the most common method to achieve this is to oversize structural elements. However, as a result more material is needed at the start of a building's lifespan, ignoring the material shortage that we already have. There is therefore a need to balance adaptability and material use. Thus this research aims to answer the question **"How can a computational workflow be used to increase the amount of adaptability in the design of a building's structure, while minimizing material use?"**.

Next to oversizing, another method to increase adaptability is to design buildings with demountable structures, but this is often too expensive. A proposed solution is to make part of the structure demountable, where this demountability is most needed. By using scenarios, potential changes to the structure can be anticipated. The demountability can be focused on the elements that are expected to need replacing. This approach can also be used for over-sizing elements. By only over-sizing elements where required, the material use can be reduced.

During this project a workflow has been created that determines which elements should be demountable or over-sized in order to enable the building to adapt to predetermined scenarios. The information about where measures are required can help an architect or structural engineer make better informed design decisions at the start of the design process. The workflow can also be used to aid the decision between grid sizes. Span is among the most important choices according to interviewees. In the workflow multiple design variants are created based on different grids. The different variants can be compared to each other, as the expected mass and amount of required changes are determined for each of the design variants. The designer can use this information to weigh the different options.

During the workflow two approaches were used to optimize the adaptation from the initial design to the scenarios. The goal of these approaches being either to minimize the mass of the final structure, or to arrive at a sufficient structure within minimal changes of the initial structure. During tests it was found that the "minimal mass" approach did not always return the structure with the lowest mass due to the usage of the "cross-section optimization" component of Karamba. When displacement is located in a small area, this component does not always lead to the most economic results. In the scenarios that were incorporated into the workflow, it could happen that the displacement was very localized. As a result the averages of the masses provided by the "minimal mass" approach was similar to that of the "minimal changes" approach. As the latter did provide a much lower amount of changes, it was chosen to use this approach for the workflow. However, this approach also has its disadvantages. Mainly, to limit the possible run time of the process, there is a maximum amount of changes set. As a result it is possible that the optimization does not reach a structure that suffices the set requirements. It could be possible that the disadvantages of both the approaches can be solved by using another programming tool. Further research could include developing a similar workflow with the use of another program and comparing the results.

The information that the workflow provides with the optimization can be used to inform different methods to increase the adaptability of a structure. As the workflow provides information about which elements might need to be replaced, it can also offer information about where demountable connections might be needed. As the locations of these elements are also known, it can also be determined which elements surrounding a connection node should be demountable. This information can be used to determine the type of demountable connection needed, as there are many types of demountable connections. However, more research into connections is needed to create more affordable connections as well as connections that allow for more possibilities to demount elements. Especially since this method of demounting elements is dependent on the possibility of replacing these elements, without having to disassemble the entire structure. This could be done by temporarily supporting the structure. However, there are also difficulties in reaching the elements, due to interior finishing. More research is required on connections and processes that simplify this process.

Another method is to already over-size the elements that would otherwise be replaced in order to adapt to the scenarios. As a result the scenarios are possible without any changes to the structure. However, the over-sizing of the elements does lead to an increase in the initial material use. Nonetheless, the oversizing is only located where it is required, limiting the extra material that is used in the design. Furthermore, as no elements will have to be replaced, over-sizing elements might be the most beneficial in the long term.

The workflow can likely be easily incorporated into the design process, as it combines different methods that are already used in practice at this moment. However, the actual implementation still depends on future research to allow for the workflow's structures to be possible. If the workflow is implemented in the design, this will also impact the architecture of said design. Currently, buildings often have a lot of repetition in elements, which also simplifies the structures. With this workflow structures are proposed with a lot of diversity in components.

The outcomes of the methods have been tested using a test case, in which designs created with the workflow were adapted according to set life-cycles. From this test case it follows that, even though the designs are able to adapt to the predetermined scenarios, combining these scenarios could lead to unexpected changes needing to be made. However, even if this was the case, the proposed methods did lead to a lower material use and lower amount of changes needing to be made to the structure. So, if applied, the workflow could lead to lower material use and therefore a smaller environmental impact.

However, this is dependent on the scenarios that are taken into account, and the actual life-cycle to the building. In case scenarios that were not anticipated are applied to the structure, the structure could not adapt in the way it was supposed to. As a result the structures offer no benefit over a standard structure, if the actual scenarios do not match the anticipated scenarios.

In case the actual life-cycle is as anticipated, the material use can be reduced by using the workflow. This can also result in lower costs. And as less adaptability measures are taken compared to other adaptable buildings, the costs could be lower compared to those buildings as well. However,the workflow does increase the complexity of the structure. The workflow leads to a larger diversity of elements and/or connections. This could increase the costs of the building.

To improve upon the workflow, more scenarios could be integrated. At the moment, this is limited to removing or adding structural elements. It would be especially beneficial to implement the scenario of changed loads. When a building is being adapted it is common for the loads on the building to change as well, especially if the function changes. In addition, the possibility to combine scenarios will further increase the adaptability. This would allow the user to ensure that multiple adaptations are possible one after the other, as well as include scenarios that impact more than one aspect.

In future research more building systems and materials could also be incorporated into the workflow. The choice of building system is also said to have a big impact, but at the moment the building system only incorporates one system, being steel frame structures with concrete floors. This could be expanded to include more building systems. This would also allow for the comparison between the different systems. Furthermore, the environmental impact of the building is currently determined by just the mass of the building. If more building materials are taken into account, the environmental footprint of each of these materials could also be taken into account.

