Development of a building adaptability indicator to encourage designing adaptable high-rise buildings

A study to the development of a building adaptability measurement tool

by

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Abstract

Policy makers have set the goal to reach a completely circular economy by the year 2050 in the Netherlands. This means that the construction industry should shift from its current ‘take-make-waste’ approach towards a circular approach. The number of buildings of more than 100 m in height are increasing in the Netherlands, due to the lack of horizontal space. This means that strategies should be investigated on how high-rise buildings can be constructed in a circular manner.

Through a literature review, it is found that there are currently a large number of high-rise buildings that are being demolished. The main reason for these demolition cases is that building owners want to replace their building with a new one, with new technologies and perhaps a new building function. A building that is adaptable to these changes would not have to be demolished, which is why the circularity strategy of Design for Adaptability is interesting for high-rise buildings. Additionally, researchers have studied the measurement of circularity. They mainly focussed on circularity on the material level, or on different circularity strategies. There is a lack of research on the measurement of the Design for Adaptability strategy on the building level. Therefore, in this research a Building Adaptability Indicator is created to measure the adaptability of a building.

The Building Adaptability Indicator is constructed from a study on how adaptability can be achieved in a building. From literature, in combination with interviews with structural designers, it is found that building adaptability is governed by three *sub-indicators*: openness, reserved capacity, and floor-to-floor height. For each sub-indicator, a Module Adaptability Indicator is constructed, which can be combined into the Building Adaptability Indicator.

The Building Adaptability Indicator will increase the incentive to implement the Design for Adaptability strategy in buildings. It helps structural designers to prove what amount of adaptability can be achieved with a certain extra material use. This research investigated the required investment in material use to reach certain levels of adaptability. It is found that the adaptability can be increased with 126% by increasing the structural element dimensions by up to 60%, leading to a total material volume increase of 38%.

The study on the material use is extended into a study on the economic and circular meaning of the Building Adaptability Indicator, to investigate what is the consequence to the economic and environmental impact. It is found that purely from a microeconomics point of view, the investment into a high adaptability cannot be justified due to the high initial investment combined with a low rent income. However, from a macroeconomics point of view, policy makers can influence the construction industry to invest in buildings with a low environmental impact, which is already done by the Dutch government through subsidies. Currently, adaptability is not considered in the calculation of the environmental impact, which means that investors do not have an incentive to implement adaptability in their buildings. In this research, the Building Adaptability Indicator is implemented in the calculation of the environmental impact, which leads to the conclusion that buildings with a high adaptability are more interesting from a circularity point of view.

It is concluded that at the moment, only investors with circularity ambitions will invest in adaptable buildings. Investors that lack circularity ambitions can be encouraged to invest in adaptable buildings as well. This can be done by implementing adaptability in the calculation of the environmental impact, for which owners of adaptable buildings will receive subsidies. This will shift the construction industry more towards adaptable buildings, which will prevent demolition and lead to a lower environmental impact across the industry.

Acknowledgements

This thesis concludes my Master's in Structural Engineering at the TU Delft. I have learned great things not only about circularity or high-rise buildings, but also about myself. The nine months that I have worked on this thesis have been a rollercoaster and I would like to express my gratitude to everyone who has guided me into making this a period that I can proudly look back on.

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Lastly, I would like to dedicate a great thank you to my friends and especially my family. Their support has given me the motivation to fight through any problems and led this thesis to be what it is.

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Contents

1. Introduction

1.1. Relevance of Research

1.1.1. Circular Economy

In recent years, research papers that are related to the concept of circular economy (CE) and the construction industry are seeing an increasing rise of attention [51]. This rise of attention identifies the realisation by researchers that the world should shift from the current linear economy of 'take-make-waste', to circularity.

The built environment has played a significant role in climate change in the past years. As shown by the most recent status report by the United Nations Environment Programme, the industry has contributed close to 36% of the total energy use worldwide in 2018. More worrisome is the fact that this is an increase of 2% compared to the year before [116]. To start the decrease of energy use by the building and construction industry, change is necessary.

Anastasiades et al. [7] argue that governing bodies are essential to establish a change in culture. The Dutch government has given a good example regarding their goals to reach a complete CE by the year 2050 [113]. This goal means that the construction sector should seek ways to achieve a completely circular built environment by 2050.

1.1.2. High-Rise Building

The Netherlands has seen an increase in the amount of buildings larger than 100m in the past years and this number will increase more in the future [83]. One of the reasons for this increase is the growth of population in urban areas. In 2018, Statistics Netherlands reported that the relative population growth was largest in and around the four largest cities of the Netherlands, while several cities outside 'the Randstad' also show growth [19].

The trend of a growing urban population is not only bound to the Netherlands. It is expected that in approximately 10 years, the ratio of urban:rural population worldwide is two to one [5]. This ratio has been increasing for the past years, which can be accounted to migration from rural to urban areas.

A few decades ago, cities in the Netherlands showed a much different image than today. Back then, the population would mostly settle outside the city centre due to the industrial pollution in the centre [70]. Ali and Al-Kodmany [5] describe that the modern day city centres "provide plenty of socio-cultural activities and services that cover daily needs such as shopping, groceries, and healthcare within walking distances". This leads to an increase in popularity to live in the lively city centres. With the scarce horizontal space in the Netherlands, a solution to increase space is to build vertically. High-rise buildings provide a suitable solution to this, because green land will be preserved due to the little horizontal space that is used by high-rise buildings [102].

Recently, due to more sustainable living and innovation, the energy use of a building during its life span is lowered. However, this means that a larger percentage of the energy use is coming from the material use, see Figure 1. This indicates that innovation is necessary in the construction industry.

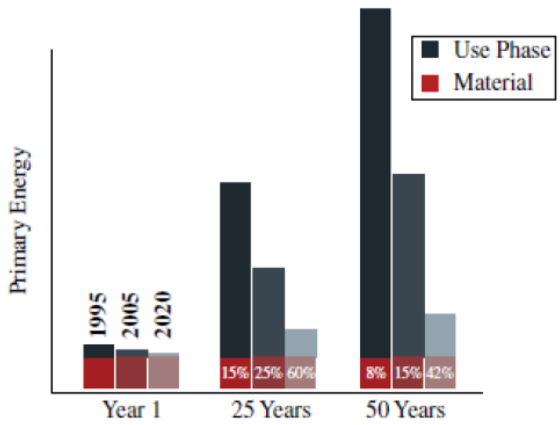


Figure 1: Transition in energy use of buildings with different life spans. Source: Veljkovic[118].

1.2. Research Aim and Questions

1.2.1. Problem Definition

From section 1.1.1 and 1.1.2, it becomes clear that an investigation to how a high-rise building could be designed in a circular manner poses a challenge. Several studies have shown what is necessary for low-rise buildings or bridges to be circular or sustainable [7; 22; 28], but for high-rise buildings this remains vague. Researchers have studied aspects of circularity in relation to high-rise buildings, but these aspects mainly include design optimization [37-39] and performing sustainability assessment [59; 85]. Additionally, Coenen [22] has constructed a framework on how to achieve circularity in bridges and viaducts, however this does not directly translate to high-rise buildings.

Study has shown that out of the large pool of stakeholders in the design of a high-rise building, the structural designers should play a significant part in forming the paradigm shift to circularity [51]. Therefore, it is investigated what is necessary from the structural designer's point of view to shift to circular high-rise buildings.

Furthermore, due to the lack of circularity measurement tools that treat circularity in its whole, structural designers have trouble to provide clients with a sound argument to implement circularity in the design of a building. Several researchers have tried to construct a circularity indicator, but these either only focus on one particular level of circularity [31] or only focus on one circularity strategy [112; 120].

1.2.2. Research Aim

From the problem definition above, the aim of this research can be divided into two parts:

1. *Gain insight in the structural design considerations to design a high-rise building in a circular manner.*
2. *Investigating the possibilities in measuring the circularity of a high-rise building and providing additional tools where necessary.*

1.2.3. Research Questions

The main research question is stated as:

How does the structural design of a circular high-rise building compare to that of a conventional one in the Netherlands?

The main research question is answered with the help of the following sub-questions:

- How can circularity be defined and what are key aspects?
- What characteristics of high-rise are fundamental to its structural design?
- What are possible design options for a high-rise structure?
- What methods can be used to implement circularity in Civil Engineering and how can this be measured?
- What aspects to the structural design process benefit the circularity concept in the structural design of high-rise?
- What differences can be observed between the circularity options of high-rise and low-rise buildings?

1.3. Methodology

The methodology of this research is divided into three segments: **obtain** knowledge, **validate** method, and **compare** results.

These segments are used to answer the research questions posed in paragraph 1.2.3. These questions are answered in an increasingly specific manner, which is moving from a broad research viewpoint to a narrower research viewpoint during the research. See Figure 2 for a graphical overview.

1.3.1. Obtain

In the first segment, the goal is to obtain knowledge about the subject through a literature review. With this knowledge, a portion of the sub-questions is answered, which will provide the means to answer the main research question through the other segments of this research.

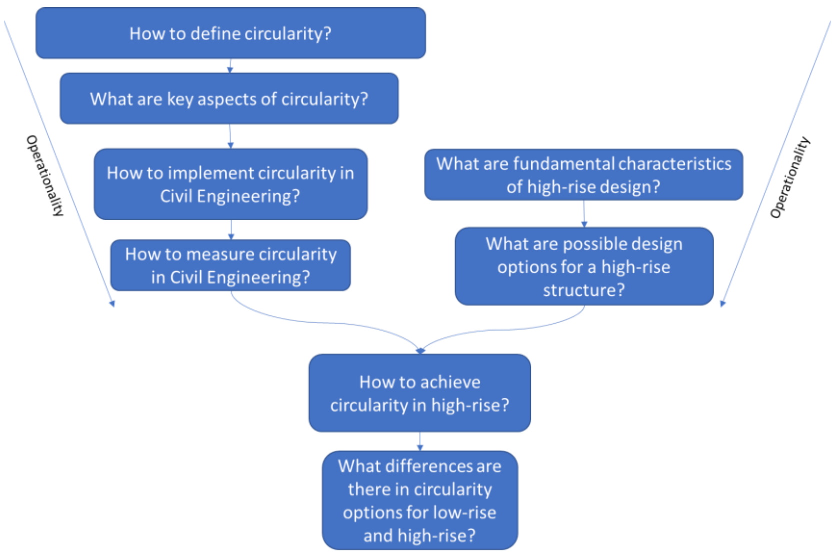


Figure 2: Overview of research questions for literature review. Format based on Coenen [22].

The literature review is split into three parts, each part answering a sub-question. These parts are circularity, high-rise buildings, and circularity in Civil Engineering. This leads to the use of the following search query in the literature search:

> (“Structural design” OR “construction design” OR “building design”) AND (“Circular economy” OR “circular design” OR “circularity”) AND (“high-rise” OR “tall building”)

Additionally, alterations to this search query have been used to obtain literature which focusses on a certain aspect of circular high-rise buildings.

1.3.2. Validate

In the second segment, the method or strategy of reaching circularity is validated. This is done by constructing a measurement tool for circular high-rise. A study is performed to identify design choices which contribute to the circularity strategy as identified in the ‘obtain’ segment. These choices are implemented into the design of a circular high-rise building as an alternative to a conventional high-rise building.

1.3.3. Compare

In the final segment, the effect of implementing circularity in a high-rise building is investigated to gain insight in the possible investments that are needed from clients to shift towards circular high-rise buildings. In this segment, a structural analysis is carried out for different variants of circular high-rise buildings, from which the structural element dimensions are determined. This will give insight in the material use, costs, and environmental impact of different variants of circular high-rise buildings. With this information, a structural designer can advise its client on the required investment of shifting towards a circular high-rise building.

1.4. Report Outline

In this report, it is investigated how the research questions, as identified in Chapter 1, can be answered. In Chapter 2, a literature review is performed, in which a part of the research questions are answered. It is investigated what circularity is, in what way high-rise structures are possible, how circularity can be achieved in the construction sector and how this can be translated to circularity for high-rise structures. In Chapter 3, a measurement tool for adaptability of buildings is created: the Building Adaptability Indicator. This measurement tool is used to identify the influence of adaptability on the choice for demolition or reuse of buildings. In Chapter 4, an analysis on the adaptability of a 100 m tall high-rise building is performed. For this building, alternative designs are proposed, which are investigated on their consequence to the environmental impact and costs. Chapter 5 will conclude this report with a conclusion and recommendations.

2. Literature Review

This literature review is performed to be able to answer several sub-questions as mentioned in paragraph 1.2.3. This aids in reaching the research objective and answering the main research question.

2.1. Circularity

Implementing circularity will result in a decrease of raw material use and waste production, while the service life of products will be extended [30]. This indicates that complete circularity will result in a sustainable earth. However, several researchers argue that circularity does not directly lead to sustainability. As the implications of circularity generally highlight one particular circularity concept, the total contribution to sustainability is limited [51]. Additionally, Sauvé et al. state that CE does indeed have implications that aid in sustainable purposes, but that its "final objective remains unclear and certainly narrower than sustainable development" [101]. It can be concluded from these researches that circularity might not directly lead to sustainability, and like Anastasiades et al. [7] state: "Where sustainability is the goal, the circular economy is a means to this end."

In this report, the focus is limited to circularity and as stated above this does not directly lead to sustainability. However, investigating how to implement circularity in a relevant manner, will provide a possible pathway to sustainability in the future.

One way to explain the concept of circularity is by using the Circular Economy System Diagram from the Ellen MacArthur Foundation (EMF), which is shown in Figure 3. The infographic can be compared to the principle of 9 R's, which is explained below.

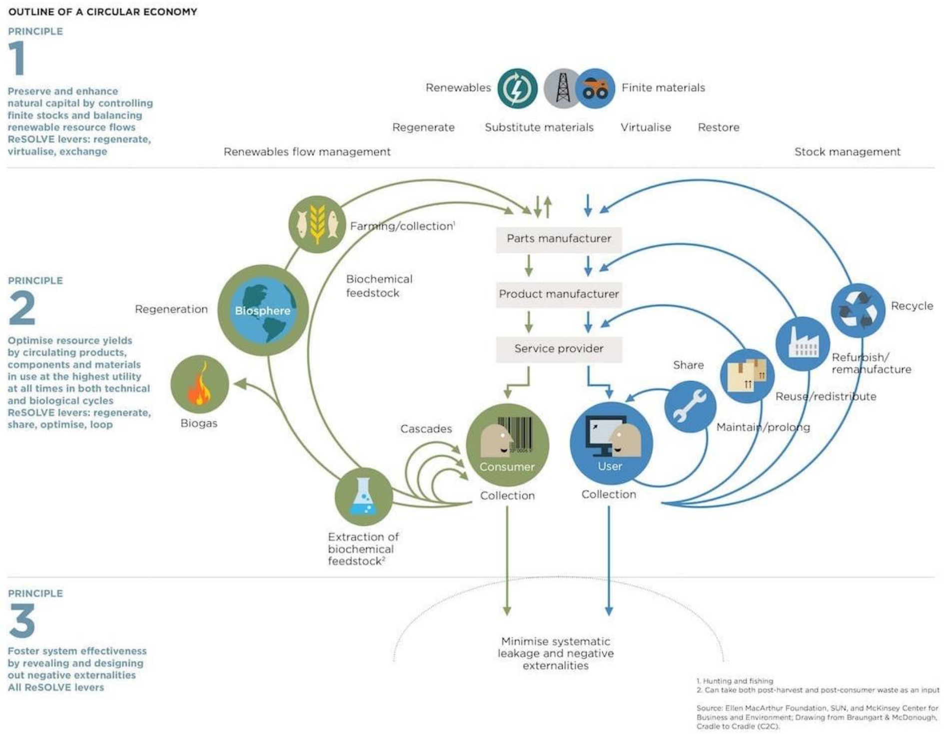


Figure 3: Circular economy system diagram. Source: Ellen MacArthur Foundation [29].

As shown in Figure 3, one of the main goals from the circular economy system diagram is to minimize raw material use and waste production. One of the other main goals is to keep materials and resources in a closed loop, which coincides with an extended life span. These goals are in line with the principle of circularity.

The diagram can be divided into a ‘Renewables flow’ and a ‘Stock flow’, where the stock flow can be compared to the principle of 9 R’s. The 9 R’s waste hierarchy is created by PBL, which has deducted it from ‘Lansink’s stairs’, created in 1979 [52]. The 9 R’s waste hierarchy is [92]: R0: Refuse ; R1: Rethink ; R2: Reduce ; R3: Re-use ; R4: Repair ; R5: Refurbish ; R6: Remanufacture ; R7: Repurpose ; R8: Recycle ; R9: Recover, see Figure 4.

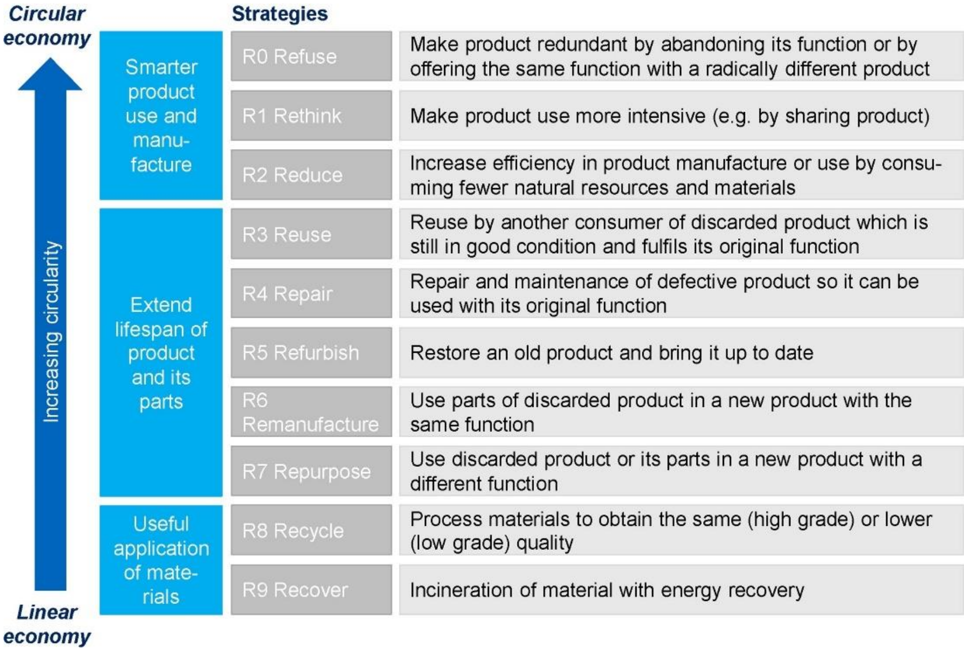


Figure 4: Overview of 9R waste hierarchy. Source: Kirchherr et al. [56].

In this waste hierarchy, R0 is the most circular option, while R9 is the least circular [22]. It can be observed from Figure 3 that the waste hierarchy returns in the circular economy system diagram in a similar manner, while this diagram also shows a re-growable flow. Both flows are shown in steps descending from high grade to low grade production applications [52], just like the waste hierarchy.

Circularity is defined by more than this waste hierarchy, which minimizes raw material input and waste production. Another factor that impacts the circular economy is a principle that is often used to describe the three pillars of sustainability: People, Planet, Profit [7]. This principle has been addressed first by the Brundtland commission in 1987, where the commission focussed on three aspects of sustainability: environmental, social and economic aspects [16]. As mentioned before, circularity is a means that provides a pathway to sustainability. This indicates that circularity should also include the pillars of sustainability, also called the 3 P's. Some papers have argued that a fourth P should be added, namely Politics [7]. It is said that politics is a key factor to commence change of cultural behaviour [7]. In that case, the Dutch government has provided a good example by setting the goal to reach complete circularity by the year 2050 [113].

Finally, it is possible to distinguish different levels of circularity, these levels being the micro, meso and macro levels [22]. The micro level focusses on the material and product manufacturing, the meso level focusses on several products assembled to one multi-purpose product, such as a building, and the macro level focusses on an entire economy or system, such as a city or neighbourhood [22; 51; 56; 90]. Currently, most research on circularity in the built environment has been conducted at micro and macro level, namely on supply chain management and eco-cities [90].

To be able to define circularity, it is important to realise that the concept should cover the relevant aspects as defined above. Research has been conducted on the definition of circularity, which resulted in the following definition by Kirchherr et al. [56]:

> *an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro (...), meso (...) and macro level (...), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers.*

In this research, this definition is considered a complete definition of circularity, as it contains the waste hierarchy, the three pillars of sustainability and the three levels of circularity. The aim of this research is to gain insight in the design considerations of a circular high-rise building, for which the definition by Kirchherr et al. is used as a guideline for what circularity means.

2.2. Circularity in Civil Engineering

As has been shown in Chapter 2.1, circularity is a concept that acts on multiple levels, principles, and systems. In this chapter, insight is given into how circularity can be achieved in civil engineering.

As discussed before, the main goals of circularity are the minimization of raw material use and waste, as well as extending the life span of products. This is in line with the key aspects of circularity in the construction sector as defined by Hossain et al. [51]. These aspects include the use of sustainable materials, reuse or recycling of materials, and avoid waste. It is generally easier to implement these aspects at the design stage rather than when a building is operational. Therefore, to be able to shift from a linear to a circular supply chain in the construction sector, the design phase is crucial [7]. There are however several reasons why circularity is not yet widely incorporated into the built environment. These reasons include the fact that the construction sector is profit-driven and lacks profound knowledge about circularity [3; 42]. Furthermore, Coenen [22] identified that the linear economy in the construction sector is maintained because the sector is “demand-oriented and tailored to one-of-a-kind projects”. It is suggested that contractors and designers should be motivated more to design for the End of Life (EoL) stage of a building [3], which would then make the shift towards circularity in civil engineering easier.

In this chapter, a focus is laid on the role of structural designers and which strategies are available in the design phase of a building to achieve circularity.

2.2.1. Strategies

For several years, strategies have been developed that enable a circular built environment. From the structural designer's perspective, these strategies are Design for Disassembly (DfD), Design for Adaptability (DfA), and Minimum Embodied Carbon (MEC).

2.2.1.1. Design for Disassembly

Principle

The principle of DfD is to extend the life span of a material or element, by using dismantling. This allows for easy replacement, reuse and recycling of the material or element [7]. This can be achieved through proper design of the building and planning of the construction [95]. Key factors that influence whether DfD can be implemented successfully are the method of disassembly, the technology to disassemble and the operator of the disassembling process [106]. Specifically, this means that connections between elements should be reversible and the reuse or recycling of elements and materials should be warranted.