Another possibility for future research is to incorporate the testing of the structures with the life-cycles into the workflow as well. Currently this is not automated, and instead a few changes are made to the workflow, in order to test the life-cycles. If this was automated, it could be easily used by designers to determine the benefit of each of the structures in more depth. However, the accuracy of these life-cycles still depends on the accuracy of the scenarios that are taken into account, both in the creation of the structures, and in the generation of the life-cycles.

All in all the workflow does not guarantee a more adaptable or sustainable building, as this depends on the accuracy of the scenarios that were taken into account and the unpredictable future. But the workflow can already be used to give more insight into the adaptability of a building from an early stage of the design process. The general steps of a scenario-based design process can be used to aid the designer to create potential scenarios, possibly increasing the workflow’s benefit. Furthermore, the workflow can already be used to accurately compare the material use of the design variants for the base structures, as this does not depend on the scenarios.

11. Reflection

During this project the research and the developed product influence each other a lot. First of all, the intended product determines the type and aim of the research. But on the other hand, the preliminary research into the topic also informs what type of product is needed in practice and what requirements it should pass.

Furthermore, during the research it becomes clear what can and cannot be achieved with the products. This is also dependent on the chosen tools and methods for the research. For instance, Grasshopper and Karamba were chosen for the development of the computational workflow. Within Grasshopper and Karamba the components are limited. Therefore the possibilities of what can be achieved with these programs is limited. As a result the development for the computational workflow was an iterative process of learning what is possible within these tools and how to achieve the goals within these possibilities.

The development of the product is also a research on its own. The approach taken during this project could be reused or adapted in order to create a new but similar product. For the computational workflow this could include adding new types of scenarios, or investigating different types of building structure.

Overall, I've been pleased with the process during this project. The used methods and tools work well to achieve the desired goals. This was especially the case during the preliminary research phase with the use of interviews. The combination of literature review and interviews with firms led to a good understanding of how theory relates to practice. Furthermore the results of the interviews led to unexpected insights, which influenced the focus of the project and research questions.

The interviews did lead to an ethical issue, as permission is required to make the results of these interviews public. This permission was not explicitly asked during the interviews, therefore a form was sent out afterwards for the interviewees to confirm permission. If the interviewee chose not to give the permission to mention their company, the information was anonymized.

Even though the focus of the project followed from the preliminary research, it was more difficult to determine the scope of the project. The tutors pointed out that I wanted to achieve too much to be feasible in the time frame of this graduation. In the end I decided to focus on the computational workflow and less on demountable connections themselves.

By focusing on the computational workflow, the aim of the research shifts more towards an academic field which has not been researched a lot yet. There is currently more information available on circularity, adaptable buildings, and demountable buildings than on the incorporation of computational workflows into the design process. The current research is even more limited on topics relating to both computational tools and circularity. By combining these two topics, this research can be a valuable addition to this research field.

The research can also be valuable to the current practice. The research aim is based on the knowledge of the current practice, acquired during the interviews. The shift in aim was due to the realization that the increased costs are the limiting factor for demountable buildings being constructed. So the costs could be reduced by determining the minimal amount of changes needed, and therefore the minimum amount of demountable components.

Due to this decrease in cost this research could stimulate the creation of adaptable buildings, if put into practice. This should lead to a more circular building approach with less material use. However, the application of this workflow into practice is still limited. Only one type of building system, and two types of scenarios are incorporated into the workflow as of now. If the workflow was extended to incorporate more of these aspects, the workflow could provide a more complete comparison and therefore be of better use.

These two topics of adaptability and computational workflow, also relate to two important topics within Building Technology, being circularity and computational design. In specific, the research is part of the design for change research topic, which relates to the adaptability of structures. As this research combines computational tools with the topic of adaptability, this connects well to the broader research topic.

By placing the product within the design process this project relates to the broader topics of the AUBS master as a whole. When put into practice the workflow could be used to better inform the design of adaptable buildings. This is also achieved by testing how such an adaptable building could be made in practice, by researching demountable connections and by testing the workflow with a testcase.

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Appendix A

During the semi-structured interviews the following set of questions were used as a guide. Because of the nature of semi-structured interviews, the conversation often deviated from these questions, as follow-up questions were asked, before continuing with the predetermined questions. Furthermore, the companies had different amounts of experience with demountable buildings and reuse, therefore some questions were more applicable to some of the companies than to others.

Note: These questions have been translated from the dutch questions used during the interviews.

Design process

- How is the decision made to either design a building to be demountable or not?
  - What hinders the transition to building more demountable buildings?
- How does the design process differ for demountable buildings, compared to non-demountable buildings?
  - Are stakeholders more involved in the process?
  - How does your role differ from normal?
- What are important decision moments in the design process of demountable buildings?
- Which bottlenecks do you encounter during the design process?
  - How could the design process be improved?

Design principles

- Which design strategies are applied to create a demountable building?
- What are the consequences of these strategies?
  - Which limitations do they create?

Reuse

- How are the reuse possibilities of the structure limited?
  - Does the structure need to be rebuilt in exactly the same way?
  - Are a few limited configurations possible?
  - Is complete reconfiguration possible?
- How do you design to be more adaptable? Are certain scenarios investigated?
- How does the experience with reuse influence the design of demountable structure?
  - Which knowledge has been gained in relation to demounting structures?

Material

- How does the application of reused materials impact the design process?
- How is the material for the structure decided upon?
  - How does this influence the reuse possibilities?

Functions

- Is it possible to change the function of a building?
  - What is needed to be able to change the function?