There are two ways in the reuse of elements, namely upstream and downstream reuse. Upstream reuse is the practice in which elements or materials for a new building are gathered from EoL buildings, also known as urban mining. Downstream reuse happens after the life span of the building is reached and focusses more on the value retention of the elements [36]. This leads to the possibility of reuse at the future EoL stage of the designed building.

One of the advantages of DfD is the fact that it benefits all the pillars of sustainability, the 3 P's. Firstly, the activity of dismantling the building takes more man hours than demolition, leading to the creation of jobs, which benefits the People aspect [7]. Additionally, dismantling required less education and skill, meaning job opportunities for low-skilled workers [95]. Secondly, it should be obvious that by reuse and recycling, there are environmental benefits to DfD, the Planet aspect. This leads to an extended life span of materials and simultaneously to less raw material use and waste production, which are the goals of circularity as identified in Chapter 2.1. Thirdly, by using DfD, a market is created in which elements are reused, recycled and reprocessed [95], which is an economic benefit, the Profit aspect. Generally, the DfD principle directly creates more flexibility and adaptability of the building [95], meaning that the DfD principle overlaps with the DfA principle, which is explained below. This overlap also works vice versa.

Indicators

There are several techniques in civil engineering that will benefit the DfD principle. These techniques are referred to as indicators. Below, some of the indicators of DfD are explained.

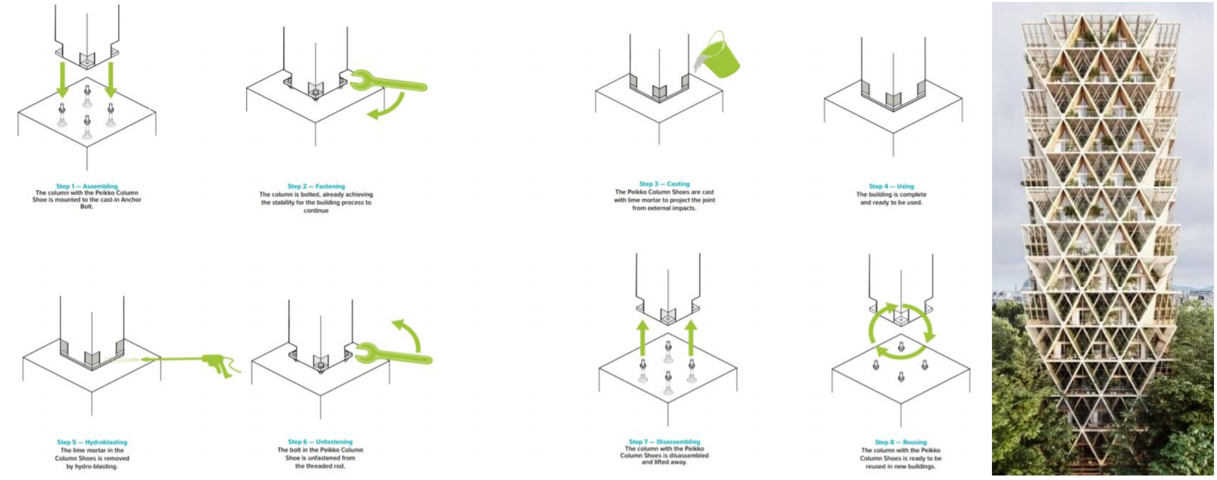
In DfD it is important that most, if possible all, connections are reversible. This is also referred to as disassemblability. A high disassemblability leads to structures that can easily be dismantled, which is key to DfD. Consequently, the elements of the structure can be more easily reused [36]. Disassemblability means different things for different materials. In steel structures, this means that mainly bolts should be used. Because breaking a welded connection will prevent the ability to reuse the elements, which should be avoided [104]. For concrete structures, it is possible to implement bolted connections into the concrete. Examples of this are solutions by Peikko [109], see Figure 5a. In timber structures, it is also possible to implement bolted connections, while dowels also provide a reversible option [105]. Avoiding the use of welds in steel connections means that a challenge arises in using rectangular or circular hollow sections and moment resisting connections, because these typically require welded connections [104]. A case study by Bertin et al. [12] has shown that increasing the use of hinged connections will increase the environmental impact of a structure by less than 1%, while it creates the possibility for a second life cycle of the elements, providing significant environmental benefits.

Furthermore, Geldermans [40] has suggested that a standardization of connections could be interesting, as this would benefit the reuse of the connections, while the structural elements can be altered. Either way, the use of disassemblability should be motivated.

Modular design is a second indicator that enables the DfD principle, see Figure 5b. In modular design, a product consists of a set of components (modules) that can be brought together in different ways to obtain an equally functional product [13]. A simple example of this are Lego blocks, where one can build a vast number of things with the same set of bricks. This principle is possible because the modules are functionally independent [107], which is an important aspect to modularity.

According to Bitovi [13], modular design is “flexible, scalable, and cost-efficient, but also customizable, reusable and consistent”. These characteristics are in line with the DfD principle. Modularity leads to environmental benefits due to, for example, the possibility of reusing the modules. Additionally, economic benefits arise due to the lower costs in manufacturing modules and assembling at a later stage [107]. Literature has shown that modularity is beneficial through the entire product life cycle, the product in this case being a building [107].

A third indicator for DfD is the simplicity of design and construction. By using prefab elements and using repetitive floor plans, the construction process will be sped up, leading to less environmental pollution during the construction process. Additionally, repetitiveness in the design will increase the potential for reuse of elements, because a large number of the same elements will become available at the EoL stage of the building [12].



(a) (b)

Figure 5: (a): Peikko solution to DfD connection in concrete. Source: Böhm and Zwaan [14]. ; (b): Modular design of high-rise. Source: Baldwin [10].

DfD in High-Rise

Implementing DfD in the structural design of high-rise buildings is something that has not received wide attention. As described above, it is important for DfD that the connections of the structural elements are reversible. Therefore, moment resisting connections should be avoided. When using mainly bolted connections in a tall building, which is typically subjected to dynamic loads such as wind or seismic loading, one should carefully treat the fatigue behaviour of the bolted connection [77]. Due to the repetitive loading on the bolt, the existing defect in the material are propagated, eventually leading to failure [119]. Therefore, an extended analysis on the bolted connections will be necessary when using DfD in high-rise.

2.2.1.2. Design for Adaptability

Principle

The principle of DfA is that a product can be adapted and altered by the users, so that the future needs, demands and conditions are met [7; 53]. It is preferred that change of the product is possible by the user, which is also called a bottom-up organization, as a top-down organization will lead to less diversity [40]. For a building this means that it should be designed in such a way that due to its adaptability it will not become obsolete [40]. This will result in an extended lifespan of the building, as it can be adapted to future needs, which avoids demolition of the building [7]. Furthermore, Rockow [98] has shown that using DfA actually enables adaptability of a building, while not using DfA disables this.

As mentioned before, DfA is about extending the life span of a building by increasing its possibilities for change. Geldermans [40] argued that the life span of a building has to be implemented into the design stage, as this means that choices in material and products can be adjusted accordingly. Additionally, it is fundamental to DfA to keep functions with a short lifespan accessible for maintenance without influencing the lifespan of long lifespan functions [22]. This can be explained by the argument of Brand [15], who argued that buildings consist of six shearing layers, each with a different lifespan. These layers consist of: site, structure, skin, services, space plan and stuff, see Figure 6.

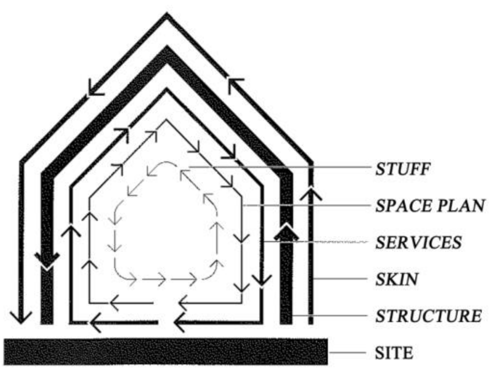


Figure 6: Brand's shearing layers of change. Source: Brand [15].

The general lifespan of a building is influenced by several parameters, namely its location, building type, preciousness and adaptability [122]. Mainly the adaptability is important in this research, as the other parameters are not changeable during the design process. Regarding the adaptability, the focus should be laid on the building aspects with a long life span [122]. Extending the life span of these aspects will greatly affect the life span of the total building, which is desirable. Opposed to this, aspects with a short life span will be replaced anyways, which means that increasing its lifespan has little to no influence on the lifespan of the total building.

Indicators

The indicators of DfA as formulated by Rockow [98] are: "reserve capacity, quality materials, floorplan openness, Floor-to-Floor (FtF) height, simple design, separated layers and accurate plans". As mentioned before, some of these indicators simultaneously apply to DfD, showing the overlap of DfD and DfA.

As for the indicator of reserving capacity to benefit DfA, it is believed that this can be done in several areas. For example, for a building to be flexible in its use and function, the dimensions, loads and installation space should have enough capacity [122]. This can be easily explained by the example that the function of a building changes from a residential to an office. In an office, it is desirable to have open spaces, which means that high ceilings are used. In a residential building, the client would like to maximize its revenue by stuffing as many stories in a building as possible, using low ceilings. Also, the demands of heating, ventilation, and air conditioning (HVAC) systems in an office are different to that of a school, especially considering the situation regarding COVID-19. This could demand for a larger available space for HVAC systems in buildings, which should be accounted for in its structural design when building adaptable.

The aspect of using quality materials indicates that materials that could support the reuse of elements for several life cycles should be used. Investments at the design stage are needed to implement high-quality materials, as to use them for several life cycles.

Openness in the floor plan gives freedom to the user to divide the floor plan in a bottom-up organization. Openness is associated with the idea that a building is divided into two domains. These are as follows: the domain that is controlled by the investor, namely the structure, and the domain that is controlled by the user, namely the interior [40]. In DfA, the investor should provide the user with enough interior space for flexible infill. This is seen as an open building.

The FtF height of a building should be sufficient to allow for installation space for example, while reserving vertical space improves the flexibility of a building. However, minimizing the FtF height leads to efficient material use, which is sustainable in itself. Therefore, an optimum should be found where there is sufficient capacity to allow adaptability, while the height is minimized for material preservation.

Simplicity of the design influences both DfA and DfD. Simple design solutions include for example modular design or using precast elements. This provides an overlap with DfD, which proves the point made above, that there is overlap between DfD and DfA [51; 95]. The use of simple design strategies improves the DfA concept, as it enhances the (partial) disassemblablity of the building, which consequently gives more flexibility to the building.

Regarding the separation of the shearing layers by Brand [15], aspects with a shorter lifespan should be accessible for repair or replacement without influencing the lifespan of longer lifespan aspects [122]. An example of this is the accessibility of installations, as these require to be repaired or replaced after approximately 10 to 15 years. Integrating these installations into the floor system could result in damage to the floor upon replacement of the installations, which should be avoided. Therefore, separation of the shearing layers is preferred, as this enables an extended lifespan of separate layers, which is one of the pillars of DfA.

DfA in High-Rise

Similar to the principle of DfD, the implementation of DfA in the structural design of high-rise buildings has not seen wide attention. However, by using the aspects of DfA for regular buildings as defined above, DfA should be able to be implemented in high-rise as well.

There have been researches that show the possibilities of adaptive reuse by repurposing existing buildings to new functions. Strelitz [110] has shown with examples of adaptive reuse in London, that this is possible for short and long term. For short term, it is possible to adapt an insurance office to a financial office for example. These sectors generally prefer different floor plans, which means that the possibility to change this should be available. For the long term, it is shown that complete repurposing of the building should be possible, as this will prevent demolition. Currently, this is mainly the case for vacant office buildings. Research has shown that there is currently less demand on office space, while the demand for residential space is high [117]. Additionally, the aftermath of COVID-19 will likely result in a decrease of office use and increase the amount of vacant offices. This indicates that adaptive reuse of vacant office buildings to residential buildings is necessary.

An interesting example of adaptive reuse is the case study by Steficek and Vancura [108] to transform the Woolworth building from an office to residential building. This office tower, finished in 1913, has seen its upper 30 storeys adapted to a luxurious residential space. This provided several challenges in upgrading the foundation or relocating elevator shafts for example. Moreover, an increase of the amount of slab penetrations for mechanical, electrical, and plumbing (MEP) systems were necessary, as a residence needs more of these systems than an office. When using DfA, the flexibility in recesses should be accounted for.

Many office towers from the 60s or 70s are designed to efficiently use materials, while the Woolworth building from the 20s was significantly overdesigned. The stiff steel frame of the historic building, together with the large mass of its terracotta slabs and heavy columns, result in no additionally needed mass or stiffness to improve the dynamic behaviour when changing from office to residence. This problem is present when adapting office towers from the 60s or 70s to residential towers. This indicates that when using DfA in high-rise buildings, one should carefully consider the dimensions and capacity of the structural elements. Because changing the function will change not only the static but also the dynamic loading on the building, which should be accounted for.

2.2.1.3. Minimum Embodied Carbon

Principle

The principle of using MEC is more straightforward than the previously discussed principles of DfD and DfA. In minimizing the embodied carbon, one changes the design in different ways and comparing these designs to choose the best option [37], namely that with the lowest embodied carbon. In recent years, the use of parametric design has gained interest. Parametric design uses a series of parameters as input for a calculation, from which relevant results can be deducted and used to alter these parameters [21]. This can be useful when using an objective function, to find an optimum value for a certain objective. Traditionally, in the design of buildings, this objective was to minimize material use [36]. Other options were to minimize the cost of a project or optimize the structural behaviour of the building [37]. Recently, this objective also includes maximizing the amount of circularity of a building. However, there are several challenges in the measurement of circularity. This is discussed in Chapter 2.5.

Indicators

Many researchers have tried to formulate equations with which the amount of circularity of a building can be determined. However, as was discussed in Chapter 2.1, circularity has a broad definition and it can be challenging to find the calculation method of circularity using a holistic approach. Therefore, many researchers choose to narrow it down to using the amount of embodied carbon [38] or calculate the shadow costs [59; 85] of a building.

As shown in Figure 3, the circular economy can be split into two parts: the stock cycle and the regrowable cycle, which is referred to as the biological cycle in this research. The common structural materials of concrete and steel are part of the stock cycle, while timber is part of the biological cycle. For both these cycles, the indicator of environmental impact can be used to obtain MEC of a building. Furthermore, for the stock cycle the recyclability of the material plays a role, while for the biological cycle the regrowability is important.

Minimum embodied carbon in High-Rise

Using the strategy of MEC and in particular using visual programming in design for circular high-rise has been performed by some researchers. For example, Gan et al. [37] have performed a case study in which design optimization was used to provide sustainable alternatives to a high-rise building design, by analysing the amount of embodied carbon. It was concluded that the material choice, as well as the choice of the structural system, is vital in the ability to reduce the amount of embodied carbon. It was seen that using recycled steel greatly reduces the amount of embodied carbon.

Other studies, by Lankhorst [59] and Palau Hernandez [85] for example, used parametric design in Grasshopper to perform a sustainable structural design of a high-rise building. Both of these studies used the shadow costs as objective that should be minimized to determine which design choices impacted the environment the least negative. For high-rise of more than 150 meters, it was found that diagrid structures uses the least amount of material and consequently has the lowest shadow costs. Furthermore, Lankhorst found that floor systems impact a significant portion of the environmental impact of the building, where hollow core slabs have the lowest shadow costs. However, using hollow core slabs in high-rise results in large masses on the floor, which could provide problems. Therefore, these conclusions might not be impactful for high-rise design of heights less than 150 meters, for which additional research is required.

2.2.2. Conclusion

From the literature study on circularity in civil engineering, it can be concluded that there are three strategies that can be used by structural designers to design buildings in a circular manner. These strategies are Design for Disassembly, Design for Adaptability and Minimum Embodied Carbon. It is concluded that each of these strategies have a set of indicators, which can be used in the measurement of circularity, which will be discussed in Chapter 2.5. An overview of the principles of the circularity strategies is given in Figure 7. To be able to draw conclusions on circularity in high-rise, an investigation on the design of high-rise buildings is necessary. This investigation will follow in Chapter 2.3.

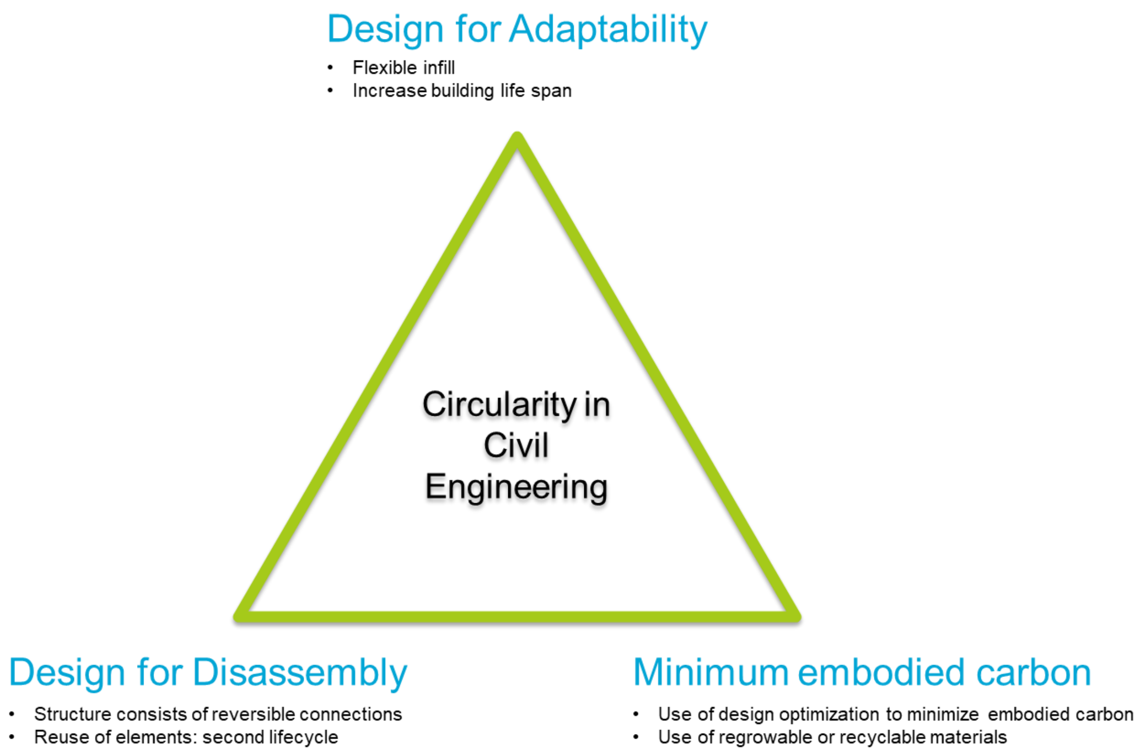


Figure 7: Overview of principles of three circularity strategies.

2.3. High-rise buildings

2.3.1. History

With its height of 10 storeys, the Home Insurance Building in Chicago is generally regarded as the world's first skyscraper [5]. Inspired by the, at the time, immense height of the Eiffel Tower in Paris, many United States architects showed pioneering work on several skyscrapers in mainly Chicago and New York in the following years [5]. This pioneering work was made possible due to the invention of using cast iron, and later steel, in structural elements. During the roaring 20s, a tall building boom was emerging, which would last until approximately the start of World War II [100]. After World War II, during which most steel was needed for war machinery, the interest in tall buildings continued. Due to improving technologies and easier calculation methods, easily constructible tall buildings could be designed and analysed [100]. For the Netherlands, it took up until approximately the 80s to start gaining widespread interest in high-rise buildings, with especially Rotterdam showing ambition in this area [59].

Around the turn to the 21st century, the use of more advanced computers started to play a larger part in the design and analysis of high-rise buildings [100]. Complex shapes are possible due to the analytical power of the modern computers. However, as the construction industry moves towards circularity, it could become more feasible to take a step back to simplicity and follow the simple designs of the 50s and 60s. This will improve the repetitiveness in high-rise construction, which benefits the reuse of materials [12].

More recently, the demand for the function of high-rise is changing. The interest in high-rise offices is passed due to digitalization and discovering reused buildings as proper workspace in the modern system [70]. Furthermore, the aftermath of COVID-19 could result in a shift away from the use of office space and more towards working from home. This results in a decrease in the demand of office towers, while an increase in demand of multi-purpose towers is observed [70]. Currently, half of the 20 tallest buildings in the Netherlands have the function of office, while 20% is a mixed-use of office and residential function [32]. This indicates that the majority of the current high-rise in the Netherlands will become obsolete in the future, when the demand of office space is lower.

2.3.2. Demolished High-Rise

As mentioned above, the reuse of buildings is gaining interest. Lately, mainly vacant office buildings are being assessed on their performance to determine whether reuse is feasible [121]. In some cases however, due to strict laws and regulations or a lack of repurposing abilities, it is chosen to demolish the building. Unfortunately, it also occurs that buildings with a long life span, such as high-rise buildings, are demolished before the end of their intended life span [23].

Demolishing a building leads to a set of negative factors considering circularity and sustainability of the building. When a building is demolished, the construction waste is being downgraded, which has a negative impact on the reuse capabilities. Additionally, the costs and emissions from the demolition activities are undesirable [39]. As a side effect of choosing to demolish a building and replacing it with a new building, a socio-geographic shift of the population can occur [63]. This means that people that cannot afford to live in a newly built building shift towards the cheaper social housing, which reflects negatively on the People aspect of sustainability [63].

Right now, one of the methods of demolishing tall buildings is to dismantle from top to bottom with cranes inside the building. However, this could be deemed unsafe due to damage to the building structure [54]. Another possible method is implosion of the building, which obviously does not lead to sustainable repurposing of the building materials. Therefore, it can be concluded that it is undesirable to demolish a tall building at all.

According to the Council on Tall Buildings and Urban Habitat (CTBUH), a high-rise of more than 187 m has never been voluntarily demolished [23]. However, as is shown in Figure 8, there is a large number of tall buildings that have been voluntarily demolished already. Reasons for demolishing a building before the end of their life span are generally due to unforeseen circumstances [122]. Figure 8 shows that these circumstances could be due to excessive damage to the building as a result of improper design or a disaster such as a fire or terrorist attack. However, most tall buildings that are demolished, are in no state of structural unsafety. An example of this is the JP Morgan Chase Tower. This tall building is being demolished to make way for the erection of a new headquarters of JP Morgan [46]. In this case it is chosen not to repurpose, but to demolish and rebuild, which leads to a heavy negative impact on circularity. One measure that could have stopped the demolition of the old JP Morgan tower is the designation of the building as a landmark, according to Kroessler [58]. However, this is no long-term solution for the problem of demolition at macro-scale.