Appendix B

This appendix presents all information that was gathered during the semi-structured interviews about the design process of demountable and adaptable buildings. Since not all interviews were recorded, summaries of the strategies and difficulties found by the companies are given, instead of the questions and answers. For a list of general questions asked during the interviews see appendix A.

For each section, first a short description about the company is provided by the author. All information after these introductions are the opinions, strategies and findings from the companies themselves, unless stated otherwise. Three of the interviewees preferred this information to be anonymized, in these cases the name of the firm has been replaced by firm A, firm B or firm C

B.1 Strackee

Strackee is a structural engineering company with experience in multiple building transformations and one demountable building. The building in question is the physics, mathematics and computer science faculty of the UvA.

Most buildings are not designed to be demountable, one reason is that the client is often not willing or able to pay for the higher costs of these types of structures. However, as the government will likely set restrictions on the environmental impact on buildings, it is expected that more buildings will become circular. Furthermore it is feasible that the costs of new material will increase, thereby pushing more people to reuse materials.

Another reason is that the structural engineers are often contacted when a general design is already decided upon. This leaves little room for big changes, such as designing the building to be demountable. If the engineers are contacted earlier, they could consult on aspects to increase the sustainability of the building. Especially since the building system has a big impact on how demountable a building will be, and this decision is made early on in the process.

When designing a demountable building, the structure should be designed starting from how it will be taken apart. As much as possible the components should be stacked on top of each other with hinge connections.

Furthermore, the connections should be as simple as possible. Preferably all connections are dry connections. In the case of the faculty building it was not feasible to design all connections to be completely reusable, as this became too expensive. In this case two solutions were used. Some bigger components were made using permanent connections, but these components were reusable as a whole. At other places permanent connections were also made, which will not be reusable, instead these connections will have to be partially cut. As a result the components will need further alterations before being reusable.

During the design of the faculty, it was determined that flexibility was more crucial in the center of the building and less towards the facades of the building. Therefore the connections in the center are designed to be easily demountable, while those at the edge of the building would need more effort to be disassembled.

In case of the faculty building, flexibility is created by designing a modular steel frame for the structure with a flexible infill. Since the structure has a longer lifespan than the infill, the infill needs to be replaceable. This is achieved by detailing the structure and infill to be separate from each other.

Steel was chosen for the structure, even though wood would have been more preferable in terms of environmental footprint. This choice was made since a steel frame can easily receive infills of different types of materials. Wooden connections would have been a lot more complicated. The frame is modular, and thus has standardized dimensions, which is efficient for production and allows for the swapping of elements. Preferably the building is as light as possible. This can be achieved by transferring the loads at regular and small intervals, limiting the required amount of material to span between these points.

For the infill of the steel frame wooden floors were used where possible. However, this was not possible everywhere, since some floors had higher loads. For these floors concrete was chosen as material. Because of the steel frame, it was possible to use two kinds of floors, and apply them where needed. Furthermore, the location of these floors could be changed in the future, if a change in layout is desired.

No used materials were used for the building, even though this was part of the project in the early stages. At the moment it is still difficult to reuse materials in a building. This is due to the small amount of information available on used materials as well as the higher costs of these materials. Furthermore there are currently no guidelines for the process of reuse, therefore no guarantees can be given about the quality of the materials.

One of the important aspects to keep in mind is stability. To achieve demountable connections the concrete floors can't be connected with a cement screed, instead stability can be created with steel braces below the floors. Lateral stability can be created with braces in the facade, leaving the rest of the floorplan open to increase flexibility.

Lastly, it is also important to consider how the loads can still be carried in case one component is damaged. With the use of in situ concrete and more reinforcement, the loads can be transferred to other elements. This is harder to achieve with demountable building systems.

B.2 Daiwa House Modular Europe

Daiwa House is a firm that produces a demountable building system. This system is used for both temporary buildings and permanent buildings (45+ years).

The system consists of standardized modules that are assembled in a factory and transported as a whole to the construction site. When the building is no longer in use, the building can be disassembled and the modules can be taken back to reuse components, if arranged with the client. At the moment up to 80% of material from old modules can be reused, the other 20% is not usable after disassembly and is recycled.

To ensure that the system can always be reused, newly developed components will always have to be able to connect to the older versions. Thus the system always uses the same standardized dimensions. A difficulty in connecting the system are the installations, such as pipes, which are difficult to connect to each other. Since a lot of precision is needed for this system, automation is used during production. This not only delivers consistent products of high quality, but also speeds up the process which in turn keeps the costs low.

Speed is also achieved by being able to construct the modules off site, while the site is being prepared. Once the foundation is finished, the modules can be stacked in a matter of weeks or days.
The speed and lower costs allow for a competitive position against other building systems, as this building system can often not be used to build a building of the exact size wanted by the client. The standard sizes limit the possibilities; A balance needs to be found between enough options to give the client what they want and using standardization to keep the building system feasible.
It is best if the building system is chosen at the start of the design process. This allows the architect to take aspects such as the proportions of the building system into account during the design. The better the architect knows the building system, the easier it is for them to design a building within its parameters. Diversity can be created by changing the configuration of modules and designing the facade, as the facade is not part of the system.

Because of the use of standard components, the modules are oversized. This does increase material use, but also ensures that the modules can be reused. Furthermore, due to each module having their own frame, columns are placed next to each other. This probably results in more material being used than needed, but this is required to create this type of module.

The system makes use of steel, concrete and wood, to benefit from the advantages that each material has to offer. The columns for example are steel, since they can handle a big load per surface area, reducing the amount of material needed.

The prefabrication process itself also enables the product to be more material efficient. For instance the floors don't have a uniform thickness, instead there are beams incorporated into the floor at two of the edges, enabling the rest of the floor to be thinner. Material is also saved by creating modules with small spans, these can be connected together to make larger dwellings.

It is important to design the details to be as simple as possible. This allows for easier and faster disassembly. Gravity is used for some of the connections by just stacking the components on top of each other; the weight keeps everything in place.

The connections should also be easily reachable. In some cases the design includes holes drilled into the columns, to allow the connections to be reached. Furthermore all connections should preferably be dry connections. However due to regulations, for instance about air tightness, this is not always feasible.

Other aspects to keep in mind are fire safety and soundproofing. Steel is not fire resistant, so fire resistant boards need to be placed around the steel frames of the modules. Steel and wood have bad acoustic properties, and the concrete floors are thin to save material. However, contact sound is prevented by only having four contact points, the columns, between the modules with very little surface area. Air-borne noise is prevented by having a layer of air between all of the modules.

It is also important to question when a building needs to be demountable. Daiwa mostly builds for temporary building permits, for which it's a requirement that the building is demountable. However, Daiwa also constructs dwellings in areas with a big housing shortage. It is possible that these buildings will remain longer than was originally intended, because there will also be a need for them after the initial use period. But in light of circularity, it is still beneficial to design these buildings to be demountable.

B.3 Mei architects

Mei architects and planners is an architecture and urban planning firm. They have experience with designing demountable buildings as well as designing transformation of existing buildings.

Currently we are dealing with a material crisis. At the same time a lot of CO_2 is emitted in the building industry. A lot of energy is required to demolish existing buildings and to create new buildings in their place. This is due to the buildings being designed for one specific purpose. Instead the building should be flexible, so it can be adapted, lengthening the lifespan of the building. Or the building should be demountable, so it can be disassembled and rebuilt elsewhere.

Since it is difficult to introduce adaptability and flexibility in the later stages of the design process, the ambitions of all involved partners are discussed at the start of the design process. Other stakeholders are often interested in these topics, especially if the exact function of the building is not known yet. However, as this is not always the case, it is also partly the architect's responsibility to advocate for flexibility and convince the other stakeholders to invest in flexibility, despite the higher costs.

Due to the high costs it is also important to keep track of the costs during the entire design process. In the general industry it is common that projects fall back to more traditional building methods, if the ambitions become too expensive. By keeping track of the costs, it is possible to check whether the ambitions of the project are still feasible within its budget. When this is not the case, it might be possible to optimize aspects of the buildings, to still allow for the ambitions to be met.

To make a building adaptable, it doesn't have to be completely demountable. If future functions are taken into account during the design process, the building can be adapted by altering parts of the building. Furthermore, it might also not always be possible to create a completely demountable building. This depends on the exact project and aspects such as the available budget. However, Mei architects and planners try to make the building as flexible and demountable as possible. In case it is not possible to create demountable elements, flexibility is created in the structure. There are multiple approaches to create more flexibility in a building, which will be explained below.

Probably the most important method to create more adaptability is to separate four components of the building from each other. These components are, structure, facade, services, and finishing. These components have different lifespans, by separating them it becomes easier to replace one, without having to also replace another. Replacing services is often the biggest problem in traditional buildings, as they are often integrated with the floors. By making the services reachable and demountable, the building becomes more adaptable, as services can be replaced, added or connected to each other when needed.

Another method is to create an excess of space. This allows for an easier transformation to another function. Excess in the height is especially important, due to the services. If extra height is added to each floor, this height can be used to add extra services during a transformation. The excess of space is not needed throughout the entire building. It is therefore only applied where the excess is predicted to be needed. This is often the plinth of the building.

Oversizing of elements is also possible, but is applied less. Most of the time, the load-bearing capacity of the original structure is big enough for possible future scenarios. However, the choice of grid size could lead to an oversizing of the foundation to some extent.

This is also where oversizing is most relevant, as it is difficult and expensive to add more foundation. When deciding on a grid-size the possible future loads are also taken into account. A smaller grid size can carry a higher load. This smaller grid-size also causes the oversizing of the foundation. As the grid size also impacts other aspects, such as the floor thickness, this is a very important decision to make.

Lastly, the flexibility of the building can be increased by applying the method of open building. This includes using a column structure. As a result spaces can be joined together more easily, as this will not impact the structure itself.

The flexibility and adaptability is created to enable the building to change, even when the future needs are unknown. By following these methods most of the time, the building can be adapted easily to the future scenarios.

These methods can be applied regardless of the choice of material. When choosing a material, the materials are used as much as possible where they have the highest advantage. The preference is for bio-based materials, such as wood, due to the environmental impact. However, these materials are not always the best fit. For instance, wood is not suitable for creating a stability core, or for columns that need to have a very high load-bearing capacity. In these cases, a lot of wood would be required. Instead other materials are chosen, often concrete and steel respectively, which will require a much lower material use. Therefore, whenever a material needs to be chosen, the consideration is made which material is the best fit and as sustainable as possible.

B.4 Firm A

Firm A is an architecture firm that focuses on prefabricated, flexible and demountable buildings. In theory, all of the buildings designed by Firm A are demountable. However, a few of their buildings have been designed with the main focus being demountability.