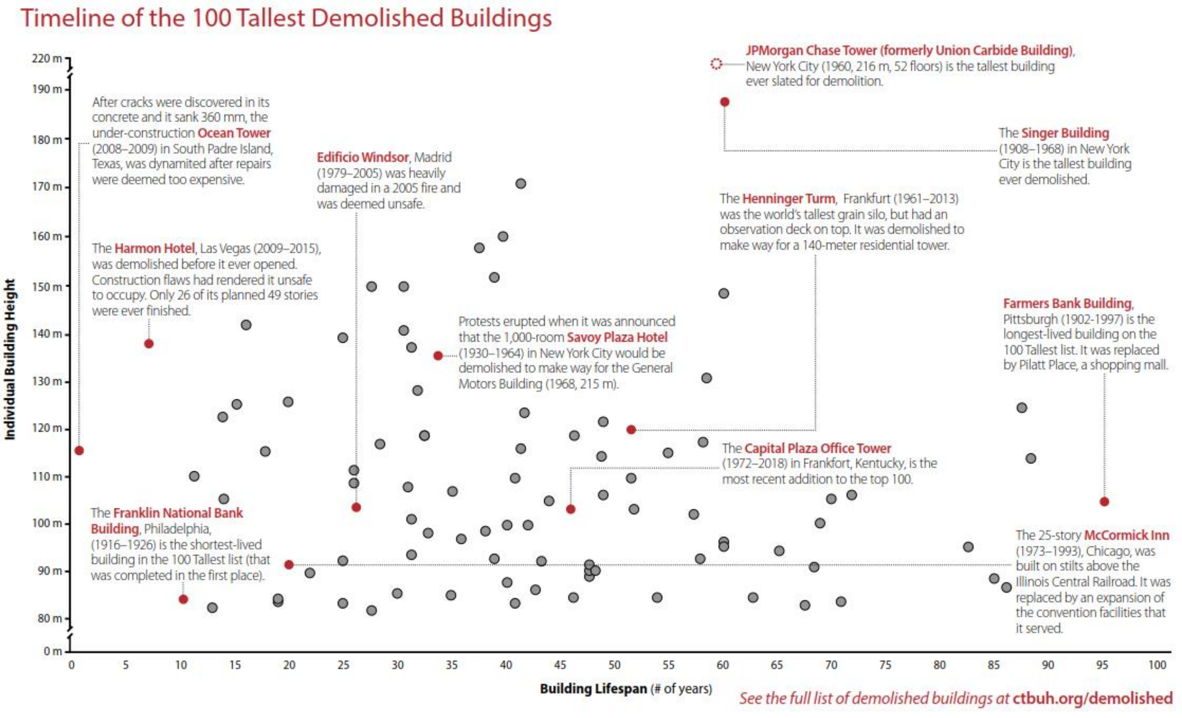


Figure 8: List of 100 tallest demolished buildings. Source: CTBUH[23].

Research shows that many buildings exceed their intended life span, which is also visible in the Netherlands. It is estimated that the average age of the Dutch building stock is 125 years old [122], which is generally more than the intended life span. Fortunately, as high-rise was not popular in the Netherlands until the 80s, these buildings generally have not yet reached their EoL stage. It is however expected that many buildings, including high-rise in some years, will reach this stage in the foreseeable future, which gives structural designers the opportunity to do better in designing new high-rise buildings [45].

Some of the scarce examples of ‘high-rise’ demolition in the Netherlands are the demolition of the faculty of Science of the University of Leiden [60] and the demolition of some of the older buildings at the Erasmus Medical Centre in Rotterdam [33]. The reason for demolition of both of these buildings is to make way for the development of new buildings. Due to the limited height of less than 60 m, the buildings could be demolished from top to bottom by using cranes from the ground. The limited height of these demolished buildings confirms the previously stated conclusion that actual high-rise in the Netherlands is not yet at its EoL stage, which is why demolition has not been widely performed.

Solutions to battle tall building demolition could be to design in innovative ways [26]. It should not be the trend to demolish a structure that is in the way of a to-be-built structure. Examples of this are DaiyaGate Ikebukuro in Tokyo, Leeza SOHO in Beijing and 271 Spring Street in Melbourne [26]. All these buildings are built around their surroundings, instead of adjusting their surroundings to fit the building, see Figure 9.

Moreover, adaptive reuse of tall buildings is also gaining interest, in London for example [110]. Several vacant London office buildings have been adapted to a new purpose, from which it can be reused.

It is concluded that due to the vast number of tall buildings that are preliminary demolished, ways to prevent this demolition should be sought. The reason for many demolition cases is the replacement with a building with new technologies or perhaps a new function. A building which is built adaptable would in theory not have to be demolished when a client wishes new technologies or functions. Therefore, the use of DfA could prove to be an important strategy in high-rise buildings.

(a) *(b)* *(c)*

Figure 9: (a): DaiyaGate Ikebukuro, Tokyo ; (b): Leeza SOHO, Beijing ; (c): 271 Spring Street, Melbourne. Source: CTBUH[26].

2.3.3. Structural Design High-Rise

2.3.3.1. Principle

One of the main differences between low-rise and high-rise design is that high-rise is likely to be governed by the serviceability limit state [100]. Compared to the design of a low-rise building, which generally focusses on the statics of the structure, a high-rise building has different demands. As the height of the building increases, vertical loads will increase simultaneously. However, the lateral loads on a building increase significantly at large heights, which is why the design of a high-rise building is generally governed by lateral loads [109], see Figure 10. It is important to achieve sufficient shear stiffness and bending stiffness of the structure, as to satisfy the maximum top displacement and inter-storey drift. Possible loads that result in a lateral motion of the building are seismic action and wind loads. In the Netherlands, wind loads are generally governing for high-rise design [59].

Although it is not a requirement, the general consensus is that the maximum drift is approximately h/500 [100]. Additionally, the motion perception of humans inside the building should not be too high, which means that the structure should satisfy the maximum acceleration as well [100; 109]. The requirements for acceleration are different for different building functions, as the motion perception of a person lying down is more sensitive [109]. Therefore, the requirements are stricter for residential high-rise than for office buildings for example.

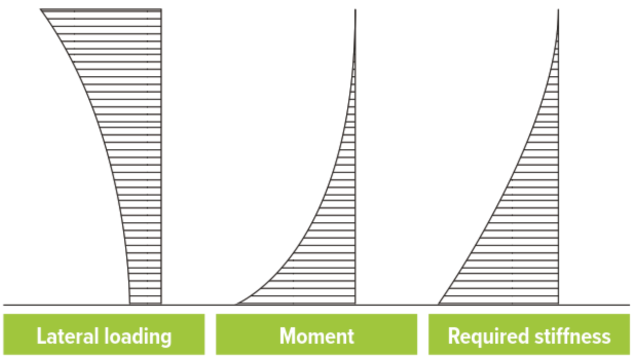


Figure 10: Increase of lateral load on high-rise building. Source: Stirane [109].

During the 60s, Khan realised that building increasingly higher would lead to a 'premium for height' [55]. For tall buildings, the vertical load bearing capacity is increased at lower floors due to accumulating the vertical loads of upper floors. However, as is shown in Figure 10, due to increasing lateral loads, the lower storey stiffnesses should be significantly higher as well. This leads to an increase of the amount of structural material of taller buildings, meaning that the phenomenon of 'premium for height' occurs [6], which is illustrated in Figure 11.

The premium for height concept provides a challenge in high-rise design. Considering the minimization of material use for sustainable building, then Figure 11 would indicate that it is wise to only construct low-rise buildings. However, as mentioned before, high-rise buildings are gaining interest in the Netherlands due to lack of horizontal space. Therefore it is important to treat design considerations carefully, to find an optimum between the material use and the building height.

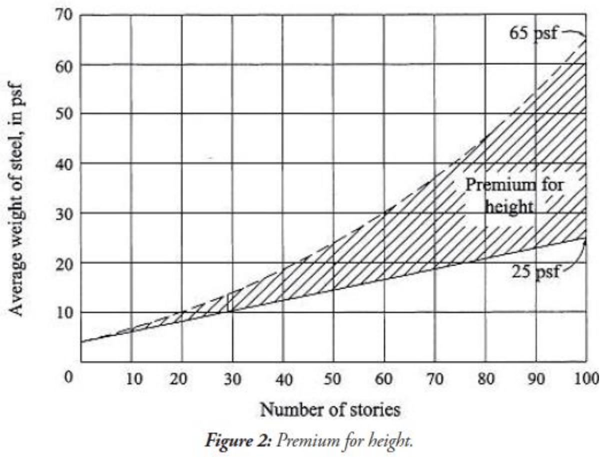


Figure 11: Premium for height principle. Source: Ali & Moon [6].

2.3.3.2. Lateral Stability Systems

Several options are available to provide lateral stability in a high-rise structure. Ali and Moon [6] have created an overview of different possible structural solutions that provide lateral stability, which shows the optimum height for the stability systems as well, see Figure 12 and 13. They divide the possible solutions into interior and exterior structures. If the lateral load is mainly transferred to the foundation through the structural components located inside the building, the system is an interior structure. For the exterior structure this holds as well, albeit that the load is mainly transferred through exterior components [6].

A selection of these possible lateral stability systems is explained in more detail. A focus is laid on stability systems that prove to be interesting for buildings of approximately 30 storeys, as this is a common height for high-rise in the Netherlands [25].

Core / shear walls

The shear and bending stiffness of a building can be provided by using a stability core. This core will essentially function as a cantilevered beam fixed to the ground [59]. The core will provide lateral stiffness similarly to a Timoshenko beam, see Figure 14a. The construction of a stability core is relatively easy and comprehensible, which is why this method is commonly used [59]. Several options are possible for the core, namely using stability walls or a braced frame. Furthermore, for the surrounding structure, hinged or rigid connections are both possible. Attention should be paid to the resulting internal forces due to the different behaviour of the shearing frame and the bending core, see Figure 14b. Most common used materials are concrete and steel, but Slooten [105] has shown that the use of timber is also possible with this stability system. Efficient use of the floor area can be achieved through locating the means of vertical transport inside the core, as this function often provides stiffness anyway.

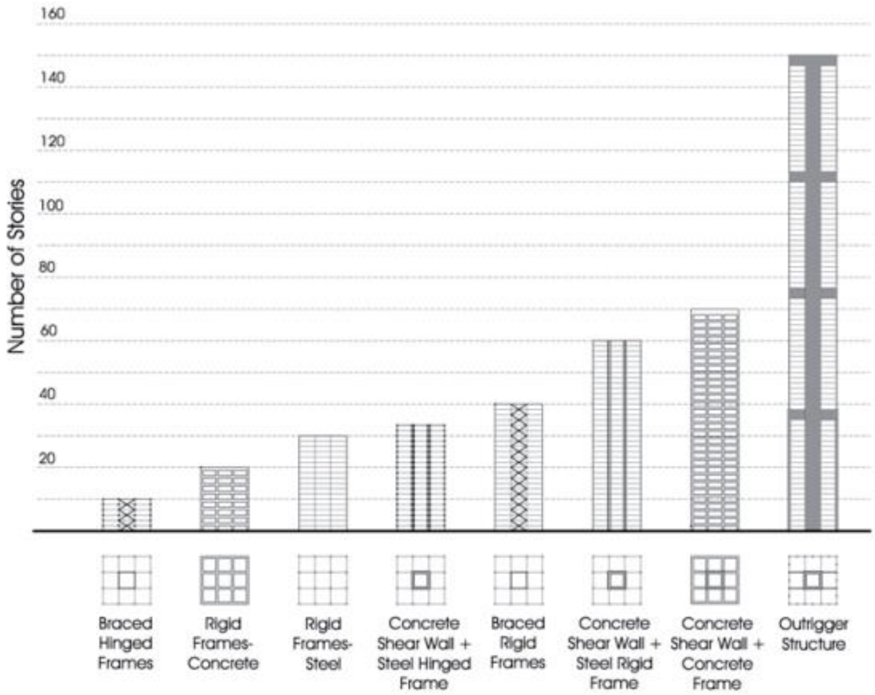


Figure 12: Overview of interior structures. Source: Ali and Moon [6].

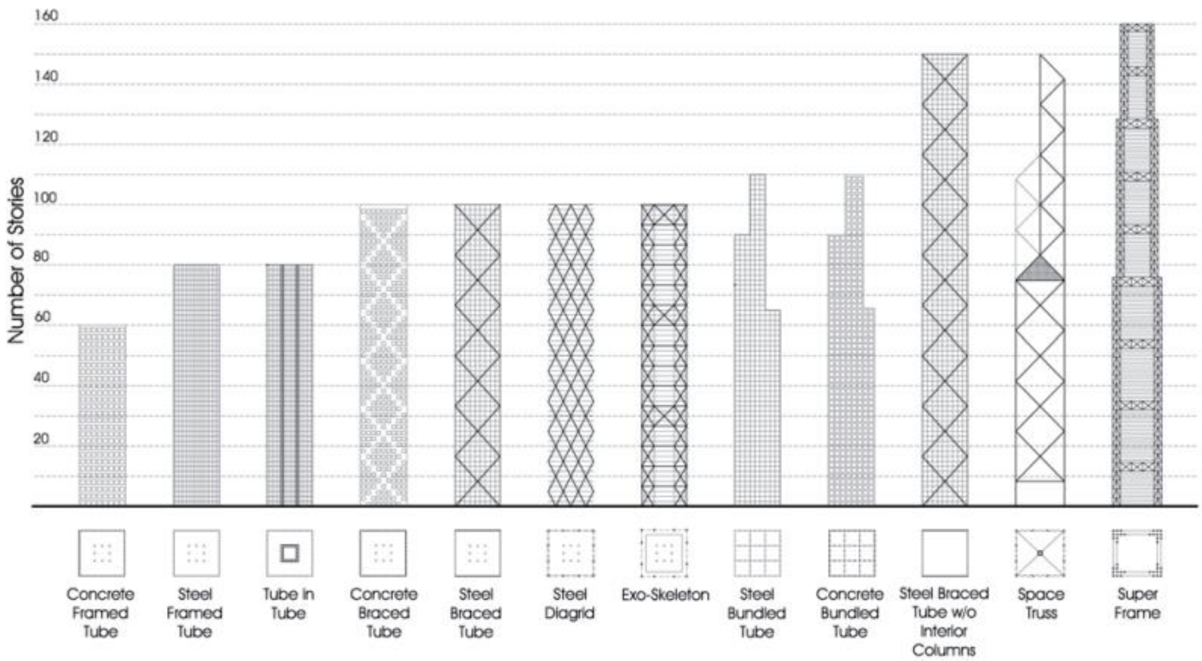
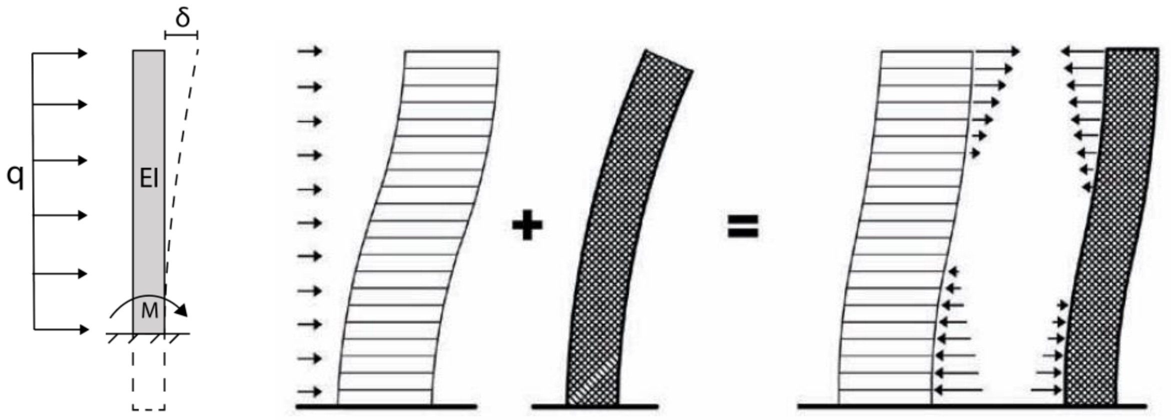


Figure 13: Overview of exterior structures. Source: Ali and Moon [6].



(a) (b)

Figure 14: (a): Overview of stability core. Source: Ham and Terwel [43] ; (b): Forces due to combination of shear wall with bending core. Source: Ali and Moon [6].

Tube system

In a tube system, the façade is built up of rigidly connected beams and columns, resulting in a rigid frame tube [43]. The lateral stiffness is generated by a tube with a decreased effective area, due to windows, see Figure 15. By minimizing the centre-to-centre distance of the façade columns, the lateral stiffness of the building acts as a complete tube. By using a large distance between the columns, the system will behave as a rigid frame. The actual behaviour is somewhere in between [103]. The stress distribution in a tube structure is not ideal, as the stress at the corners is larger, due to shear lag [43]. Shear lag occurs due to the axial stresses not being able to flow around the corners of a tube structure, leading to a stress concentration in the corners. This phenomenon is shown in Figure 16. Shear lag should be carefully considered in the design of a tube structure, as the large corner stresses could cause problems. The shear lag can be minimized by decreasing the centre-to-centre distance of the façade columns, as the building then effectively becomes a closed tube [6].

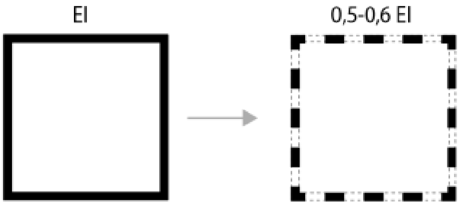


Figure 15: Reduced effective area due to windows. Source: Ham and Terwel[43].

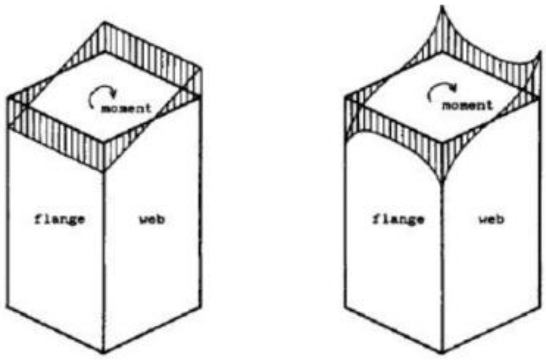


Figure 16: Schematic overview of shear lag. Source: Ham and Terwel[43].

Outrigger

An outrigger system is a variant of a core structure, where the bending stiffness is increased by adding riggers. Across the width of the structure, a truss is constructed that often spans one or two storeys, which provides a connection between the exterior columns and the core [43]. At the height of the outriggers, the bending moment is reduced due to the stiffness of the outrigger, see Figure 17. To distribute the compressive and tensile forces over the exterior columns, belt trusses are often used [6]. Because of the outriggers and belt trusses, the flexibility of the floor plan is limited, especially when the outrigger spans multiple storeys [59].

One advantage of the outrigger system is that the exterior columns are activated in normal stress instead of bending. This allows for more slender columns and larger column spacing [6]. Furthermore, due to the large stiffness of the outriggers, the beam connections can be hinged instead of rigid [59], which has advantages in the flexibility of the structure.

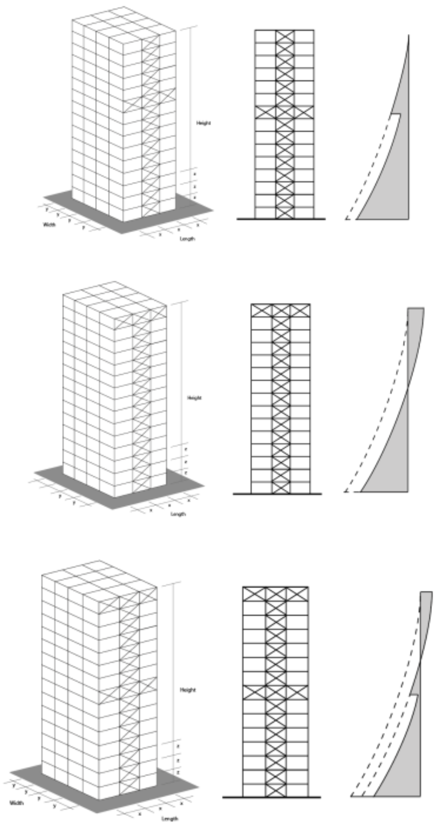


Figure 17: Overview of different applications of outrigger. Source: Ham and Terwel [43].

2.3.3.3. Floor Systems

The choice of the floor system is important in high-rise design, as it determines the largest portion of the vertical load of the structure and impacts the nuisance between floors. Additionally, in circular design, one should carefully choose how to integrate installations into the floor system. This also affects the choice of floor system, because separating the structural elements and the installations leads to a circular design following the layers of Brand [15].

Flat slab floor

Flat slab floors are cast in-situ concrete floors, which means the use of expensive formwork but a general freedom of the floor plan. Spans of approximately 7 to 8 meters are possible, for which the thickness of the slab can be altered. It should be noted that possible measures have to be taken to prevent punching shear, which include column heads or drop panels for example.

Additionally, construction time is relatively long due to the time for hardening of the concrete, which is a crucial factor in high-rise construction [87].

Reinforced plank floor

The reinforced plank floor is a precast concrete plank with bottom reinforcement. After mounting the planks, a top layer of concrete is cast, where the plank and top layer are connected by lattice girders. This method typically does not require formwork, which speeds up the process. The lattice girders provide strength of the plank during construction and transport, as well as support for the top reinforcement. Generally, spans of up to 7 or 8 meters can be reached with a reinforced plank floor, however propping might be needed during construction [87].

BubbleDeck floor

A BubbleDeck floor is a precast concrete plank, with plastic ‘bubbles’ that act as a means to reduce the self-weight of the floor. These bubbles take up the space where concrete has a relatively inefficient use, reducing the weight of the floor. Similarly to the reinforced plank floor, the plank can be hung into place, after which concrete is poured on top. Spans of up to 8 to 10 meters are possible, where propping is required [87].

Hollow-core slab floor

The fully precast hollow-core slab uses empty tubes inside the slab to lower the self-weight of the floor. The slab is prestressed in a factory, ensuring its quality and speeding up the construction time. Spans of up to approximately 18 meters are possible, without the use of propping [87].

Composite floor

A composite floor is a floor which typically combines a steel skeleton with a cast concrete top layer. The concrete layer is often connected to the steel through headed studs or other shear connectors. A thin steel sheet on top of the steel beams acts as formwork and contributes to the bearing capacity of the floor system simultaneously. To increase the moment resistance of the floor in one direction, the sheet is ribbed. The concrete layer is cast on top of the ribbed sheets. Spans of up to approximately 6 meters can be reached with floors that are less than 200 mm thick. The installations can be integrated between the steel beams [87].