The most important step towards designing more demountable buildings is a change in the approach of architects. A building should be seen as a product instead of as a singular structure. Since a building is a product, it should be assembled from a kit of prefabricated parts. Prefabrication allows for better quality as well as more possibilities for the production of components. On site the components should only be assembled.

During the design process one of the difficulties of demountable buildings lies with the approach of contractors, who also don't see the building as a product. They aren't familiar with the different way of building. Furthermore, they think per building and therefore they don't benefit from research into different ways to build.

In an ideal situation each design would be an improvement on an earlier version, similar to the production of cars. However, since each building is designed for a specific design question, this is not possible. It is however possible to reuse solutions that were found during the design of previous buildings to solve certain problems.

During the design process it is also important to carefully decide upon the modularity to work with. It is possible to change the design within this modularity by playing with the determined kit of parts. However it is difficult to change the modularity later on, as this will impact the entire building's design. The spacing in a building is also bound by regulations, for instance working spaces have to be within 7,2 m from the facade. Regulations like these also need to be considered.

Because the building is designed with a kit of parts, it remains flexible during its entire lifespan. Once the construction is finished, the building is not done, the user can change it as they please. The building could be extended, moved, or assembled in a different configuration. And due to the demountability each component can be replaced if desired.

However, there are limitations to the possible changes. The building can be taken apart and be reconstructed elsewhere. But due to the same system being used, the reconstruction will be similar to the original.

It is also difficult to accommodate a different function, in case this hadn't been designed for. Different functions are bound to different regulations, so if a kit of parts is designed for an office function, it should remain an office function. However, if it's feasible that the function of a building will change, this can be taken into account and designed for during the design process. And the more similar the functions are, the easier it is to combine them in one design.

The structure is designed as a steel frame, onto which the rest of the building can be placed. Steel is chosen because of its architectural qualities; slim profiles offer a lot of light. But steel also has many options for remanufacturing steel. By separating the layers more quality can be achieved, as each person is just in charge of their area of expertise.

At the same time, each aspect of the design should be integrated. The installations often take up more space than necessary. By planning where the installations will go and how they will be placed throughout the building, the quality can be improved. For instance, in one of the buildings they designed all technical spaces are within one area of the building, allowing the installations to be efficiently clustered in this area. Furthermore, the components needed for the installations can then be prefabricated as well.

One of the buildings designed by Firm A has been disassembled and has been reassembled in another location. The collaboration with the firm that disassembled the building led to the realization that not every small component needs to be demountable, as long as the larger component they're part of is demountable. For instance, a staircase can be reused as a whole, the separate steps don't have to be demountable.

B.5 Firm B

Firm B is an architecture firm that has designed multiple circular buildings, including some demountable buildings.

There is an increasing need to build circular buildings, because of the decreasing amount of new materials. However the client determines whether a building will be demountable or not. Even if the architect wants to create demountable buildings, the client will have to pay for the higher costs associated with these constructions. However, when working with the municipality, they often want more demountable buildings and can make it a demand for a building.

This does however beg the question for when demountable buildings are needed. Dwellings often have a long lifespan and therefore won't benefit much from being demountable. Temporary buildings would benefit from being demountable, but it's not uncommon for temporary buildings to be used for longer than intended.

Instead it can be more beneficial to reuse or transform a building, increasing the lifespan of the building. A building can be designed to be adaptable to future needs, for instance by using oversized components. But the possible future uses need to be taken into account during the design process. Whether or not a building is designed to be flexible is also up to the client, since this will also increase the building costs.

The decision to create a demountable building should be made early in the process, as it's very difficult to make a design demountable later in the process. Some of the most impactful decisions in the design process are the choice of structural material and building system.

There are multiple demountable systems already available, including concrete, CLT, wooden and hybrid systems, but they all have implications on the eventual design. Often the size of the building components is predetermined, so you have to know and design with these limitations. It is therefore beneficial to include the building system manufacturer early on in the process as well.

When the building is being disassembled, the components should still have a good quality. For instance, by using oversized wooden beams and columns, the outer layer of the component can be removed. The resulting component will have a better quality, even though the dimensions will be slightly smaller. Similarly holes and similar alterations should be avoided in the components. In a building Firm B designed this was done by separating the structure from installations, removing the need to put screws into the wooden beams.

Another aspect to take into account is that demountable buildings still need to pass the regulations for airtightness and acoustics. Most of the time this is still achieved by using a small amount of material that requires a chemical connection, even in otherwise demountable buildings. There are some products on the market to replace these materials, but they do not meet the required standards yet.

Even though reusing material is desired, there are still some difficulties relating to reuse. Materials are preferably reused one on one, meaning the component is placed in the new building without alterations. However, this is often not possible, so changes need to be made, which results in a loss of material.

Furthermore, no guarantees can be given for used building materials after a building is being disassembled. There are no testing methods for the components, and it's not sure if the components still have the same quality as they had when installed. Therefore it's also unknown if they meet the required standards. Moreover, the building regulations have become stricter over time. So it's possible that even if the components still have the quality they had when installed, they still do not meet current regulations.

When designing for and with reuse, a database with information about available materials is also very important. This database allows designers to know what material is available, where, and when. But also contains information on how to disassemble connections and retrieve components. However, right now not enough information is available about reusable materials.

Another logistic issue is the storage of material. Reusable components might need a lot of storage space, this might become very costly, especially if the materials need to remain stored for a longer period.

Lastly, reuse of materials is only part of the solution. Even if all building materials from buildings that are being demolished would be reused, this still accounts for just 20% of required building materials for all new development.

B.6 Firm C

Firm C is an architectural firm that focuses on circular buildings. Some of the buildings designed by Firm C are completely demountable.

It’s always a question whether demountable buildings are needed, due to the general lifespan of buildings. And to what extent the building should be demountable, or how much flexibility is needed? Demountable buildings are expensive, by making just part of the building demountable, the building will become more feasible in terms of costs. The best approach depends on what will happen with the building in the long term. If a building will have a long lifespan, the focus should be on using a minimal amount of material, instead of increasing demountability.

The goal should never be to make a building demountable. It should be a result of trying to achieve other goals. For instance creating flexibility, using prefabricated elements, or the goal to reuse or recycle the components.

Prefabrication itself is being applied more and more. It allows for better working environments, better quality of product, fast production and more production possibilities. For example, with concrete elements it’s possible to apply pretension, reducing the amount of needed material.

Versatility, being able to adapt the building over time, is also more important than demountable buildings. The order of priority is first excess, excess space creates more adaptability; second lightweight, minimizing the amount of material needed; and third reuse potential in the future, such as demountable structures.

It is important to take scenarios into account, and leave possibilities open for the future. By doing preliminary work now the lifespan of the building can be increased. One of the aspects to design is to separate the layers, leaving each material as pure as possible. This allows for more adaptation possibilities in the future.

It’s also possible to change the function of the building, but the different regulations need to be considered. Dwellings have the strictest regulations, such as acoustics, fire safety, outdoor space, ventilation and the amount of installation and therefore openings needed in the structure. The function can be more easily changed by designing for the strictest standards. Furthermore, versatility should be designed, by for instance increasing the storey height. The excess will increase the lifespan of the building.

Creating demountable buildings is a design problem. While designing, the right conditions need to be created for the building to be able to be demountable. Technical aspects matter for the connections, but not the overall design.

There are multiple types of demountable building systems available, working with different structural materials. One of the first steps in the design process is to choose a construction system, as this has a big impact on the rest of the design. The span is another important aspect. Some materials can only achieve small spans, while other building systems can achieve larger spans with less material. A larger span creates more flexibility for the infill, but also has an impact on the material efficiency.

Demountable building systems differ greatly from regular building systems. The main difference being that most connections are hinge connections. This impacts how a lot of components can be designed, for instance balconies can not cantilever from the building, but need to be supported on both sides.

The building system also impacts the stability of the building. For demountable buildings it is best to stack the components as much as possible. Due to the hinge connections stability needs to be created elsewhere. Depending on the system this could be achieved by using metal braces or by using a bracing wall.

The choice of building system even affects the possibilities for installations. Especially for dwellings a lot of perforations are needed in the structure, for example for the construction of shafts. Some of the building systems lend themselves better for these kinds of perforations than others.

Lastly, it is important to consider the disassembly process of the building. It is best to design the connections as simple as possible. But even if a connection is easily demountable in theory, it could still end up being very hard to remove due to for example corrosion. This will lead to even more labor being needed to disassemble the building, which is already labor intensive on its own. Therefore the costs will increase. It might be more efficient to cut the elements next to the connections and reuse the remaining part of the component.

Appendix C

Step 1: Line models design variants

Input
- Preliminary design containing: line drawing exterior walls, line drawing interior walls and height per storey
- Spans to use for the grids
- Number of design variants n

Create grid-points based on the provided spans

For all grids:

Determine point on walls on floor plan closest to each grid point
Determine distance from point on walls to closest grid point
Determine average and largest absolute distance between grid-points and point on the walls

Determine n grids with the smallest average and absolute distance to walls
For the rest of the workflow, these n grids are the design variants

For each design variant:

Create surfaces with the grid-points as corner-points
Copy the grids to the heights of the floors and roof
Move the line drawings of the exterior walls to the floor height
Copy the line drawings of the exterior walls to the ceiling height
Remove all surfaces with a centroid that lies outside of the boundary of the exterior walls
Extract the corner points and line segments of the surfaces

Remove duplicate lines, the resulting lines are the beams
Create lines from points lying directly above each other, these are the columns
Divide the surfaces into two groups, based on whether there are other surfaces above them or not, divide into floor and roof surfaces
Find which grid points lie closest to the interior and exterior walls
Create surfaces from the points closest to the walls, points adjacent to these points and points above, these surfaces are the facade surfaces
Create diagonals on all surfaces, these are bracing elements

Output
- Beams, columns, roof surfaces, floor surfaces, facade surfaces, bracing elements floor and roof surfaces, bracing elements walls, location supports.
- Surfaces created from the grid points

Step 2A: Line models scenario - adding floors

Input - Number of scenarios m
- Line drawing of interior walls, line drawing of exterior walls and height of additional floors for m scenarios

For each scenario:

Move the line drawings of the exterior walls to the floor height
Copy the line drawings of the exterior walls to the ceiling height
Remove all surfaces with a centroid that lies outside of the boundary of the exterior walls
Extract the corner points and line segments of the surfaces

Remove duplicate lines, the resulting lines are the beams
Create lines from points lying directly above each other, these are the columns
Divide the surfaces into two groups, based on whether there are other surfaces above it or not, divide into floor and roof surfaces
Find which grid points lie closest to the interior and exterior walls
Create surfaces from the points closest to the walls, the points adjacent to these points and the points above, these surfaces are the facade surfaces
Create diagonals on all surfaces, these are bracing elements

Output - Beams, columns, roof surfaces, floor surfaces, facade surfaces, bracing elements floor and roof surfaces, bracing elements walls, location supports.