Cross-laminated timber floor

Slooten [105] has shown that by using measures to increase the fire resistance, timber floors are a possibility in high-rise structures. Advantages for using cross-laminated timber (CLT) floors are that it is a regrowable material, which is in line with the MEC circularity strategy. Another important aspect is the light weight of the panels. This greatly impacts the design of the vertical load bearing structure. However, it can also negatively affect the dynamic properties of the floors, because it means timber is more prone to vibrations.

Kerto Ripa timber floor

A second option of a timber floor is the use of the Kerto Ripa floor system. This system uses Laminated Veneer Lumber (LVL) beams, which are stiffly glued to an LVL plate. This effectively results in a timber hollow-core slab floor system. Spans of up to 7 or 8 meters are possible. Installations can be integrated between the LVL ribs of the floor system [66].

2.3.3.4. Foundations

To transfer the loads on a building to the soil, a foundation is necessary. There are three general foundation types: Shallow foundation, pile foundation, pile raft foundation. A shallow foundation directly transfers the loads to the soil just below the level of the foundation. A pile foundation transfers loads to a deeper sand layer, while a pile raft foundation uses a combination of the two [34]. For high-rise structure design, in the Netherlands shallow foundations are not applicable. This is due to the high vertical pressure on the soil due to the self-weight of the structure. Therefore, pile foundations are generally used in high-rise [34]. The substructure of a high-rise building has dense pile groups, which should be treated differently to single piles. The load capacity and deformations of a pile group are different than if these same piles would be treated individually. This occurs due to the interaction of the piles with the soil. Typically, to obtain the capacity of a pile group, the single pile capacity is multiplied by the amount of piles and a factor that depends on soil properties and the foundation geometry [85].

2.4. Circular High-Rise

Combining the knowledge on circularity in civil engineering with the knowledge on the design of high-rise buildings, the concept of circular high-rise buildings can be investigated.

2.4.1. Case studies

In this chapter, several case studies on the design of circular high-rise are shown. This aids in the choice of a strategy for circularity in high-rise.

2.4.1.1. Timber High-Rise ; Slooten[105]

A master thesis at Delft University of Technology by Slooten reviewed the possibility to construct a high-rise building by using timber. The use of timber is interesting, as it is a regrowable material. It should however be noted that timber is only circular once the time of regrowth is shorter than the building life span. In high-rise buildings, the use of timber is challenging due to its light weight. It results in a less favourable dynamic behaviour and thus requires large connections. However, the study by Slooten resulted in a 300 m tall building, consisting of a timber-concrete hybrid structure. The lateral stability of the structure was ensured by using an outrigger, with a concrete core and the surrounding structure of timber. Due to the consequence class of high-rise typically being CC3, a structural fire resistance of 120 minutes needs to be ensured. This is possible by using coating on the timber elements, while also applying a sprinkler system.

The study showed that the use of hybrid structures can lead to tall timber buildings. The use of clever innovations and additional measurements in connections and fire safety ensures the robustness of the building.

2.4.1.2. Modular High-Rise ; Precht[93]

The design of a timber high-rise building by Precht uses a stiff timber core and modular elements in the surrounding structure, see Figure 5b. Between the core and the modular A frames, there is a large open space. This ensures that the user has a free choice of the floor plan lay out, which is part of the DfA principle. Furthermore, the modular elements, which are part of the DfD strategy, are prefabricated off site. This shortens the construction time of the building and decreases nuisance to the surroundings of the building site.

This design is a combination of several aspects of DfD and DfA, while using a bio-based material for the structure. This results in a circular tall building.

2.4.1.3. Solutions for Circular High-Rise ; Peikko[109]

In a webinar by Peikko, several solutions to circular high-rise have been presented. For example, by using a composite flooring system, the floor thickness can be reduced. This saves material and leads to better use of space. However, it should be noted that the floor thickness also affects the integration of installations, which should be carefully considered to be able to separate the shearing layers of the building. Furthermore, Peikko has many solutions to reversibly connect prefab elements to each other or to cast in-situ concrete. This can be useful when pouring a stiff concrete core and connecting this to the columns through diaphragm action [14], see also Figure 5a. The use of prefab elements results in simplicity of the design, which decreases the construction time, which is part of the DfD principle, as well as the use of reversible connections. Therefore, the solutions by Peikko can be interesting in high-rise design.

2.4.2. General Considerations Circular High-Rise

By combining the knowledge that has been obtained above, the different strategies for circular high-rise can be further explained. First of all, one of the major differences between low- and high-rise is that most high-rise is built for a life span of at least 50 years, while low-rise often has shorter life spans. It is easy to imagine that the principle of DfD plays a larger part in a building that is designed for 15 years than one designed for 50 years. This indicates that circular high-rise can still be accomplished by using the DfD strategy, but this will be less beneficial than for circular low-rise designs.

High-rise should be built for a lengthy life span. This would mean that DfA plays a significant role in designing circular high-rise, as the flexibility of the building will increase its life span even further. This idea is supported by the fact that a flexible building is used for adaptive reuse more often, which reduces demolition at the EoL stage of the building.

Using the strategy of minimizing the embodied carbon in a high-rise structure will result in an optimization in material use and emissions. Obviously, this is desirable not only for high-rise, but for all structures. However, a high-rise building with optimized embodied carbon that is not adaptable or disassemblable will pose problems at its EoL stage. This indicates that the use of design optimization to minimize the embodied carbon can be used as a relevant strategy, but only in combination with other circularity strategies.

It is concluded that all three circularity strategies play a relevant role in the shift towards a circular high-rise construction industry. In particular the DfA strategy, because increasing the life span of a building with an already long life span will likely prevent preliminary demolition. Therefore, it should be investigated how circularity of high-rise buildings can be measured, in particular its adaptability.

2.5. Circularity Measurement

Researchers have tried to measure circularity with different measuring tools. Hossain and Ng [50] have mapped a large amount of researches that used a wide variety of methods to determine the impact of a building on the environment. These methods or tools are important to gain insight in the impact of different design choices, so that the degree of circularity of a building can be maximized. Below, some of these tools that are common in the Netherlands are explained, to gain insight in how circularity is measured and how this can be used in the shift towards circular high-rise buildings.

2.5.1. Circularity measurement tools

2.5.1.1. Life Cycle Assessment (LCA)

The LCA is a method that considers the life cycle of a building and can be used in different ways to determine the environmental impact of a building. LCA is also part of the European standard EN 15804, where it is used to take different life cycle parts of a building into account, see Figure 18. According to Jonkers [52], by choosing the different stages of the life cycle, one can assess the impact of cradle-to-gate or cradle-to-cradle for example and identify the points of improvement.

Performing an LCA requires four steps, where each step contributes to the outcome of the environmental impact of the building. In step 1, the goal and scope are defined, which is essential to LCA, as this defines the boundaries of the assessment. In step 2, the Life Cycle Inventory is investigated. This gives insight into the total amount of materials and transport

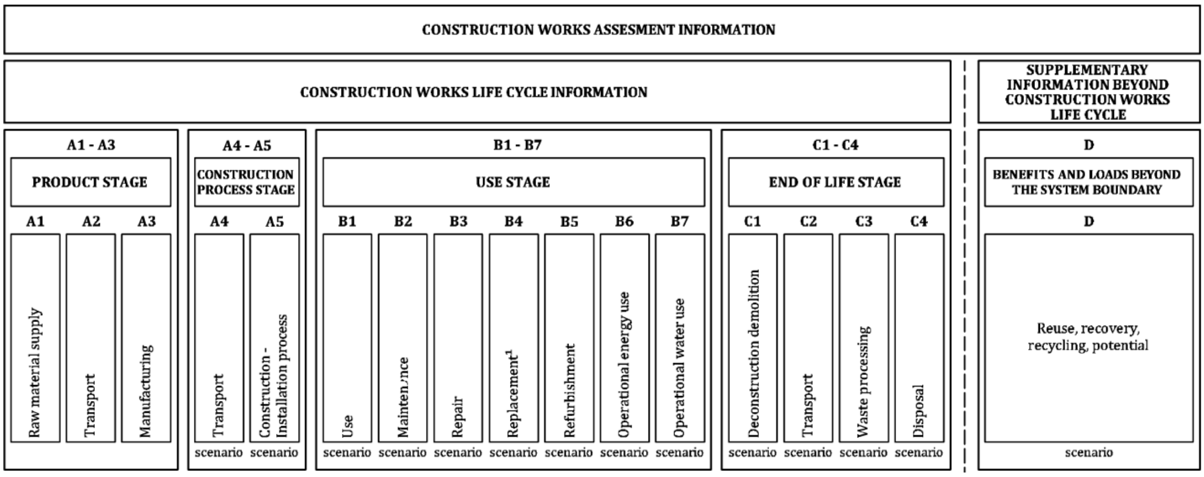


Figure 18: Life cycle stages of a building. Source: NEN [80].

that is needed during construction, and possibly deconstruction. In step 3, a Life Cycle Impact Assessment is performed, which means that the information obtained in step 2 is converted into the environmental impact. The Life Cycle Impact Assessment can be done with a wide variety of tools, which calculate different values such as the embodied carbon or the shadow costs. These are generally calculated by using databases which contain information on the equivalent emission of carbon dioxide for the materials and transport. In step 4, the results are analysed and discussed, to be able to reach the goal of the LCA.

To summarize, an LCA uses the material quantities to calculate a value of environmental impact for each component. These impact values can be summarized to obtain the environmental impact of the entire building.

2.5.1.2. Building Circularity Index (BCI)

The BCI, which has been built by Verberne [120] and further developed by Teunizen [112], uses different indicators which are combined to form the BCI, see Figure 19.

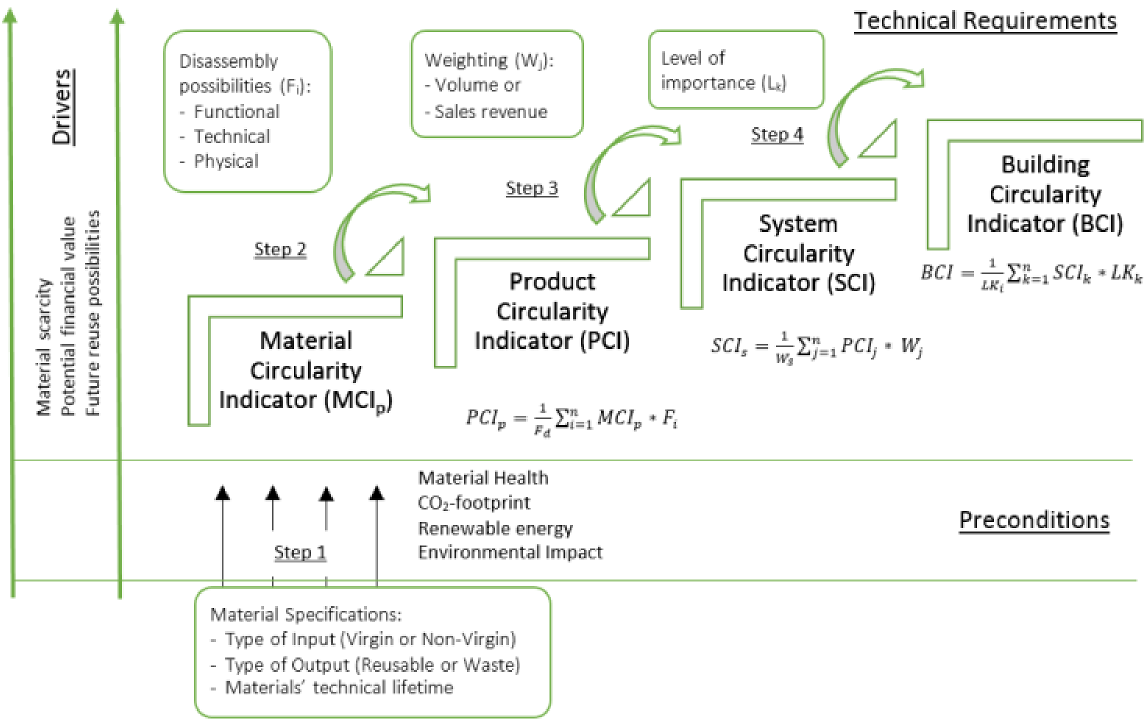


Figure 19: Model of calculating the BCI. *Source: Verberne [120].*

First, a Materials Circularity Index (MCI) is calculated, after which the Product Circularity Index (PCI) and the System Circularity Index (SCI) are calculated. This forms the base for calculating the BCI.

The calculation of the MCI is done by using the input and output of materials. Additionally, a weighted factor is given to each material, to account for their respective life spans.

Then by using the Disassemblability Index, which is developed by Alba Concepts, the PCI can be calculated. The Disassemblability Index is based on 3 factors, namely technical, process and financial [4]. Technical disassemblability is determined by the type of connection between elements, the accessibility during dismantling, crossing of elements (where modular design results in no crossing), and whether elements are enclosed or not. The process disassemblability covers the dismantling instructions, which should be included into a materials passport. The financial disassemblability covers whether or not it is financially feasible to dismantle a building instead of demolishing it. The use of the Disassemblability Index indicates that this model focusses on the DfD circularity strategy.

Afterwards, by weighting the theoretical value of MCI and the practical value of PCI, two SCI’s can be calculated. The values of MCI and PCI are normalized to their volumes to calculate the SCI’s.

Finally, these SCI’s are combined into the BCI. All values that are calculated have a value between 0 and 1, where 1 is completely circular and 0 is completely non-circular. As can be seen from Figure 19, the BCI is built up from the materials, product, and system components. This is an effective way to approach the assessment of circularity in a systematic manner.

2.5.1.3. Platform Circulair Bouwen 2023 (CB’23)

The circularity assessment tool that is developed by Platform CB’23, which is hereafter called the CB’23 tool, calculates the value of three key factors in building circularity [89]. These factors are: protecting the material stock, protecting the environment, and protecting the value.

The materials stock factor is calculated by the indicators of used material (input), the available material for the next cycle (output), and the lost material (output). The environment factor is calculated by the indicator for environmental impact, which is determined by nineteen categories that influence the environment. The value retention factor is calculated by the indicators of initial value (input), the available value for the next cycle (output), and the lost value (output). This results in seven indicators that determine the circularity of a building, see Figure 20, resulting in a value for the three key factors. Currently the CB’23 tool does not yet combine these key factors to a single circularity factor.

One advantage of this tool is the inclusion of a report on the building adaptability, which influences the scores of the tool. This report consists of two parts, which are the functional adaptability and the technical adaptability (also known as disassemblability).

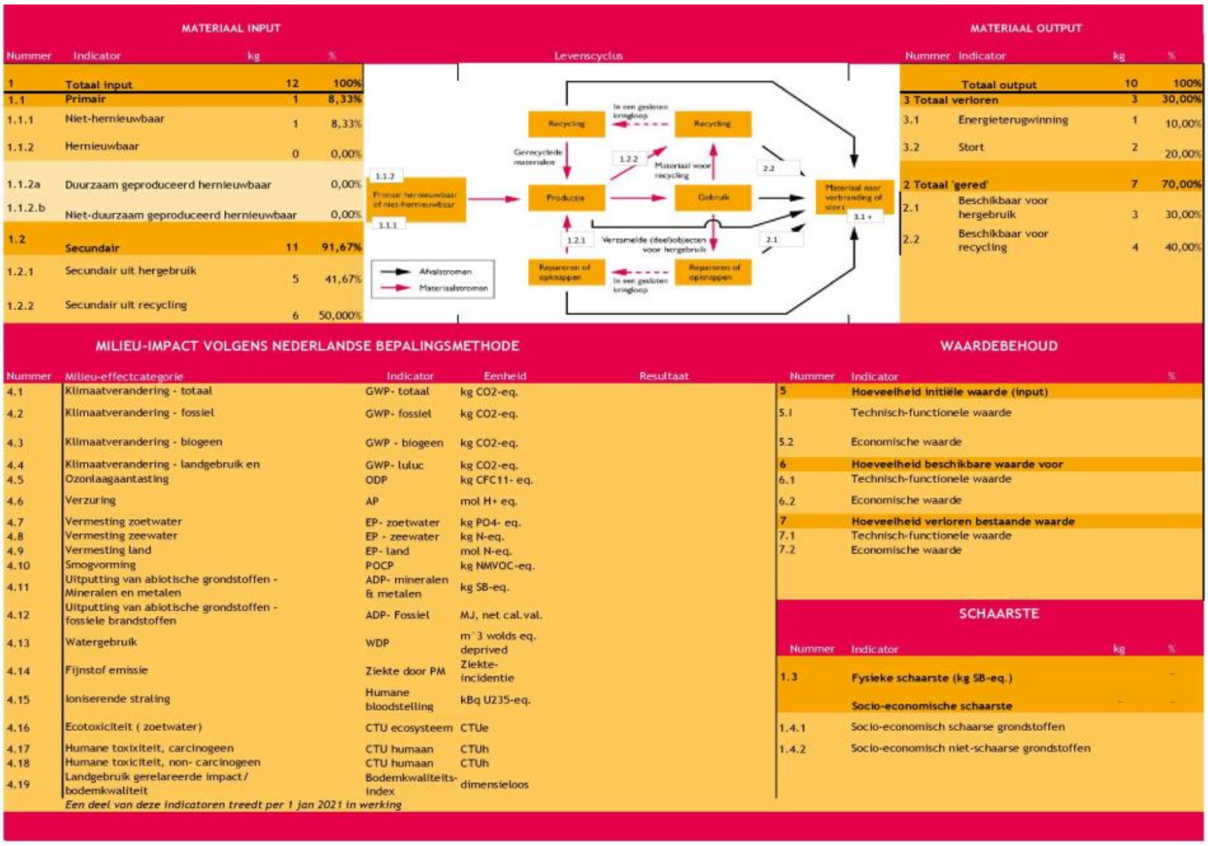


Figure 20: Example of calculation tool CB'23 in Dutch. Source: Platform CB'23[89].

The adaptability report takes into account all the relevant factors of building circularity which have also been identified in Chapter 2.2. Through evaluation of disassemblability and modularity of the shearing layers, the strategy of DfD is covered. By evaluating the reserved load capacity and the flexibility or openness of the building, the strategy of DfA is covered. The environmental impact of a building is calculated in the fourth indicator, which means that the factor of MEC is covered. This indicates the completeness of the CB'23 tool, because all relevant circularity strategies as identified in Chapter 2.2 are included.

However, the major downside of the CB'23 tool is the lack of development of the adaptability report. The tool is currently in its development and is not yet able to quantify the adaptability.

2.5.2. Measurement of Circularity in High-Rise

The indicators for each circularity strategy as mentioned in Chapter 2.2 can aid in identifying aspects that influence the circularity measurement. For the DfA strategy, the large number of indicators are grouped into five new indicators: reserved capacity, openness, floor-to-floor height, internal disassemblability, and separation of layers. The indicator of quality materials is seen as part of the reserved capacity, the indicator of simple design is seen as a flexible infill or also called internal disassemblability. The indicator of accurate plans is not considered in the measurement of circularity, as this is a subjective aspect. An overview of the indicators that correspond to the circularity strategies, mentioned in Chapter 2.2, are shown in Figure 21.

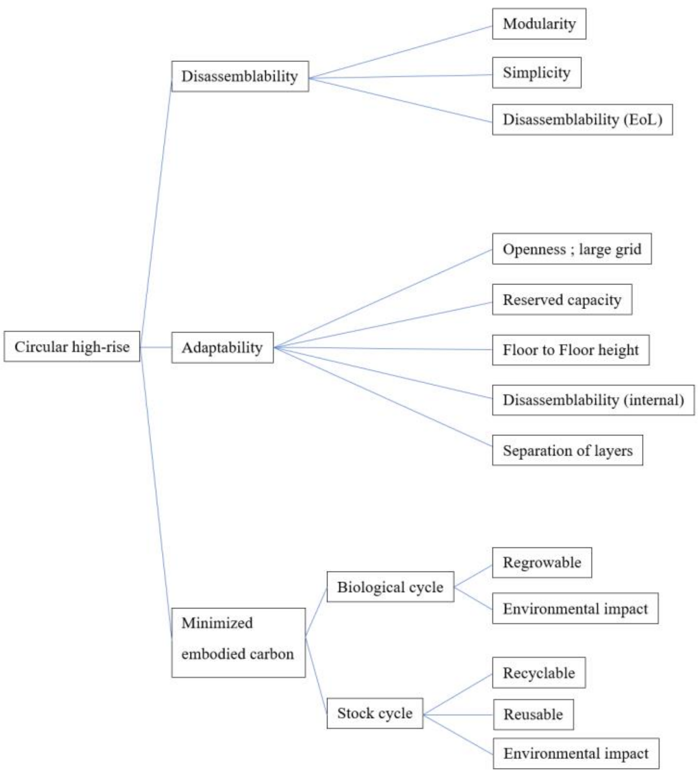


Figure 21: Indicators of circularity measurement for a high-rise building.

It is concluded from Chapter 2.4 and 2.5.1 that measuring circularity of high-rise buildings is possible with several tools. However, due to the relevance of the DfA circularity strategy for high-rise buildings, one should be able to quantify adaptability in a building. The CB'23 tool will provide an adaptability report in a future version of the tool, but this is not readily available yet. Therefore, it is concluded that a measuring tool for adaptability of a building should be constructed using the indicators of DfA from Figure 21, in order to measure circularity in high-rise buildings. This will increase the incentive to use the DfA strategy by structural designers, as it can be proven what level of adaptability can be reached with a certain design choice.

2.6. Conclusion Literature Review

From this literature review, it can be concluded that the concept of circularity consists of three fundamentals: the 9R waste hierarchy, the 3P's, and acting on different levels. This results in the definition by Kirchherr et al. as mentioned in Chapter 2.1.

Furthermore, circularity in civil engineering is found to consist of three strategies: Design for Disassembly, Design for Adaptability, and Minimum Embodied Carbon. Each strategy has its corresponding indicators, which aid in the measurement of circularity. These indicators are relevant for the measurement of circularity in high-rise buildings.

From the investigation on high-rise buildings, it is found that high-rise buildings only became popular around the 80s in the Netherlands. This means that currently, the high-rise in the Netherlands is not yet at its EoL stage, but this will be reached in the near future. However, it can be concluded that a current trend increases the risk of vacancy of high-rise offices, partly due to COVID-19 and more people working from home, leading to the buildings effectively reaching its EoL stage now. Using the DfA strategy, the choice of reusing the building can be encouraged by aiming for an adaptable building in the design stage. This means that it is less likely that demolition takes place, which means that the building's environmental impact will lower.