Step 2B: Line models scenario - removing elements

Input - Number of scenarios m
- Volumes within which elements are removed for m scenarios

For each scenario:

For surfaces, columns, beams and bracing:

Determine centroids of element
Determine whether the centroids lie within the volumes
Remove elements that have centroids within the volumes

Output - Beams, columns, roof surfaces, floor surfaces, facade surfaces, bracing elements floor and roof surfaces, bracing elements walls, location supports.

Step 3: Calculate mass of the floor surfaces

Input - List of potential cross-sections for the floor with varying thickness
- Load-cases to be applied to the structure

For each design variant:

Take one floor element
Take 10 points along each side
Create supports on these point with free rotation in x and y direction
Create a shell from the surface with the first cross-section from the list
Apply load-cases to the surface
Assemble and analyse model
Optimize model using cross-section optimization and the list of possible cross-sections
Determine mass and area of the floor

Output - Mass per square meter floor area

Step 4: Optimization

Input:
- Load-cases to be applied to the structure
- List of potential cross-sections for the columns and beams
- Cross-section bracing elements

For all design variant models:

For columns and beams:

Create structural elements from the lines and apply the first cross-section from the list of possible cross-sections

For bracing:

Create structural elements from the lines and apply the bracing cross-section

Create fixed joints at the end of the columns, beams and bracing structural elements
Create supports on the predetermined points with free rotation in x, y and z direction
Apply load-cases on roof, floor and facade surfaces and the structural elements, this includes the calculated weight of the floor
Assemble and analyse model

Remove bracing elements on 60% of the locations according to the elements with the lowest tension
Optimize the beams and columns with a cross-section optimization with the list of potential cross-sections
Determine mass of the structure

Output - Optimized design variant model
- Mass optimized design variant models
- Locations bracing elements

For all scenario models:

Extract the cross-sections from the optimized design variant models and their element IDs

For columns and beams:

Use the element IDs to match elements from the scenario models to the design variant models
Create structural elements from the lines and apply the cross-sections from the design variant model

For bracing:

Create structural elements from the lines and apply the bracing cross-section

Create fixed joints at the end of the columns, beams and bracing structural elements
Create supports on the predetermined points with free rotation in x, y and z direction
Apply load-cases on roof, floor and facade surfaces and the structural elements, this includes the calculated weight of the floor
Assemble and analyse model

Use the location of the bracing elements from the optimized design variants to remove the same bracing elements as in the design variant models

For the adding floors scenarios models:

Remove of the added bracing elements on 60% of the locations according to the elements with the lowest tension

Calculate the utilization in all of the beams and columns
Determine the elements with the highest utilization, use this element to start a list of elements to replace

While utilization > 1.0 and deformation > L/200

For all objects in the list of elements

Determine current cross section of element
Increase the cross-section of the element a maximum of ten times

Determine elements with the highest utilization
Add element with the highest utilization to list of elements to replace

Output - Optimized scenario models

Step 5: Output workflow

Input
- Optimized models design variants
- Optimized models scenarios
- Location all connection nodes

For all design variants

For all elements of design variant

Use element IDs to match with elements in scenario models
Compare cross-section of elements
If the cross-section is not the same add to list of changed elements

For demountable elements method:

Use the length of the list to determine the amount of demountable elements
Use location of elements and location of connection nodes to determine which elements around a node will have to be demountable
Assign a binary code to each connection node, which can be used to determine the connection type required at node
Create list of connection types and amount of each type required in the model

Output
- Model with elements which need to be demountable
- Amount of demountable elements required
- Connection types and amount of each type required

For over-sizing method:

For each element

Determine largest cross-section across the scenario models
Apply the largest cross-section to element

Assemble and analyse model
Determine mass of model

Output - Model with specific element over-sized
- Mass of model with over-sized elements

Appendix D

The following values and load-cases were used for the structural calculation

D.1 Grid sizes

The design variants are based on different grid sizes. The list of grid sizes is the result of every combination possible from a list of spans in x and y direction. The following spans were used to generate the grid sizes:

3.6
4.8
6.0
7.2
8.4

This list of spans results in 25 different grid-sizes, which were used in the test-case of this research.

D.2 Load-cases

Self-weight	= 1,4 * F weight
	= 1,4 * (F weight structure + F weight floor + F weight facade)
	= 1,4 * (F weight structure + F weight floor + 0.6 kN/m^2)
Live load	= 1,2 * F weight + 1,5 * F live load
	= 1,2 * F weight + 1,5 * (F live load floor + F live load roof)
	= 1,2 * F weight + 1,5 * 2,5 kN/m^2 + 1,5 * 1 kN/m^2
Wind	= 1,2 * F weight + 1,5 * F wind side * shape factor + 1,5 * F wind suction roof
	= 1,2 * F weight + 1,5 * 0,65 kN/m^2 * 0,6 + 1,5 * 0,4 kN/m^2

The weight of the structure is calculated during the optimization, to accurately reflect the weight of the structure during the optimization. This is done by selecting "Gravity" as type of load in the "Loads" component from Karamba. The weight of the floors is calculated as part of the computational workflow. The weight depends on the required thickness for each of the design variants. For wind four load-cases have been used, to simulate different possible wind-directions.

D.3 Material properties

Floors	Concrete :	C40 / 50
	Steel:	ReinfSteel
Bracing	Steel:	S450
Columns and Beams	Steel:	S275

The bracing material was given a specific weight of 0,1, so the deformation of the bracing elements would not be taken into account during the optimizations.

D.4 Cross sections

These are the cross-sections that were available for the optimizations.

Floors

Thickness (cm):
10, 15, 20, 25, 30, 35, 40, 45, 50

Bracing

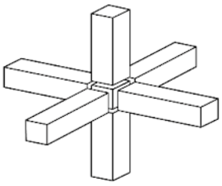
Hollow, rectangular section
Height 8,5 cm
Width 4 cm
Thickness 0,5 cm

Columns and Beams

Name	Height (cm)	Width (cm)	Flange thickness (cm)	Web thickness (cm)
HEA 100	9.6	10	0.8	0.5
HEA 120	11.4	12	0.8	0.5
HEA 140	13.3	14	0.85	0.55
HEA 160	15.2	16	0.9	0.6
HEA 180	17.1	18	0.95	0.6
HEA 200	19.0	20	1.0	0.65
HEA 220	21	22	1.1	0.7
HEA 240	23	24	1.2	0.75
HEA 260	25	26	1.25	0.75
HEA 280	27	28	1.3	0.8
HEA 300	29	30	1.4	0.85
HEA 320	31	30	1.55	0.9
HEA 340	33	30	1.65	0.95
HEA 360	35	30	1.75	1.0
HEA 400	39	30	1.9	1.1
HEA 450	44	30	2.1	1.15
HEA 500	49	30	2.3	1.2
HEA 550	54	30	2.4	1.25
HEA 600	59	30	2.5	1.3

Appendix E

Demountable elements and corresponding connection types



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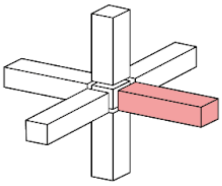

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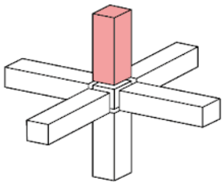

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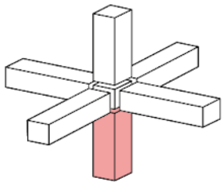

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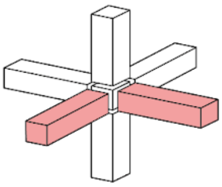

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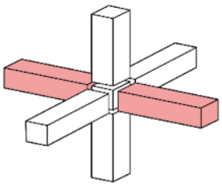

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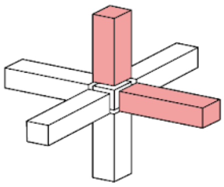

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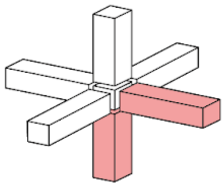

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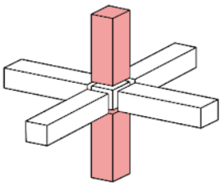

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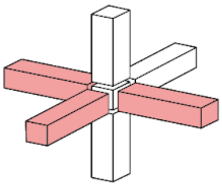

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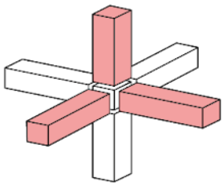

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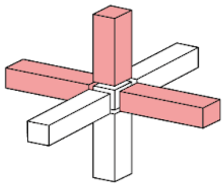

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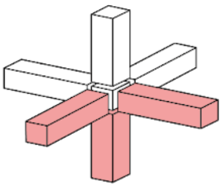

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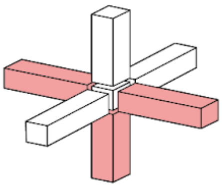

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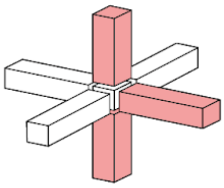

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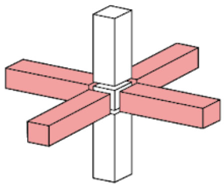
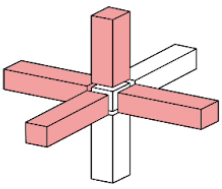
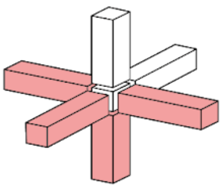
Connection type 15



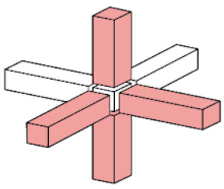
[1,1,1,1,0,0]
Connection type 16



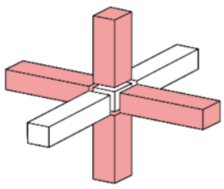
[1,1,1,0,1,0]
Connection type 17



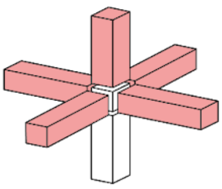
[1,1,1,0,0,1]
Connection type 18



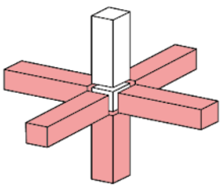
[1,1,0,0,1,1]
Connection type 19



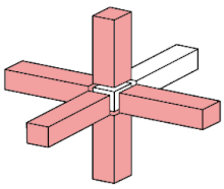
[1,0,1,0,1,1]
Connection type 20



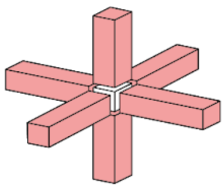
[1,1,1,1,1,0]
Connection type 21



[1,1,1,1,0,1]
Connection type 22



[1,1,1,0,1,1]
Connection type 23



[1,1,1,1,1,1]
Connection type 24