Due to the lack of an adaptability measurement tool, structural designers have a hard time convincing clients of the benefits of DfA. Additionally, DfA is a strategy that can prevent demolition of high-rise buildings in the future, which will reduce the environmental impact of the building over its total life span. Therefore, it is concluded that an adaptability measurement tool should be constructed, to increase the incentive of using the DfA circularity strategy.

3. Building Adaptability Indicator

In this chapter, the strategy of reaching circular high-rise, as proposed in Chapter 2, is validated by creating an adaptability measurement tool: the Building Adaptability Indicator (BAI).

To create the tool, it is first investigated how the adaptability of a high-rise building is affected by the indicators of DfA as depicted in Figure 21: openness, reserved capacity, FtF height, Internal disassemblability, and separation of layers. This is done by performing indicator studies.

3.1. Indicator Studies

There are several requirements that make a building adaptable, which are studied below through indicator studies. However, an adaptable building should satisfy the future needs of the building. Due to the long life span of high-rise buildings, it is therefore necessary to investigate how high-rise buildings are likely to evolve in the next 50 years.

3.1.1. Future High-Rise

In general, literature shows that the vision of future high-rise is that the building will serve as a place of community and meeting people [73]. This indicates that high-rise in the future will consist of a mix of functions [41]. An example of this is the vertical city, where a set of buildings is connected via sky bridges, to create a sense of connection and unity between the buildings [24]. This is done with the reason to minimize transport, because that results in pollution. Examples of future high-rise buildings can be found in Figure 22. Within these buildings, one could find all desired services, meaning an entire city will fit into a cluster of buildings. Furthermore, it is expected that buildings will consist more green to improve the quality of living [115]. The use of sky gardens and parks are examples of this. Other visions include the use of drones as transport and increasing the use of wind and solar energy.

According to Sanghvi [99], the future of high-rise offices is highly influenced by the COVID-19 pandemic. He argues that working from home will stay popular, while there will also be a shift in the behaviour of working in the office. Currently, office space is mainly occupied by individual workspaces. Due to a possible shift to a more collaborative use of office space, it is expected that a large amount of this individual workspace will change to conference rooms for example. This is in line with the idea that high-rise buildings will serve as a place of community and meeting people.

High-rise buildings in the future are expected to be able to accommodate a mix of different functions, to create a vertical city. Therefore, when talking about adaptable buildings, it means that the building should be adaptable in its function. Table 1 lists the building functions as mentioned in the Dutch guidelines. A building that is completely adaptable should be able to change to all functions with little effort.

Table 1: Overview of building functions. Source: Bouwbesluit 2012 [69].

Gathering function	For gathering of people
Prison function	For custodial stay of people
Healthcare function	For medical research, care, and nursing
Industrial function	For treatment and storage of products or agricultural use
Office function	For administration
Lodging function	For offering recreative stay to people
Education function	For providing education
Sport function	For practicing sports
Shopping function	For trading materials, goods, or services
Residential function	For residence

Figure 22: Visions of future high-rise. Sources: (a):Robinson [97]; (b): Williams [124]; (c): eVolo Magazine [35]; (d): Herr [48]; (e): National Geographic [73].

3.1.2. Indicator Study Openness

The openness of a floor plan is determined by several factors, such as the grid size, the use of a column or wall grid, and the stability system. The study by Rockow [98] shows that columns provide more openness than walls, which is why an open building is desired to have a column grid instead of a wall grid. The study also shows that the use of a relatively large grid size will increase the openness, due to the low amount of area that is restricted by columns. Commonly used grid sizes of each building function are shown in Table 2.

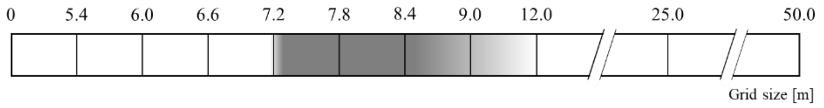
The size of the grid has an influence on the floor plan of the building, as well as the possible stability systems, which are mentioned in Chapter 2.3.3.2. The size of the grid also has an influence on the type of floor system that can be used. Common spans for different floor systems are discussed in Chapter 2.3.3.3.

The openness of the floor plan is largely influenced by the stability system of a high-rise building, because the stability system covers a large portion of the floor plan. A number of potential stability systems are discussed below. For an adaptable building, it is preferred that the floor plan is built up of a column grid, because the number of functions that are realistically possible with a wall gird are limited. These functions are prison, lodging, and residential.

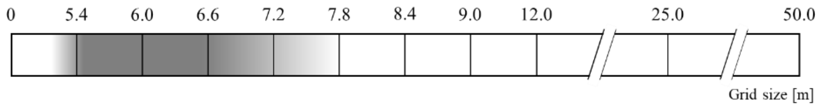
Table 2: Overview of grid size for different building functions. Source: Mondeel [71].

Building function	Grid size

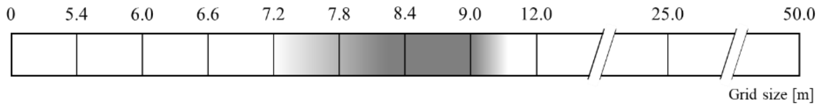
Gathering



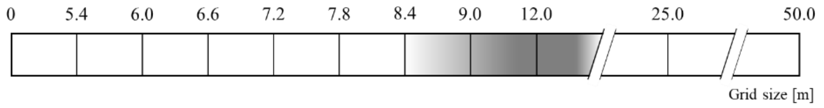
Prison



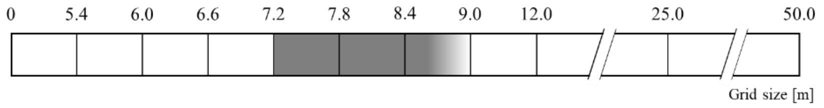
Healthcare



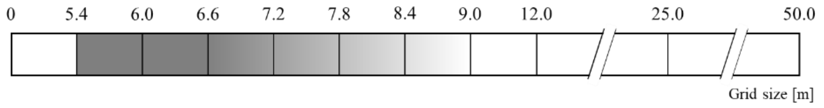
Industrial



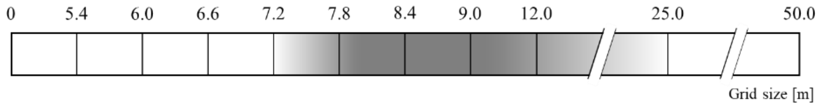
Office



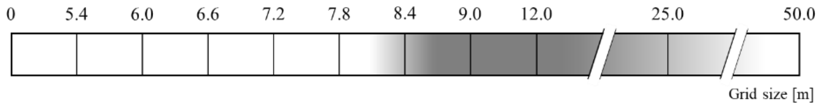
Lodging



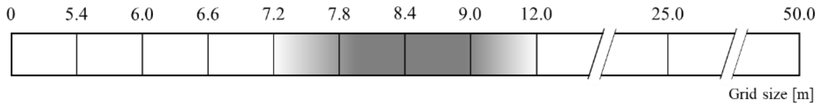
Education



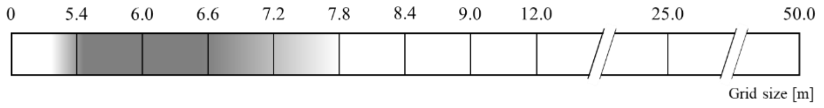
Sport



Shopping



Residential



3.1.2.1. Core

The use of a central core is an efficient way to create a relatively open structure. The floor plan will have room for different functions surrounding the core. Simultaneously, the means of vertical transport and installations can be implemented inside the core. The location of these services will generally be central anyways, because there are no requirements on the amount of daylight for these services [69]. An example of high-rise which uses a core structure in the Netherlands is the Rembrandt tower, of which the floor plan is depicted in Figure 23. Because the Rembrandt tower has an office function, the capacity of vertical transport and installations are relatively large compared to a residential tower for example. This will be further discussed in the study on Reserved capacity. Due to the difference in these capacities, the size of the core should allow for change in the capacity of vertical transport and installations. Only then can the building be adaptable.

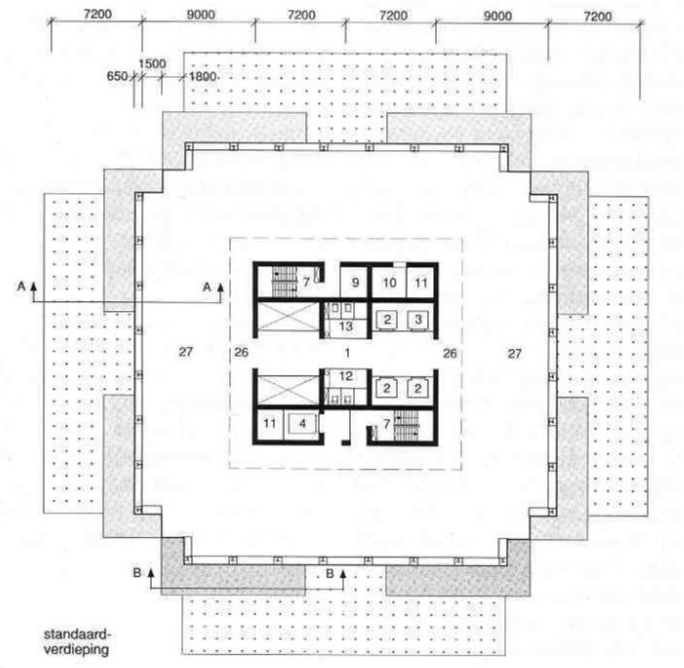
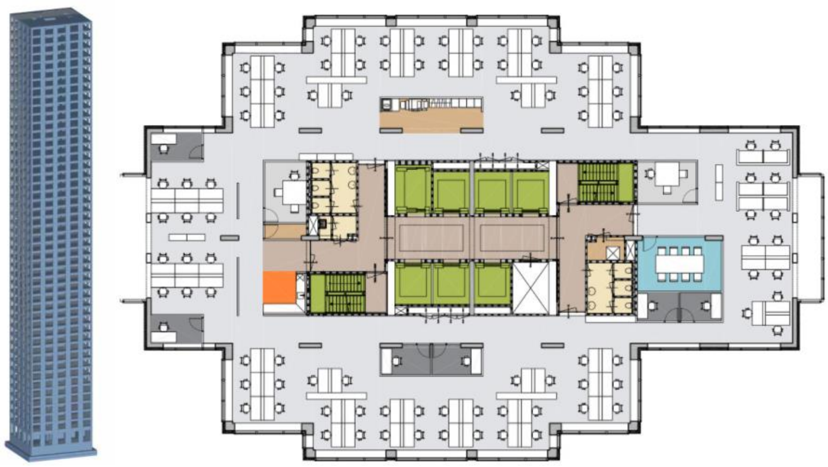


Figure 23: Floor plan of Rembrandt tower. Source: Abspoel [1].

3.1.2.2. Tube

Another possible stability system is the tube structure. Here, a stiff façade will provide the lateral stability of the structure, while columns can provide vertical load bearing capacity. Therefore, this system is possible with using a completely open floor plan, with only the columns and vertical transport limiting the openness. Examples which use a stiff façade as tube structure are the Baan residential tower in Rotterdam, see Figure 24a, and the Mondriaan office tower shown in Figure 24b. Both structures use a cast in-situ concrete frame, which leads to stiffness in the façade, providing lateral stability. The location of the vertical transport and installations is in theory completely flexible. It can however be seen from Figure 24b that these services are generally located centrally due to the aforementioned reason that elevators and stairs are characterised as functional area and therefore do not require daylight. This is why the elevators and stairs are generally situated centrally. One downside of a tube structure is that there is less flexibility in the esthetics of the façade, as this is the main load bearing mechanism and can therefore not be adapted.



(a) *(b)*

Figure 24: (a): Overview of tube structure Baan tower. Source: Treels [114] ; (b): Floor plan of Mondriaan tower. Source: CBRE [18].

3.1.2.3. Tube in tube

A combination of a stiff core and stiff façades is called a tube in tube structure. This combination means that the size of the core can be minimized because it is not the only element that has to provide stiffness. An example of a tube in tube system is 432 Park Avenue in New York, see Figure 25. This residential tower uses a tube in tube structure to create an extremely slender tower at a ratio of 1:15. Using a tube in tube system limits the position of vertical transport and installation services and leads to less flexibility in the façade, similar to the tube structure.

3.1.2.4. Outrigger

The use of an outrigger system can increase the stability capacity of using a central core. This way, the façade is not limited to being a structural element, but can also serve as an esthetic element. However, the use of outriggers limits the adaptability of the floors where these outriggers are located. Examples of high-rise which uses outriggers are the Blaak office tower and the Cool residential tower. The Cool tower uses its stiff core and outriggers to create the stiffness in the building, so that the façades can be more open [11]. The Blaak office tower spans the outriggers over two floors, to divide the floor plan limitations over two stories, see Figure 26. Some other examples show that the position of outriggers can be cleverly combined with the locations of installation rooms. This can be seen in the Amstel tower and Shanghai tower, see Figure 27. The limitations caused by the outriggers are combined with the limitations by the installation rooms, to create one or more floors that serve a functional purpose, while the other floors can serve a profit-driven purpose. This provides flexibility in the installation plan.

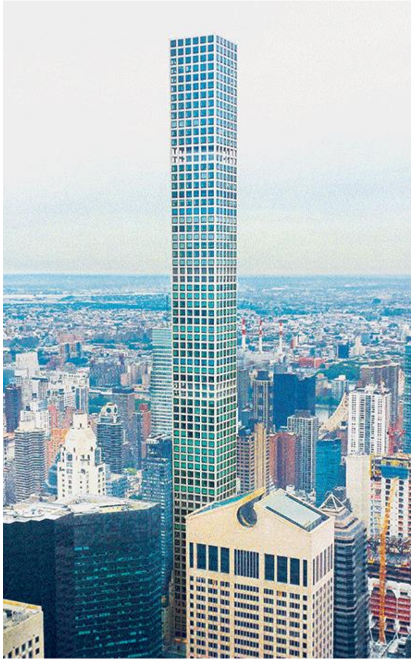
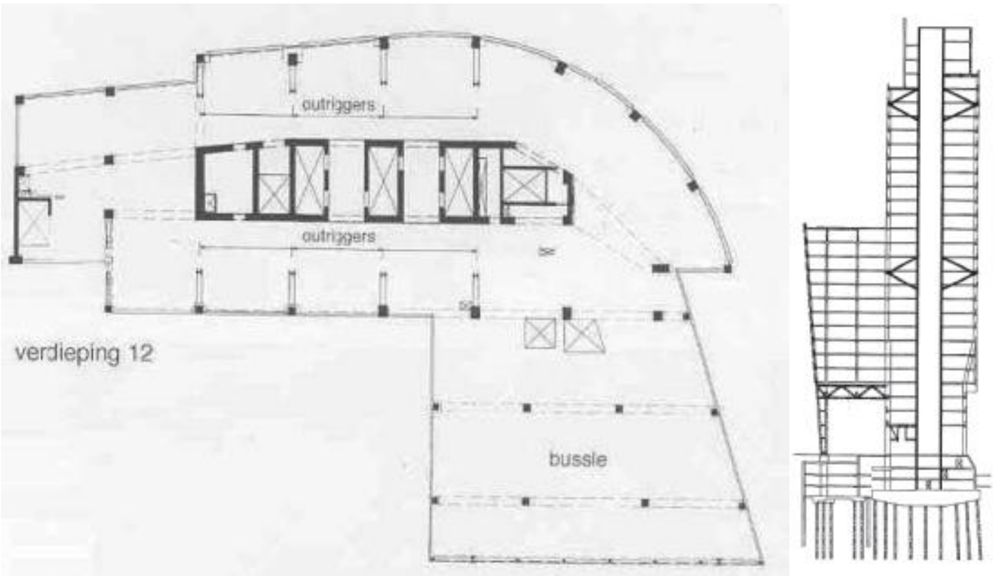
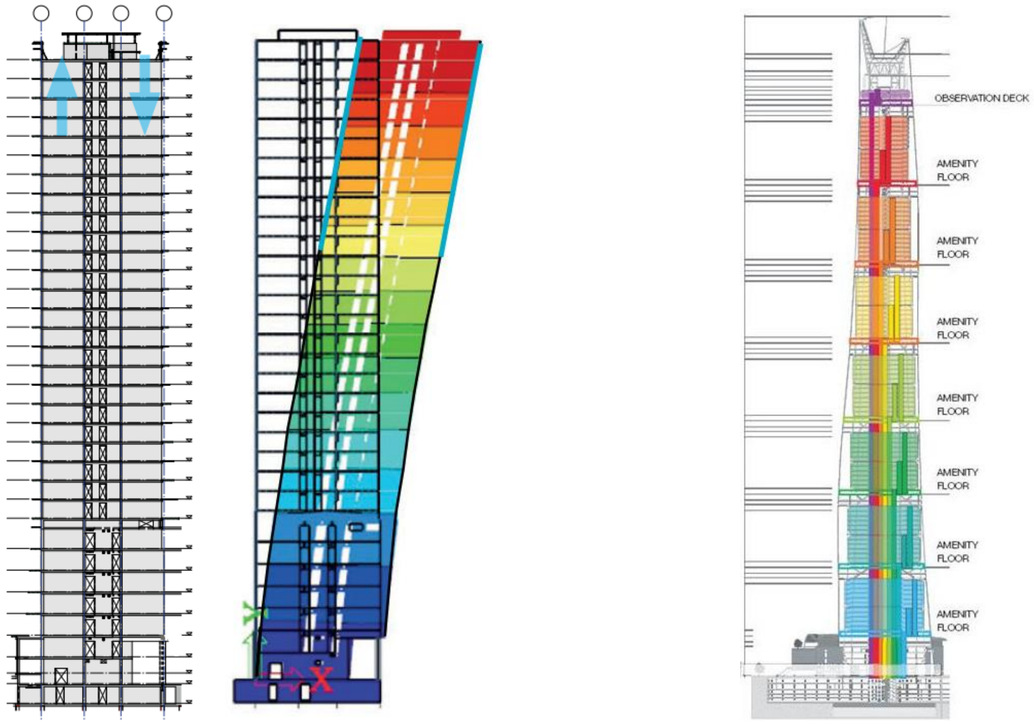


Figure 25: Stiff façade of 432 Park Avenue. Source: Reid [94].



(a) *(b)*

Figure 26: (a): Floor plan Blaak office tower ; (b): Cross section of Blaak office tower. Source: Abspoel [1].



(a) *(b)*

Figure 27: (a): Stiff installation room serving as outrigger in Amstel tower. Source: Andjelic et al. [8]; (b): Overview of installation zones corresponding with outrigger locations Shanghai tower. Source: Risen [96].

3.1.2.5. Core layout

The services inside the core should have different capacities for different building functions. For the core layout, it is essential to fit in enough capacity for installation and vertical transport services of the different functions. However, it is easy to imagine that designing a residential high-rise building with a large capacity of elevators would lead to missing out on rentable area, which results in less profit. Therefore, it should be possible to flexibly add or remove services from the core, to be able to maximize the use of the floor plan and maximize profit from the property. For example, a residential building will have a smaller core than an office building due to the lower amount of elevators and stairs required, see Chapter 3.1.3. However, to account for future elevators or stairs, the walls of the core can be extended, which provides a possible area for these services. An example is shown in Figure 28. There should be a recess in the structural floor to account for the future use of elevators or stairs, which is covered up by a floor that can be easily removed.

3.1.2.6. Conclusion

The openness study shows that the use of a column grid is desired. The grid sizes corresponding to each function is shown in Table 2. Furthermore, the stability system has a major influence on the building's openness. It is concluded that the use of a tube or a tube in tube system is not desired, because this would lead to a façade that is not adaptable. The shearing layers of structure and skin would not be separated, meaning that this option is not adaptable. Therefore, the choice of a stability core, possibly in combination with outriggers, is preferred to design an adaptable high-rise building. The shape of the core should allow for future capacity expansion of the services inside the core, see Figure 28.

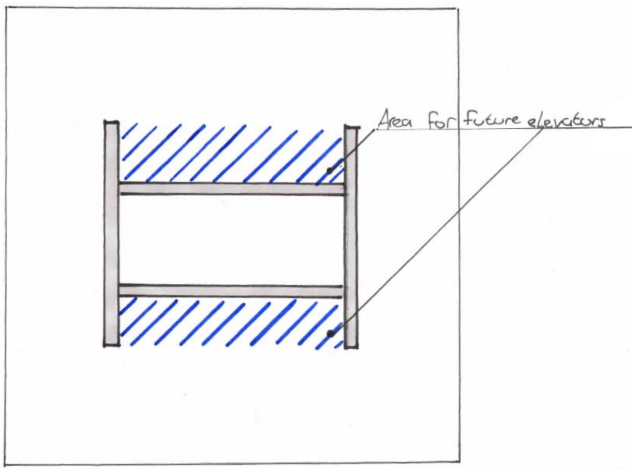


Figure 28: Overview of core shape which allows area for future elevators.

3.1.3. Indicator Study Reserved Capacity

The reserved capacity study is split in two parts. One regarding the vertical load capacity of different functions and one regarding the capacity of the vertical transport and installations.

3.1.3.1. Load capacity

The vertical load that corresponds to a function is determined in the variable load of that function. The variable loads of different functions are described in Eurocode 1 [79]. For certain structural calculations, on the foundation for example, it is allowed to decrease the variable load with a temporary load factor. The temporary load factor follows from Eurocode 0 [78]. Additionally, for some functions the variable load will be increased to account for the weight of partition walls. The weight of the partition walls is between 0.8 and 1.2 kN/m^2, which is applicable to the following functions: prison, healthcare, office, lodging, education, and residential. The weight of the walls is determined by their height, where a large wall height will result in a heavier load.

To adapt a building to different functions, the load capacity of the structure should follow the variable loads as depicted in Table 3. This will have a consequence to the load on the structural elements, which should have sufficient capacity in its material strength or dimensions.

Table 3: Overview of variable load values for different building functions. Source: EN-1991-1-1 [79].

	Gathering	Prison	Healthcare	Industrial	Office	Lodging	Education	Sport	Shopping	Residential
Variable load [kN/m^2]	5.00	1.75	5.00	5.00	2.50	1.75	2.50	5.00	4.00	1.75
Temporary load factor [-]	0.4	0.4	0.4	1.0	0.5	0.4	0.4	0.4	0.4	0.4
Temporary variable load [kN/m^2]	2.00	0.70	2.00	5.00	1.25	0.70	1.00	2.00	1.60	0.70

3.1.3.2. Vertical transport and installations

The installation capacity and lay out vary significantly for different building functions. For a prison, lodging, or residential function, there are a large number of drainage installations required compared to other functions. This is due to the high amount of toilets, showers, and possibly kitchens in these functions. The drainage installations are too large to be integrated into a floor system. Therefore, for the aforementioned functions, the vertical path of the installations are spread out over the floor plan. For other functions, all installations are accommodated in the core, so that no floor plan area is sacrificed for installations. When designing an adaptable high-rise building, recesses for the spread out installations should be accounted for. In the case that these recesses are not needed, because installations run through the core, they can be covered up with a removable floor.

Table 4: Maximum waiting time for elevators. Source: NEN[75] & Wit[125].

Building function	Maximum waiting time [s]
Office	25 – 35
Residential	60 – 130
Lodging	20 – 30

For the vertical transport, the number of elevators is determined by the building function and the waiting time for an elevator to arrive. The commonly used maximum waiting time for some functions can be seen in Table 4. It shows that for residential buildings, the requirements are less strict, meaning that a lower number of elevators can be used in that case. When designing an adaptable high-rise building, one should calculate the estimated waiting time to determine the number of elevators that are needed.

3.1.4. Indicator Study Floor-to-Floor Height

There are different FtF heights that are common for different building functions. Therefore, an adaptable building should have an FtF height which suffices for multiple functions, because the FtF height cannot be adapted. Ideally, each storey will have an FtF height which complies with the most commonly used FtF height of each building function. Data from Arcadis on a large pool of buildings in the Netherlands results in an overview of the lowest, highest, and most common FtF height of different functions, see Table 5.

Table 5: Overview of FtF height for different building functions. Source: Arcadis [9].

	Gathering	Prison	Healthcare	Industrial	Office	Lodging	Education	Sport	Shopping	Residential
Lowest FtF height [m]	4.6	2.7	3.8	4.4	3.3	3.0	2.9	4.2	4.1	2.7
Common FtF height [m]	6.2	2.9	4.0	6.2	3.8	3.3	3.7	5.8	4.4	3.1
Highest FtF height [m]	8.3	3.1	4.1	11.3	4.4	3.5	4.4	7.0	4.7	3.9

For a circular building, it is important to not just use an FtF height which is as large as possible. This would result in material waste and waste of available vertical space. Furthermore, using a large FtF height results in less rentable area and thus to a loss of profit. Therefore, a balance should be sought in which adaptability is achieved, while the FtF height is not disproportionally large.

In the choice for the FtF height, it is also important to consider the space for installations. In an adaptable building, the installations should be separated from the structural floor. This could lead to the situation that more vertical space is needed for the installations.

3.1.5. Indicator Study Disassemblability

For adaptable high-rise buildings, it is desired to create structural flexibility by using elements that are easily removable. For example, as shown in Figure 28, it is desirable to create recess flexibility to be able to expand the number of elevators. This increases the flexibility in the core lay out. A possible solution to create this recess flexibility is the use of removable floor systems.

For a floor system to be removable, it is desired to use as many prefab elements as possible, as the use of cast in-situ concrete leads to limitations in removing the floor [123]. This indicates that the choice of floor system is essential in its disassemblability.

Another example of structural flexibility is the use of a disassemblable façade, which is not possible in a tube structure, or the use of removable partition walls. This kind of adaptability can be achieved by using techniques that ensure reversible connections of the façade and partition walls. Thus, to increase the internal disassemblability, a structural designer should implement smart building solutions to the façade and partition walls. This does not influence the main load bearing structure of the building.

3.1.6. Indicator Study Separation of Layers

There are several elements which have to be taken into account regarding the separation of layers by Brand. This separation will lead to easier replacement of the services such as installations, as well as inducing flexibility into the interior of the building.

To separate the installations from the structure, several options are possible. One option can be seen in Figure 29, where the finishing floor is elevated from the structural floor, to create space for installations. Another option is to hang the installations underneath the floor. This is especially efficient when using beams underneath the floor system. This leaves space for the installations, which can be covered up by a suspended ceiling.

Another important aspect to consider is the recess flexibility. As mentioned before, the installations of a prison, lodging, or residential functions are spread out over the floor plan, leading to a large number of recesses in the floor plan. This makes it difficult to change to a function that does not require the installations to be spread, due to the recesses in the floor. A solution that will prevent these recesses are to separate the installations from the floor, because then the large drainage pipes can flow towards the core. Another option is to use a removable floor system such as a plywood panel to cover up the recesses, see Figure 30. This means that the installations for a residential building can be spread over the floor plan, because there is recess flexibility.

As is the case for disassemblability, the indicator for separation of layers can be improved by using smart building solutions. This means that this indicator is not governing in the adaptability of a high-rise building.

Figure 29: Solution of elevated floor to separate installations from structure. Source: ABT [2].

Figure 30: Bottom view of closed recess in hollow-core slab by using plywood panel. Source: Havel [44].

3.1.7. Conclusion Indicator Studies

It is concluded that the indicators for disassemblability and separation of layers are improved by the use of smart building solutions such as removable floor systems or an elevated finishing floor. In this research, it is chosen to focus on the more ‘structural’ aspects of adaptability, namely the indicators of openness, reserved capacity, and floor-to-floor height. These structural indicators are generally considered fundamental in the measurement of adaptability, which is why they are used in the first development stage of an adaptability measurement tool. The use of smart building solutions can however also influence the adaptability of a building, which means that it is recommended to include the indicators for disassemblability and separation of layers in future research on the adaptability measurement tool.

The openness is mainly influenced by the choice of grid size, use of a column or wall grid, and the stability system. The stability system is determined by weighing the different options of core, tube, tube in tube and outrigger structures. The reserved capacity is influenced by the foundation capacity, material quality, and the dimensions of structural elements. Additionally, the core shape should be such that there is a possible area for expansion of the core, to ensure adaptability of the core.

3.2. Development Building Adaptability Indicator

From the indicator studies, it is shown what is required in the design stage to realise an adaptable high-rise building. To face the challenge of increasing the incentive to use the DfA strategy in high-rise buildings, a measurement tool should be created.

As has been mentioned in Chapter 2.5, researchers have tried to formulate a measurement tool for circularity as a whole. These studies either focussed on a different level of circularity or on a different strategy. Therefore, this research proposes a measurement tool of adaptability: The Building Adaptability Indicator (BAI). This measurement tool is created by using the indicator studies above and by conducting interviews with structural designers, which are shown in Appendix A.

From the indicator studies, it is shown that not only structural aspects influence the adaptability of a building, but aspects such as installations and the façade also play a role. Additionally, the interviewees mentioned that the choice of demolition or reuse is not only governed by structural aspects. However, the interviewees generally agreed that the three structural indicators identified in Chapter 3.1.7 play a significant role in the adaptability of a building, namely the openness, reserved capacity, and floor-to-floor height. These indicators are further referred to as the *sub-indicators*. Therefore, it is chosen to focus on a BAI that uses the structural sub-indicators of openness, reserved capacity, and floor-to-floor height. These sub-indicators are considered as governing in the adaptability of a building. However, other aspects such as installations, façades and fire safety do play a role in adaptability, Therefore, it is recommended that for future research the influence of these ‘architectural’ aspects on the adaptability of a building is investigated.

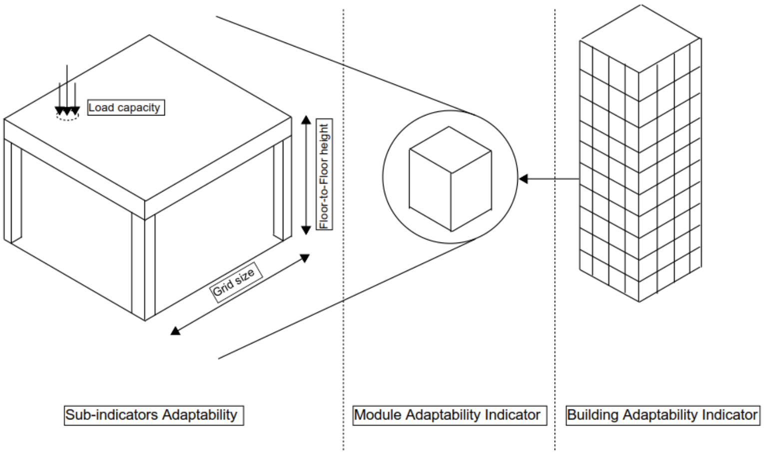


Figure 31: Scheme for Building Adaptability Indicator.

To determine the adaptability of a building, the sub-indicators first determine the adaptability of a module of that building: the Module Adaptability Indicator (MAI), which is depicted in Figure 31.

3.2.1. Module Adaptability Indicator

Each module is defined as a part of the building, consisting of one grid, one story, and one floor load. The value of the MAI is based on the possibility of accommodating a function in the module, depending on the properties of the module regarding its openness, reserved capacity, and floor-to-floor height. The MAI for each sub-indicator has a value between 0 and 1, where 1 means that all functions fit, thus maximum adaptability is achieved.

The value of the MAI increases when a new function fits in the module. The increase of the MAI is dependent on the function that becomes available, where each newly available function will result in a jump of the MAI. The height of this jump is determined by the weighting factors for each newly available function as shown in Table 6. The weighting factor takes into account the property value of 1 m^2 of each building function in combination with the area of each function in the Netherlands. Using these properties, the weighting factor for building function i is determined as:

$$W_{MAI,i} = a \times \frac{V_{p,i}}{V_{p,tot}} + b \times \frac{A_i}{A_{tot}} \quad (1)$$

Where:

$W_{MAI,i}$ = Weighting factor of MAI for building function i

a = Factor property value

$V_{p,i}$ = Property value for building function i

$V_{p,tot}$ = Total property value

b = Factor area

A_i = Area of building function i in the Netherlands

A_{tot} = Total building area in the Netherlands

Table 6: Determination weighting factors MAI.

Building function	V_p [€/m^2]	A [10^6 m^2]	W_{MAI} [-]
Gathering	1050	35	0.07
Prison	900	5	0.06
Healthcare	1300	40	0.08
Industrial	750	265	0.08
Office	1100	90	0.08
Lodging	2100	20	0.13
Education	1150	35	0.08
Sport	750	15	0.05
Shopping	2300	55	0.15
Residential	1700	905	0.23
TOTAL	13100	1465	1.00

It is important to understand that the resulting weighting factor is the result of an indication of the value and the demand of each function. It is always desired to be able to accommodate a new function in a building, but some functions are more desired than others. This difference should not be unreasonably large. Therefore, it is chosen to formulate the weighting factor of each function in such a way that the property value contributes more than the area, namely with a factor a and b. This will lead to weighting factors that are more representative of the reality. Functions which are in high demand and have a high property value have a higher weighting factor and vice versa. For simplicity, in this research the factors a and b are estimated by the author at 0.8 and 0.2, respectively. This ensures that no exceptionally large spikes occur in the MAI, which would result in an unrealistic adaptability measurement. For future research, the value of a and b should be more elaboratively determined.

Furthermore, it should be noted that the property values as depicted in Table 6 are estimates, because these values are highly fluctuant and dependent on the location of a building. It is considered that using the estimate of the property values together with the area will add some nuance to the weighting factors, meaning that the weighting factors are less prone to this fluctuation.

The property values from Table 6 are derived from The Benchmark Municipal Real Estate ("De Benchmark Gemeentelijk Vastgoed") [27], with the missing values estimated by the author in correspondence with a financial expert at ABT. The property area of residential buildings follow from the Central Bureau of Statistics [20] and the areas of the other functions follow from Niessink et al. [82].

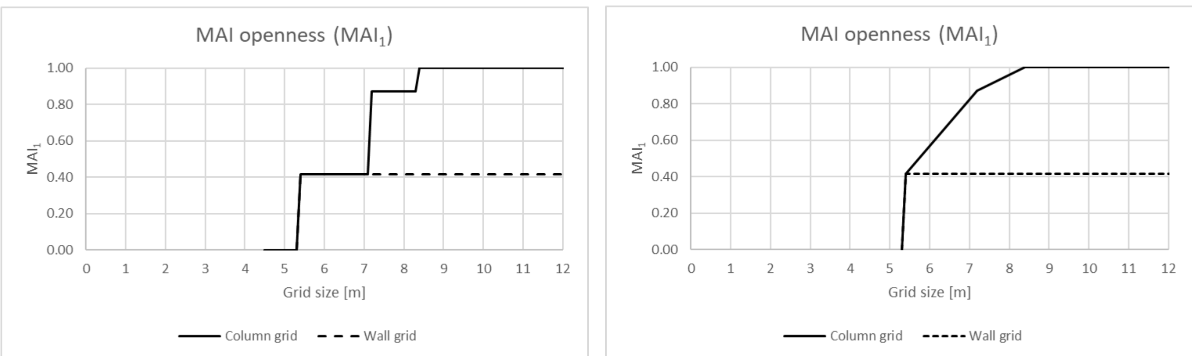
Next, the MAI is determined for each sub-indicator. The determination of the MAI for the sub-indicators is based on the indicator studies of Chapter 3.1 and is shown below.

3.2.1.1. MAI Openness

The MAI for the sub-indicator openness, also referred to as MAI_1, is determined by the grid size and the choice of using a column or wall grid. As mentioned in the indicator studies, the use of a wall grid is limited to merely three functions: prison, lodging, and residential. It could in theory be possible that other functions will also fit in a module with a wall grid, for example an office function with a large grid size. However, as this is not realistic in practice, these functions are disregarded in the MAI for a wall grid. This means that the MAI for a wall grid tops off at a value of, see Figure 32:

$$W_{MAI;prison} + W_{MAI;lodging} + W_{MAI;residential} = 0.06 + 0.13 + 0.23 = 0.41$$

The MAI for openness in Figure 32a is a graph which increases in intervals, because the MAI will jump at specific grid size values. However, the difference in MAI just before and after a jump is not as large as Figure 32a suggests. The adaptability of the module just before a jump should be almost as high as after the jump. Therefore, the graph is smoothened into a line that follows a linear path, leading to Figure 32b. This is the final MAI_1 as it is used in the calculation of the BAI. The initial jump from an MAI of 0 to 0.41 is kept intact, because grid sizes smaller than 5.4 m are considered impractical and are considered as zero adaptability.



(a) *(b)*

Figure 32: MAI for Openness (MAI_1).

The fact that the graph of MAI is chosen at a linear scale is the authors' interpretation of the MAI. It could be possible to use a polynomial regression line for example, but this would mean that the exact adaptability from the interval graphs would at times be lower than what is proposed with the polynomial. This is deemed unrealistic, which is why a linear line that runs through the jump points is used, which follows previous research by Rockow [98] and McFarland [64]. The values through which the linear MAI's run are determined from the interval graphs. An example from Figure 32 is the value of MAI_1 at a grid size of 7.2 m with a column grid. The value from the interval graph is:

$$W_{MAI;gathering} + W_{MAI;prison} W_{MAI;healthcare} + W_{MAI;office} + W_{MAI;lodging} + W_{MAI;education} + W_{MAI;shopping} + W_{MAI;residential} =$$

$$0.07 + 0.06 + 0.08 + 0.08 + 0.13 + 0.08 + 0.05 + 0.23 = 0.87$$

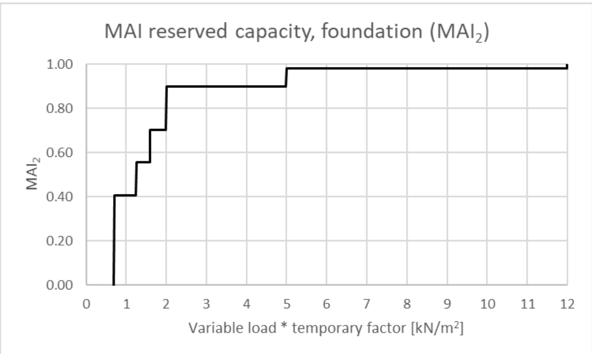
The linear graph of MAI_1 runs through the same value of 0.87 at a column grid size of 7.2 m, see Figure 32b.

3.2.1.2. MAI Reserved Capacity

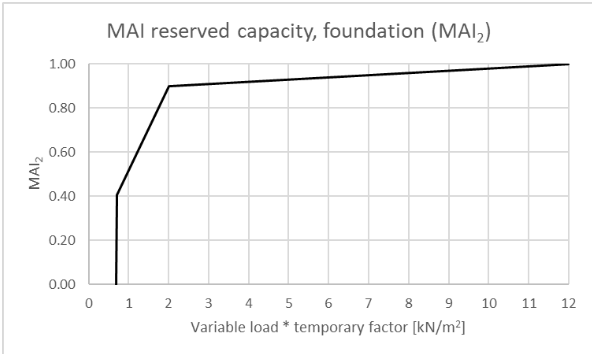
The MAI for the reserved capacity is split into two parts, namely the foundation load capacity and the floor load capacity, which are referred to as MAI_2 and MAI_3 respectively. The foundation load capacity is determined by the temporary variable load as depicted in Table 3, while the floor load capacity is determined by the variable load from Table 3. This is due to the fact that for the structural analysis of the foundation, it is allowed to use the temporary loads, while for the analysis of the floor load capacity this is not allowed. Additionally, as mentioned in Chapter 3.1.3, for some building functions an additional variable load of 0.8 kN/m^2 should be taken into account. This is the load of the partition walls, which are relevant for the following functions: prison, healthcare, office, lodging, education, and residential. The load of the partition walls will be added on top of the values from Table 3, resulting in the MAI's, see Figure 33a and 34a.

The MAI does not yet reach its maximum value of 1 at a value of 5 kN/m^2, the maximum load in Table 3, corresponding to an industrial function. This is due to the possibility of unforeseen loads on the floor, such as a heavier function or heavy machinery. An example of this is a data-centre function. The variable load for a data-centre is 12 kN/m^2, which means that the value of 5 kN/m^2 would not suffice. It is estimated by the author that these unforeseen functions will have a weighting factor of 0.02. This means that at a value of 12 kN/m^2, the MAI's will jump from 0.98 to 1.00.

Again, following the same logic as MAI_1, the interval graphs are converted to linear graphs. This is shown in Figure 33b and 34b, which are the MAI's for Reserved Capacity. The initial jumps from the interval graphs are however kept intact. A reserved capacity of less than 0.7 kN/m^2 and 1.75 kN/m^2 for the foundation and the floors respectively, are deemed impractical, leading to an MAI of 0.

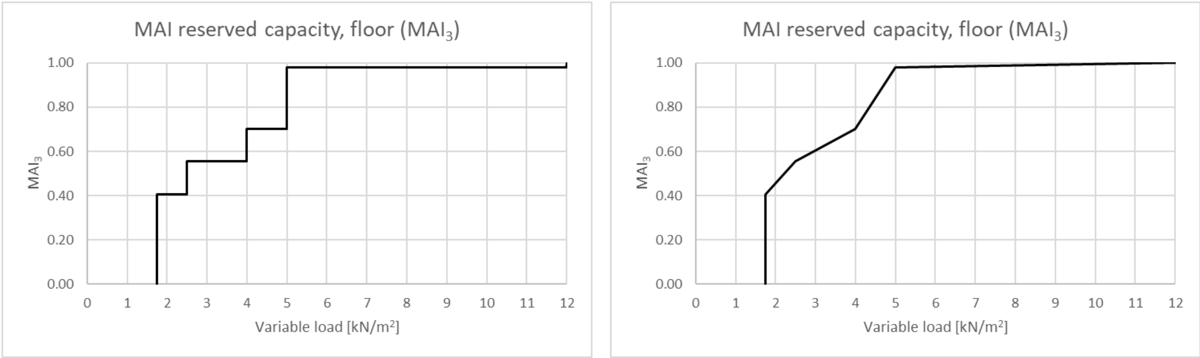


(a)



(b)

Figure 33: MAI for Reserved capacity foundation (MAI_2).



(a) *(b)*

Figure 34: MAI for Reserved capacity floor (MAI_3).

3.2.1.3. MAI Floor-to-Floor Height

To determine the MAI of the FtF height, referred to as MAI_4, it is possible to distinguish three models, see Figure 35. The different models represent the options to split the stories by using removable floors between the original floors. There are two options for splitting the stories: either use a single removable floor, or use double removable floors. However, in the latter, it can also be possible to split the storey with a single removable floor when desired. This leads to a high amount of adaptability.

The values of the FtF height at which a function fits in the module are deducted from the common FtF heights for different functions as shown in Table 5. These values are simplified in the way that is shown in Table 7. This simplification improves the readability of the MAI, because the number of intervals is decreased.

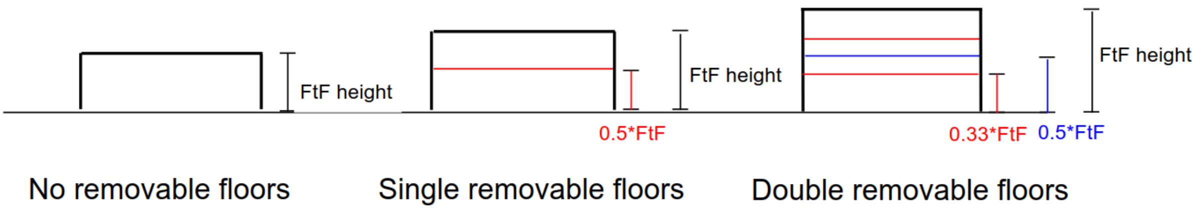


Figure 35: Different models for removable floors.

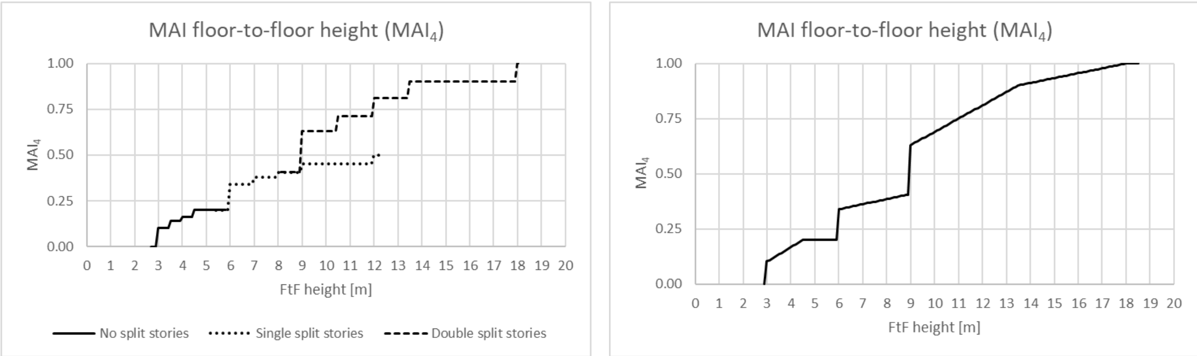
Table 7: FtF height corresponding to different functions to fit in the module.

Floor-to-Floor height	Functions becoming available
3.0	Residential, Prison, Lodging
3.5	Office, Education
4.0	Healthcare
4.5	Shopping
6.0	Gathering, Industrial, Sport

This results in the MAI of the FtF height as shown in Figure 36a. As can be seen from this graph, the MAI increases significantly at the values where it becomes possible to split the stories with removable floors, which is at 6.0 m and 9.0 m.

The maximum MAI of 1.00 is reached when all functions fit between the double removable floors, which is at 18.0 m. In this case, the module is split in three stories, see Figure 35. This leads to the possibility to fit all functions in three stories, plus the option to remove the two removable floors and fit a single removable floor. This brings the total sum of the available functions to four times that of using one story. The total sum of the weighting factors is normalised to have a value between 0 and 1, which means that for MAI_4, the weighting factors from Table 6 are divided by four.

Again, following the same logic as before, the interval graph is converted to a linear graph. This is shown in Figure 36b, which is the MAI for the floor-to-floor height. The initial jumps from the interval graphs are however kept intact, because an FtF height of less than 3.0 mis deemed impractical, leading to an MAI of 0.



(a) *(b)*

Figure 36: MAI for Floor-to-Floor height (MAI_4).

3.2.2. Building Adaptability Indicator

To obtain an adaptability indicator for a building, the MAI of the sub-indicators are combined by using weighting factors, based on the interviews with structural designers from Appendix A. Using the answers from the interviewees, the author has come up with weighting factors that convert the MAI to the BAI:

$$BAI = \sum_i^4 MAI_i W_i \tag{2}$$

Where:

MAI_i = MAI of the sub-indicators

W_i = Weighting factor of sub-indicator

The properties of the BAI are shown in Table 8, where the values of MAI_i follow from Figures 32b-36b.

Table 8: Weighting factors BAI.

Sub-indicator name	Sub-indicator score	Weighting factor
Openness	MAI_1	$W_1 = 0.35$
Reserved capacity ; foundation	MAI_2	$W_2 = 0.15$
Reserved capacity ; floor	MAI_3	$W_3 = 0.10$
Floor-to-Floor height	MAI_4	$W_4 = 0.40$

The weighting factors W_i are determined based on the answers on the interviews, see Appendix A. The interviewees generally agreed that the FtF height is a parameter that cannot be adapted, which is why the weighting factor of this sub-indicator is the largest. The same yields for the openness, specifically the grid size. It is not possible to choose a new grid configuration, it is however possible to remove a wall to increase space for example. Therefore, openness has a slightly lower weighting factor than the FtF height. Finally, the interviewees mentioned that the Reserved capacity of the floors and the foundations is something that can possibly be increased. This is however a costly operation, while the practice of increasing the foundation capacity is challenging. Therefore, the weighting factor of the foundation capacity is slightly larger than that of the floor capacity. Using this information, as provided by the interviewees, the weighting factors from Table 8 are estimated by the author, which are used to determine the BAI.

This research combines the scores of MAI_i in a linear manner with the use of the weighting factors W_i. This linear combination means that a building with a large $MAI_{1\text{-}3}$, but a low MAI_4, could still result in a high BAI. However, a low MAI_4 means that a low, non-adaptable, FtF height is chosen, which in turn means that the number of building functions that can be adapted to is limited. Therefore, the BAI does not necessarily tell something about the number of functions that a building can be adapted to. This is only the case for the MAI’s. The

BAI rather provides an indication of a building's adaptability in a more general sense. More discretely this means that the BAI provides an indication of the possibility that a building is reused, not the possibility of adapting to a certain function.

3.3. Case Studies Demolition – Reuse

To investigate whether a high BAI will indeed lead to less demolition and thus to less environmental impact, two case studies are performed on demolished buildings and two case studies on reused buildings. By using the BAI that has been created in Chapter 3.2, conclusions can be drawn on the influence of a high adaptability on the choice of demolition or reuse. Table 9 shows the properties of the studied buildings. Additionally, to increase the number of data points, several example projects from ABT are discussed in the interviews with structural designers, which are shown in Appendix B. These projects are added to the results in Chapter 3.3.5.

Table 9: General properties of demolished or reused building case studies.

Project name	270 Park Avenue	AfE-Turm	Hudson Commons	The Woolworth Tower
Location	New York	Frankfurt	New York	New York
Year of completion	1960	1972	1962	1913
Year of demolition/reuse	2021	2014	2020	2019
Life span	61	42	58	106
Demolished or Reused?	Demolished	Demolished	Reused	Reused
Height [m]	216	116	42	241
Number of floors	52	32	8	57
New height [m]	423	145	128	241
New number of floors	70	41	25	57
Original function	Office	Educational	Industrial	Office
New function	Office	Lodging	Office	Residential
FtF height [m]	4.00	3.50	4.35	3.60
New FtF height [m]	6.00*	3.30*	4.35	3.60
Grid size [m]	6.1	6.8	7.3	8.2
Columns or walls?	Columns	Columns	Columns	Columns
New grid size [m]	9.0*	8.5*	7.3	8.2
BAI	0.41	0.46	0.62	0.57

*Estimated from drawings and/or photographs.

3.3.1. 270 Park Avenue [Demolished]

The former Union Carbide Building, located at 270 Park Avenue, is the tallest voluntarily demolished building at 216 m, as of 2021. The building was demolished as a result of the desire for a new building for the tenant, the JP Morgan Chase bank. The motive for demolition was to create space for a taller building, which could provide office space for more employees and will be a more flexible building [62].

As is shown in Table 9, the original structure has a load capacity of an office building, with a typical FtF height for an office building of 4.0 m. Furthermore, the grid size of 6.1 m is on the low side for office buildings. Table 9 also shows the properties of the proposed design of the new building at 270 Park Avenue. The larger FtF height and the increased grid size show the ambition of JP Morgan Chase to realise a flexible building.

3.3.2. AfE-Turm [Demolished]

AfE-Turm was a 116 m tall building, serving an educational purpose for the university of Frankfurt. Due to the overcrowding of students in the building in its later years, it was decided to move the students to a different location. Furthermore, the high amount of technological errors and the lack of elevator capacity meant that the building became vacant and unsuitable for reuse. In 2014, the building was demolished by means of implosion.

Table 9 shows that the structure had the load capacity for an education function, with a FtF height of 3.5 m and a grid size of 6.8 m. It can also be seen from Table 9 that the function of the new building that is realised at the location of AfE-Turm is a mix of lodging and residential, with a FtF height of approximately 3.3 m and a grid size of approximately 8.5 m. These properties should in theory also be possible with the old AfE-Turm, but the location of installations and the capacity of the elevators determined that the building had to be demolished. This indicates that the choice for demolition is not only based on the structural adaptability, but also on the adaptability of the interior. However, one could ask the question whether it was possible to implement a different installation plan and new elevators, so that demolition would be prevented.

3.3.3. Hudson Commons [Reused]

The former warehouse Hudson Commons, which has been used as an office for the past 40 years, has been expanded with a 17-story skyscraper on top of the original building. The main initiative of expanding the building followed from the ambition of the architect KPF [88]. KPF saw the opportunity for expansion of the building, to provide for the residential demand in New York City. The ambition of KPF to expand the building follows mainly from the fact that the environmental impact of the building will be limited, but also to show what can be done by creative thinking [57].

In Table 9, the original function of the building is listed as industrial, because it was designed as a storage facility. The vertical load bearing capacity of the structure is already at a high level due to its original function, but are also increased by retrofitting the columns and foundation. The original FtF height is 4.35 m and the grid size is 7.3 m. The core of the additional levels is integrated into the original building by demolishing a small part of the interior structure, see Figure 37. This new core provides the lateral stability and stiffness of the taller structure [126].

In this case, it is shown that a high amount of adaptability could also possibly lead to expansion of the building. Whether a building is changed from the inside or expended to the outside does not change the fact that demolition is prevented, meaning the original building has a low environmental impact.

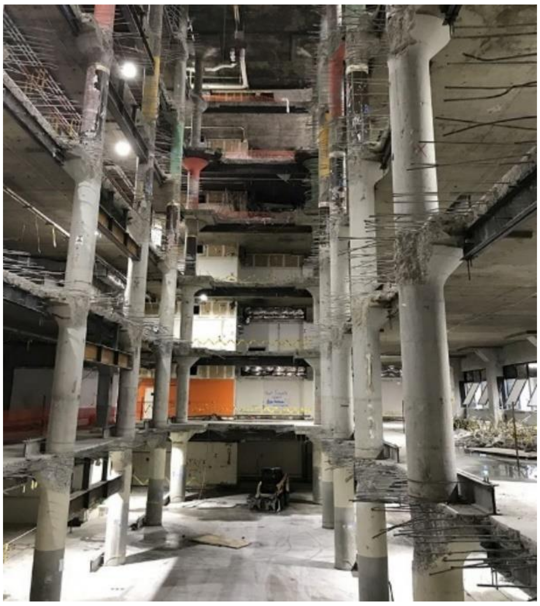


Figure 37: Demolished interior structure to implement new core for Hudson Commons. Source: WSP [126].

3.3.4. The Woolworth Tower [Reused]

In 2019, the upper 30 stories of the Woolworth tower have been adapted from an office function to a residential function. The building of more than 100 years old had been landmarked in 1966, which means that the building has historic value, for example in its pinnacle. Furthermore, the structure and proportions of the building align with the current typical layout of residential use, which further motivated the choice for reuse. The outdated services of the building had to be replaced, such as the elevators, stairs, and installations. Despite the challenge of these alterations, the historic value of the building motivated the functional change, which would not have been possible with a low amount of adaptability.

The building has the load capacity of an office building, see also Table 9. The FtF height is 3.6 m and the grid size is 8.2 m. These dimensions are more than sufficient for a residential function [108].

3.3.5. Results

With the use of the BAI as defined in Chapter 3.2, the adaptability of buildings can be quantified. The BAI for the aforementioned case studies, together with the example projects from ABT are shown in Figure 38.

From Figure 38, it is concluded that the adapted buildings generally have a higher BAI than the demolished buildings. One could argue that this means that a higher adaptability index results in a lower probability of demolition. However, as Rockow [98] has shown, there are other factors that influence the choice of demolition or adaptation. In their guideline for building life cycles, W/E [122] mentions that a building which is either dearly valued or highly adaptable is not likely to be demolished. As these two studies indicate, the choice for demolition or reuse is not only governed by adaptability, but also by other factors.

In the interviews, these factors that influence the choice for demolition or adaptation have also been discussed. Factors that could play a role according to interviewees are: costs, technical quality, updated laws, circularity goals and historic value. The interviewees all mentioned that the financial side is governing for most clients. The costs of adaptation are determined by the boundary conditions of the building. Factors that are seen as boundary conditions are the technical quality and adaptability of the building. Restrictive boundary conditions will significantly limit the possibilities of adaptation, which means that the building will then be demolished. Therefore, a lack of adaptability will likely lead to demolition.

In Figure 38, it is seen that there are no buildings that are reused when its BAI is low. From the interviews, this is explained by the notion that the lack of adaptability will serve as a disqualifier for reuse. One interviewee explained this as: “if the desires of the client do not fit in the building, demolition is necessary”.

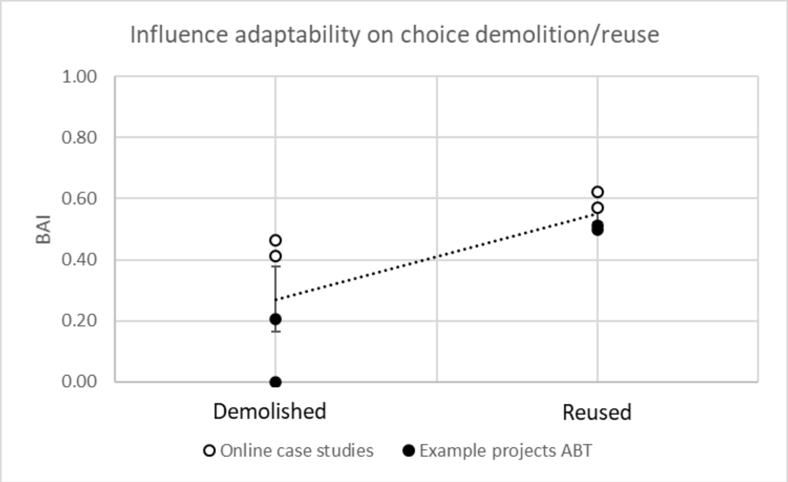


Figure 38: Influence of adaptability on choice of demolition or reuse.

3.3.6. Conclusion

It is concluded that a low BAI will certainly result in demolition, but it is also seen that a high BAI does not necessarily lead to reuse. As mentioned by the interviewees: a lack of adaptability acts as a disqualifier for reuse. Therefore, a high adaptability is not enough to ensure reuse of buildings, but it is the least that structural designers can do. This means that structural designers should try to incorporate at least some sense of adaptability in their designs, which increases the probability that the building is reused in the future.

4. Implementation Building Adaptability Indicator

In this chapter, the consequence of implementing a high BAI in the design of a high-rise building is investigated. This is done by performing a case study on an existing design of a high-rise residential tower, after which the design is altered in its adaptability. This results in the additional research question:

What is the consequence to the material use in high-rise of implementing a high BAI?

Because there is a lack of research on circular high-rise buildings of around 100 m tall and there is an increase in the amount of buildings that exceed 100m that are being built in the Netherlands, it is chosen to study buildings of this approximate height, as this could be useful in practice.

4.1. Existing Design

First, the existing design will be specified, to gain insight in the limitations in its adaptability. For this existing design, a tower with a height of 100m is chosen. In the Netherlands, this height is indicated as high-rise. As discussed before, there is currently a housing problem in the Netherlands, which is why the function of the existing design is residential. The tower is located in Amsterdam, the Netherlands. The size of the floor plan is 36.0 m x 25.2 m, see also Figure 39.

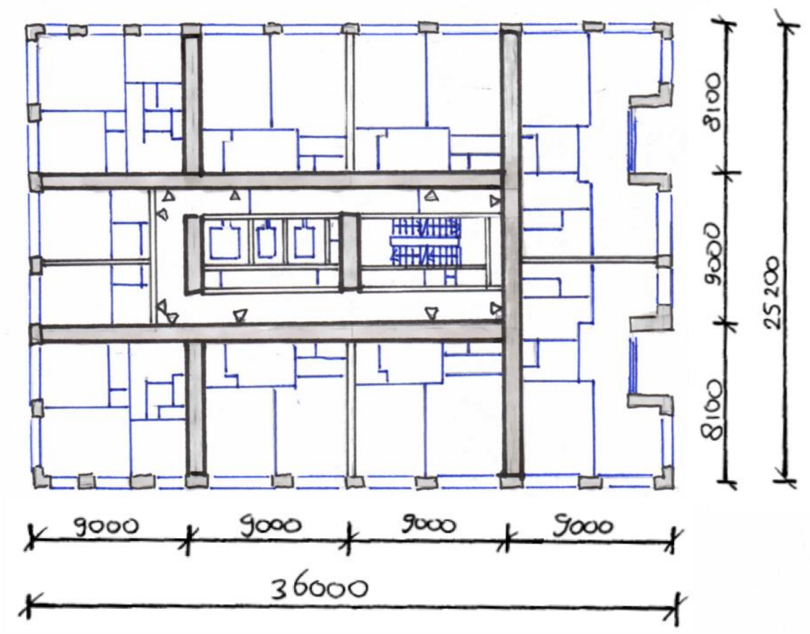


Figure 39: Standard floor plan of existing design.

4.1.1. Technical Specifications

It is important to gain insight in the technical specifications of the design, as this determines the score of the BAI. The existing design of the high-rise structure makes use of prefab concrete stability walls to create a stiff core, see also Figure 39. The stability walls are continuous over the height, to ensure stiffness over the height of the structure in both transverse and longitudinal direction. The stability walls are assumed to be monolithic, which means that the connections between walls at different floors are stiff. The walls have a thickness of 350 mm.

On the outer dimensions of the structure, columns are used for the vertical load bearing. These columns have an increased thickness towards the bottom of the structure due to the increasing compression force, where the largest column is 1000 mm x 1000 mm.

The floor system used in the existing design is a hollow-core slab floor, which is prefabricated. These floors span approximately 9000 mm and have a thickness of 310 mm (260 mm with 50 mm finishing floor).

The floor load on the structure is that of a standard residential function, namely 1.75 kN/m^2 variable load, with the addition of 0.8 kN/m^2 for partition walls. The temporary variable load in this case also that of a regular residential function, namely 0.7 kN/m^2. The FtF height is 3040 mm.

4.1.2. BAI Existing Design

By using the BAI, the existing design can be assessed on its adaptability. The results are shown in Table 10.

Due to the use of a wall grid in the floor plan, the MAI for openness is limited to a value of 0.41, see Figure 32b. The use of standard loads for a residential function means that there is no capacity in the foundation, see Figure 33b. For the floor loads, there is a slight capacity due to the implementation of the extra weight by the partition walls, see Figure 34b. The MAI of the floor-to-floor height is close to 0, because a low FtF height is used to maximize the rentable area of the tower. The value of MAI_4 follows from Figure 36b. By using Equation 2 and the weighting factors from Table 8, the BAI is calculated.

From Table 10, it can be concluded that the existing design is not adaptable and thus not circular. Ways to improve the adaptability of the design should be investigated.

Table 10: Calculation BAI of existing design.

MAI_1	0.41
MAI_2	0.41
MAI_3	0.56
MAI_4	0.10
BAI	0.30

4.1.3. Improvement Points

The adaptability of the existing design has several points of improvement. First, the use of a wall grid greatly limits the MAI for openness, which is why it is proposed to use a column grid for the alternatives. Furthermore, the use of the load capacity of a residential function means that there is almost no possibility in adapting to a different function, which is why the structural analysis should use an increased variable load, to create reserved capacity in the floors and foundation. The current FtF height of 3040 mm limits the BAI, which is why alternatives that use larger FtF heights should be investigated. This will influence the number of stories of the building that are possible within a height of 100 m, which is why the choice of the FtF height should be carefully investigated.

Other factors limiting the adaptability of the existing design are the capacity of the vertical transport and the installation plan. These are typical for a residential tower, but should be able to change to accommodate different functions.

The improvement points will be taken into account in the next step of this research, where alternatives to the existing design are investigated.

4.2. Alternative Designs

Taking into account the improvement points from Chapter 4.1.3 on the existing design, an alternative design with different configurations of openness, reserved capacity and FtF height are proposed. First, the starting points of this design are specified, after which the configurations are discussed. Finally, the material use of the configurations are compared to the existing design and to each other.

4.2.1. Starting Points

The general properties of both the existing and alternative design are shown in Table 11. It is shown that the dimensions of the building are the same for both options, but using a different stability system, material, and floor system. The choice of each starting point of the alternative design is explained below.

Table 11: Starting points alternative design.

	Existing design	Alternative design
Building dimensions	36.0 m x 25.2 m	36.0 m x 25.2 m
Building height	100 m	Maximum 100 m
Material	Concrete	Timber (core in concrete)
Stability system	Stability walls	Core
Floor system	Hollow-core slab	Kerto Ripa

4.2.1.1. Building Dimensions

The building dimensions of the alternative design is chosen to be the same as the existing design, as this will lead to an honest comparison of the alternative designs with the existing design.

4.2.1.2. Building height

The building height of the existing design is exactly 100 meters high, but the alternative design will have different configurations of the FtF height. This means that it is not possible that each design is equal to exactly 100 meters in height, because for example 30 floors with a FtF height of 3.3 meters, means that the building will be 99 meters high. Therefore, it is chosen that the height of the alternative design has a maximum height of 100 meters, but can be lower.

4.2.1.3. Material

In this research, the aim is to compare a conventional high-rise design with that of a circular one. The circularity strategy that is treated in this research is Design for Adaptability, but this can be combined with the strategy of Minimum Embodied Carbon. The use of timber as a construction material leads to a lower environmental impact of the building, due to the regrowable property of timber. Therefore, it is chosen to design the alternatives in timber, to combine the two aforementioned circularity strategies.

4.2.1.4. Stability system

The choice of the stability system has an influence on the openness of a high-rise building, as is discussed in Chapter 3.1.2. However, stability system also determines the lay-out of the floor plan, which influences the capacity of the vertical transport and the installations. Therefore, it is explained below what type of stability system and lay-out allows a high adaptability of the alternative design.

Chapter 3.1.2 discussed the different possibilities of stability systems in a high-rise building of approximately 100 m high. It is concluded from this study that the use of a stiff façade is not desired. This is because a façade that contributes to the lateral stability is less adaptable, meaning that the exterior of the building can become obsolete before the EoL stage of the total building. Therefore, a choice should be made between using solely a core system, or a core combined with one or more outriggers. Because both of these options use a central core, the lay out of this core is first determined as it greatly influences the capacity of vertical transport and installations. After that, the choice on the stability system is made.

Core lay-out

In Chapter 3.1.2.5, it is concluded that the shape of the core should follow that of Figure 28. This allows for possible expansion of the installations or vertical transport in the core, which increases the adaptability of the core. Using the shape of Figure 28, the smallest possible core which allows for a large number of building functions is determined. The result is shown in Figure 40.

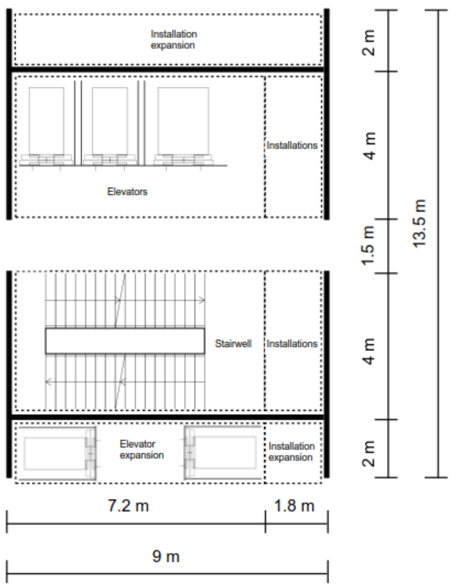


Figure 40: Smallest possible adaptable core lay out.

The requirements on the services in the core for different functions are discussed with a fire safety expert at ABT. From this discussion, it is concluded that the use of a large stairwell, with a total width of 4 meters is sufficient for the escape route for most functions, even with a large amount of people per floor. Furthermore, there should be an area available inside the core, which is a separate fire compartment from the rest of the building, so that people can safely be gathered in this area in case of a calamity. This area is provided by the hallway in between the stairwell and the elevators, which has a width of 1.5 meters. The remaining area inside the core is used to accommodate installations. It is estimated by the author that two areas of 1.8 m x 4 m are sufficient for the installations inside the core. On the outside of the core, an area of 9 m x 2 m can be used for a possible expansion of the installation capacity.

The requirements on the number of elevators for different building functions have been discussed in Chapter 3.1.3.2. Table 4 shows the maximum waiting time for an office, residential, and lodging function. With these requirements, together with a rough estimate of the number of people on each floor for different functions, a calculation is made to determine the number of required elevators for a residential function and an office function. These two calculations will be sufficient, because an office function is governing in the elevator capacity due to the number of people per floor and the low maximum waiting time. By calculating the time of one elevator ride, the round trip time (RTT), the waiting time can be determined and compared to the requirements in Table 4. The RTT is determined as [111]:

$$RTT = 2Ht_v + (S+1)t_s + 2Pt_p + 2t_e \quad (3)$$

Where:

RTT = Round trip time [s];

H = Average highest reached story;

t_v = Transfer time one story [s];

S = Average number of stops;

t_s = Time needed to stop [s];

P = Average number of passengers;

t_p = Transfer time [s];

The calculations of the RTT of a residential and office function are shown in Appendix C.1. This results in the use of 3 elevators in the case of a residential function and 5 elevators in the case of an office function, as depicted in Figure 40.

From the requirements in fire safety, installations, and elevator capacity it is concluded that the minimum possible core size for the alternative designs is 9 m x 13.5 m.

Core material

As mentioned in Chapter 4.2.1.3, the material of the alternative designs is timber. It is possible to use CLT wall elements as a core, but using these walls as a stability system leads to a high amount of steel connectors, see Figure 41. This is because in the case of using CLT walls as a stability system, the wall elements have to be stacked on top of each other and connected with steel connectors. Due to the high in-plane flexural stiffness of the CLT elements, rocking of the components occurs, which will lead to large displacements. To prevent large displacements, a high amount of steel connectors should be used, which is why CLT walls as a stability system is undesirable from a circularity point of view.

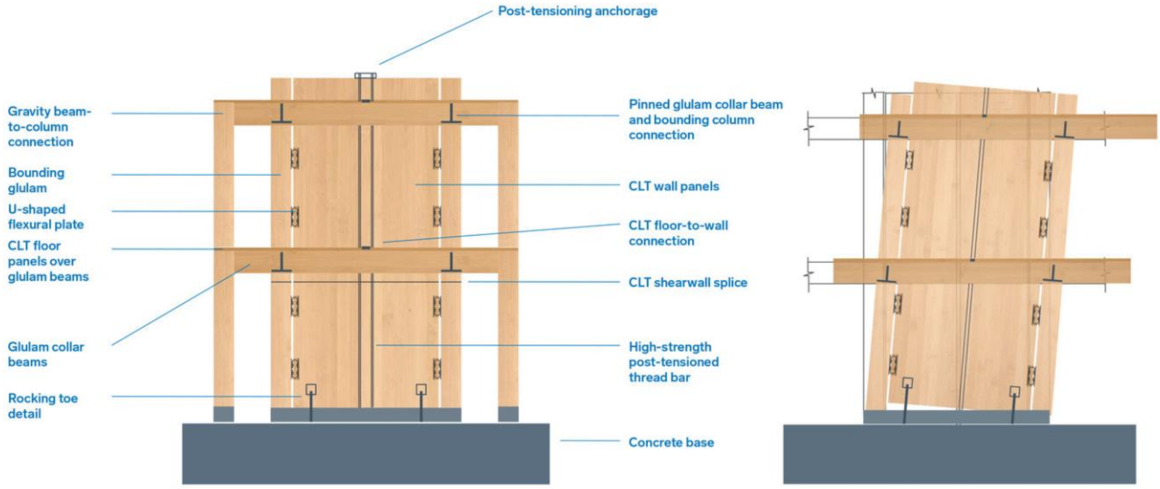


Figure 41: Rocking of CLT elements leads to high amount of steel connectors. Source: Lever Architecture [61].

A possible solution is to use the timber core only as a vertical load bearing mechanism and not as a stability system, which means that a stiff façade should be used. Another solution is to use a core in concrete, leading to an increase of the environmental impact. A stiff façade has a negative influence on the adaptability of the building, while this research focusses on how to increase adaptability. Therefore it is chosen that the negative consequence to the environmental impact of using a concrete core is the better choice in the alternative design.

Lateral stability calculations

Finally, it is compared whether the use of an outrigger is more material efficient than the use of a core by itself. To be able to determine the required dimensions of the core in each case, the lateral wind load should first be determined using EN 1991-1-4 [76], see Figure 42.

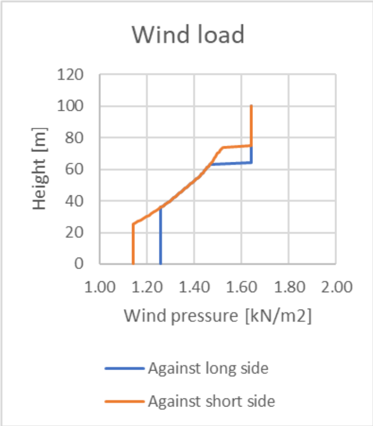


Figure 42: Lateral wind load against alternative design according to EN 1991-1-4.

Using the wind loads from Figure 42, the dimensions of the core options are determined in Appendix C.2. This results in the options as depicted in Table 12.

It should be noted that the lateral stability calculation from Appendix C.2 serves as a method to determine the core size of a fictive alternative design at an early stage. For this fictive case, knowledge on the stiffness of the soil and foundation is limited. Therefore, it is chosen to only check the lateral stability on the core stiffness and not on the foundation stiffness, see Appendix C.2. This is justified by the fact that the stability calculation only serves as an indication of the core size.

Table 12: Options for stability system ; 100 m high, 30 stories, FtF height 3.3 m.

	Core (1)	Core (2)	Core (3) + Outrigger
Wall thickness [m]	1.00	0.50	0.35
Core length [m]	9.0	12.0	9.0
Core width [m]	13.5	14.5	13.5
Outrigger height [m]	-	-	3.5
Concrete volume [m^3]	4455	2624	1559
Rentable area [m^2]	24651	23003	23829

It is concluded that option 1 for the core is not desired, because a wall thickness of 1 meter leads to a large amount of material use. Therefore, it is concluded that it is not possible to maintain the minimum core size of 9 m x 13.5 m without using an outrigger.

Comparing the rentable area of using a larger core without an outrigger with that of a smaller core with an outrigger, it is seen that the benefit in rentable area of using an outrigger is relatively small. Additionally, the implementation of the outrigger leads to extra costs due to the use of timber beams in the outrigger, which is an expensive construction material. The dimensions of the columns will also increase, because these will contribute to the lateral stability with the outrigger. The material cost that is saved in the concrete core does not outweigh the extra timber costs, which is why it is chosen to use option 2 of the core with a size of 12 m x 14.5 m.

4.2.1.5. Floor system

There are two main options for timber floor systems in high-rise, which have been discussed in Chapter 2.3.3.3. These are a CLT floor and a Kerto Ripa floor. The advantage of a CLT floor is that the thickness of the floor can be limited, while the Kerto Ripa floor is generally a thicker floor due to the use of LVL beams underneath an LVL plate. A CLT floor can realistically only span up to 6 meters, which is a large disadvantage in using the floor for a building with high adaptability, because large grid sizes are desired. A Kerto Ripa floor can span up to 8 or 9 meters for different functions. Additionally, with the Kerto Ripa floor, installations, acoustic, and fire safety measures can be mounted in between the LVL ribs of the floor, which leads to an efficient floor thickness. For a CLT floor this would lead to extra floor thickness, because these services would be mounted underneath the floor. Therefore, it is chosen to use a Kerto Ripa floor system in all alternative designs, even the ones where a CLT floor would be possible, for an honest comparison.

Because a timber floor system generally has a large thickness, it is possible to integrate the floor into the beams underneath. This will limit the total structural height, which will lead to a higher ceiling height and thus more adaptability. Integrating the floor system into the beams means that at this point, attention should be paid to the shear capacity of both the floor and the beam.

4.2.1.6. Conclusion Starting Points

Using the general properties of Table 11, a standard floor plan is drawn up. This floor plan is shown in Figure 43. Additionally, a standard cross-section of one story is shown in Figure 44. In these standard drawings, the openness, reserved capacity, and floor-to-floor height will be altered to compare the material use of different levels of adaptability in Chapter 4.2.3.

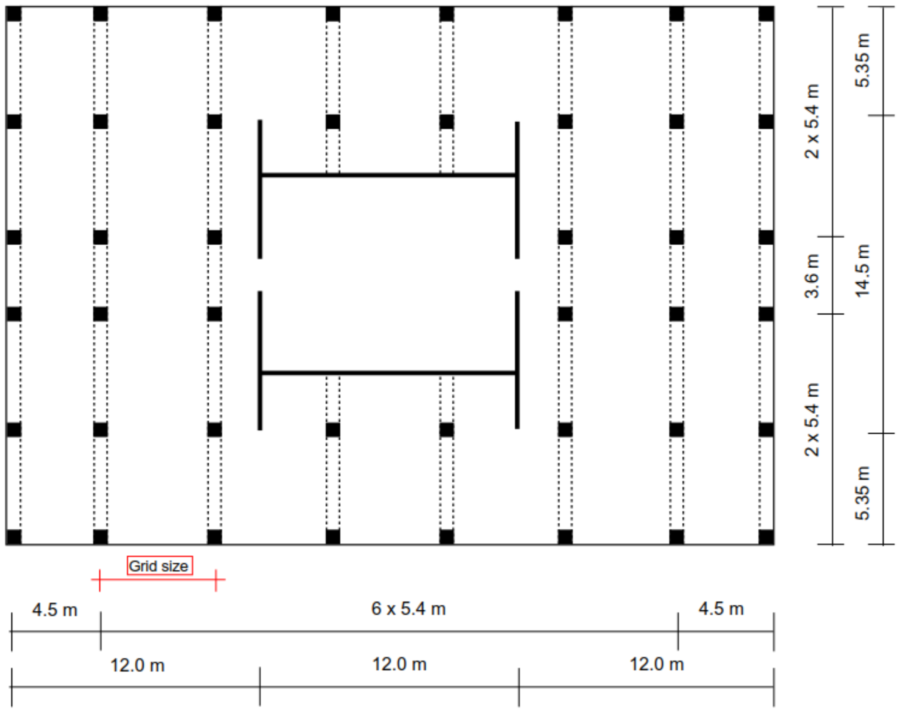


Figure 43: Standard floor plan of alternative design, example with grid size 5.4 m.

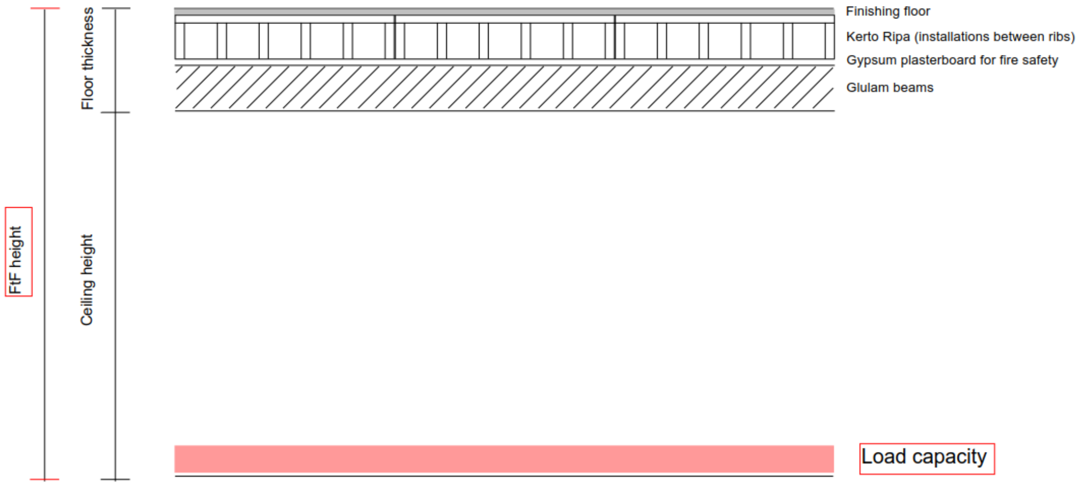


Figure 44: Standard cross-section of alternative design, floor thickness is dependent on loads.

4.2.2. Alternative Design Configurations

Using the starting points of the alternative designs, different configurations are analysed on their material use. The material use of the configurations is determined by a structural analysis of the designs. This analysis includes the calculation of the dimensions for the floors, beams, and columns. The calculations include the wind load, self-weight, and variable load. The configurations differ in their grid size, load capacity, and FtF height. The possible configurations are shown in Table 13, where the first row of parameters represents a baseline for comparison. The calculations of the baseline are shown in Appendix C.3.

In each calculation of the configurations, one parameter is altered to understand its influence on the material use of the building, the results of this are shown in Appendix C.4.

Table 13: Possible configurations alternative designs. Note: these parameters can be combined.

Steps	Grid size [m]	Variable load [kN/m^2]	Temporary load factor [-]	FtF height [m]
Baseline	5.4	1.75 + 0.8	0.4	3.0
1	6.0	2.50 + 0.8	0.5	3.3
2	6.6	4.00	0.4	3.5
3	7.2	5.00	1.0	4.0
4	8.4	5.00 + 0.8	0.4	4.5
5		12.00 + 0.8	1.0	6.0
6				9.0

4.2.2.1. Conclusion

From Appendix C.4, it is concluded that a variation in the grid size greatly affects the material use. This is because the floor thickness and beam dimensions increase significantly at a large grid size. It is seen that a grid size larger than 7.2 m is no longer interesting from a materials point of view, due to the large increase of the floor thickness and beam dimensions. The results from Appendix C.4 also show that an increase in the grid size can improve the BAI with 70%.

Furthermore, an increase in the load capacity will mostly affect the column dimensions. It is seen that with relatively little extra material use the load capacity can be increased, leading to a significant increase of the BAI. It is concluded that the use of a load of 12 kN/m^2 is unreasonable, due to the large amount of extra material use. For a large load capacity, the BAI is increased with 41%.

Lastly, a larger FtF height leads to a decrease of the material use, due to a lower amount of stories that will fit in a 100 m high building. This does however also lead to a decrease of the rentable area. The results from Appendix C.4 show that the use of split stories will partly negate the downside of using a larger FtF height, because the loss of rentable area is kept low. Structural designers should carefully consider the loss of rentable area compared to the decrease of material use when choosing a FtF height. These factors influence the value and the environmental impact of the building, which are assessed in Chapter 4.3.

4.2.3. Resulting Alternative Designs

Using the results of the configurations, a total of four alternative designs are proposed to be further investigated: one baseline with a similar BAI to the existing design, option 1 with a slight increase of the BAI, option 2 with a moderate increase of the BAI, and option 3 with a large increase of the BAI. The properties of these alternative designs are shown in Table 14. The comparison of the BAI's between the alternative designs is shown in Table 15.

Table 14: Properties of alternative designs.

Options	Grid size [m]	Variable load [kN/m^2]	Temporary load factor [-]	FtF height [m]
Baseline	5.4	1.75 + 0.8	0.4	3.0
1	6.0	2.50 + 0.8	0.5	3.5
2	7.2	4.00	0.4	4.0
3	7.2	5.00 + 0.8	0.4	6.0

Table 15: Calculation BAI of alternative designs compared to existing design

Options	Existing design	Baseline	Option 1	Option 2	Option 3
MAI_1	0.41	0.41	0.56	0.87	0.87
MAI_2	0.41	0.41	0.62	0.75	0.93
MAI_3	0.56	0.56	0.63	0.70	0.98
MAI_4	0.10	0.10	0.14	0.17	0.34
BAI	0.30	0.30	0.41	0.56	0.68

The baseline variant is one with the properties of a typical residential building, similar to the existing design, but with a smaller grid size and using a column grid instead of a wall grid. This leads to a BAI of 0.30.

Option 1 is a variant with a slightly increased BAI of 0.41, due to the larger grid size, load capacity, and FtF height. Appendix C.4.1 shows that for a grid size of 6 m, the total material volume is lower than that of the baseline due to the decrease of the number of columns. Appendix C.4.2 shows that increasing the load capacity to that of an office building, the increase of the BAI is significant compared to increasing to a heavier load capacity. This is partly due to the higher temporary load factor for an office function. Finally, it is concluded from Appendix C.4.3 that a slight increase of the BAI can be achieved with the use of a FtF height of 3.5 m. This height is typical for an office building, which is why this height is chosen for option 1.

Option 2 is a variant with a moderate increase of the BAI, namely 0.56. The use of a grid size of 7.2 m is interesting in terms of the number of columns in the floor plan, which leads to an efficient material use per m^2 of rentable area, see Appendix C.4.1. In this variant, a load capacity of 4.00 kN/m^2 is chosen. Appendix C.4.2 shows that this load capacity does not significantly impact the BAI, but the influence on the material use is also limited. The use of a lower load capacity is deemed risky, because it could prevent adaptation of the building. For this option, a FtF height of 4.0 m is chosen. The sacrifice to the rentable area of a larger FtF height, without using split stories, is not worth it, see Appendix C.4.3.

Option 3 is the variant with the largest BAI of the alternative designs, namely 0.68. The BAI is not increased further, because a larger grid size, load capacity, or FtF height leads to an unreasonable amount of material use without a large increase of their respective MAI's. The grid size for this variant is again chosen at 7.2 m, with the reasoning that the use of a larger grid size will lead to an unreasonable floor thickness, see Appendix C.4.1. The load capacity is that of a healthcare function, with a floor load of 5.80 kN/m^2. The FtF height is chosen as 6.0 m, because this means that the stories can be split, which in turn means that the sacrifice to the rentable area is limited, see Appendix C.4.3.

The result to the material use of the variants from Table 14 are shown in Figure 45 and Table 16.

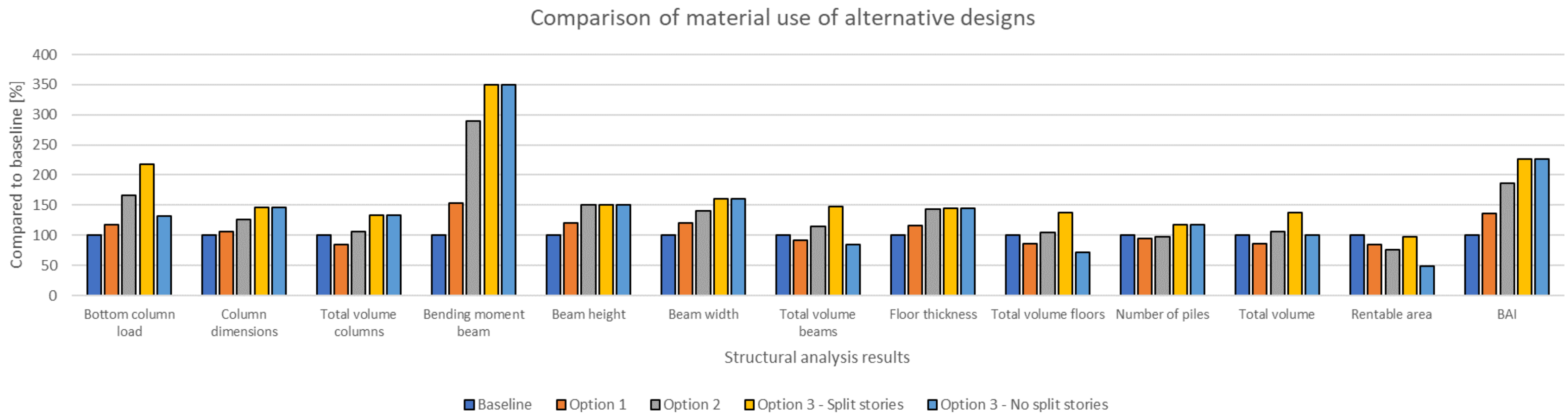


Figure 45: Alternative designs material use.

Table 16: Results structural analysis alternative designs.

Baseline											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Floor thickness	331.00	100	Bending moment beam	229.45	100	Bottom column load	10759.30	100	Number of piles	276	100
Total volume floors	1571.64	100	Beam height	500.00	100	Column dimensions	750.00	100	Total volume	3958.37	100
			Beam width	250.00	100	Size (2/3)	600.00		Rentable area	26175.6	100
			Total volume beams	753.23	100	Size (3/3)	450.00		BAI	0.30	100
						Total volume columns	1633.50	100			
Option 1											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Floor thickness	385.00	116	Bending moment beam	351.90	153	Bottom column load	12674.38	118	Number of piles	260	94
Total volume floors	1360.83	87	Beam height	600.00	120	Column dimensions	800.00	107	Total volume	3427.85	87
			Beam width	300.00	120	Size (2/3)	650.00		Rentable area	22209.6	85
			Total volume beams	695.02	92	Size (3/3)	500.00		BAI	0.41	137
						Total volume columns	1372.00	84			
Option 2											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Floor thickness	475.00	144	Bending moment beam	663.36	289	Bottom column load	17838.00	166	Number of piles	268	97
Total volume floors	1634.61	104	Beam height	750.00	150	Column dimensions	950.00	127	Total volume	4224.17	107
			Beam width	350.00	140	Size (2/3)	800.00		Rentable area	19830	76
			Total volume beams	867.56	115	Size (3/3)	550.00		BAI	0.56	187
						Total volume columns	1722.00	105			
Option 3											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Thickness	481.00	145	Bending	803.05	350	Compression split	23472.16	218	Number of piles	324	117
Volume split	2171.56	138	Height	750.00	150	Compression nosplit	14266.32	133	Total split	5475.81	138
Volume nosplit	1122.30	71	Width	400.00	160	Size (1/3)	1100.00	147	Total nosplit	3945.34	100
			Volume split	1115.77	148	Size (2/3)	900.00		RA split	25382.4	97
			Volume nosplit	634.56	84	Size (3/3)	650.00		RA nosplit	12691.2	48
						Volume	2188.48	134	BAI	0.68	226

4.2.4. Discussion and Conclusion

The baseline variant is an alternative design of a typical residential building. The three building functions that generally fit in this building are: prison, lodging, and residential. In theory, this option is able to freely switch between these three functions.

The results show that the BAI is increased 37% in option 1, with only sacrificing 15% of the rentable area. Additionally, the total material volume is decreased with 13%, due to the lower number of columns and less stories. The increase in the dimensions of the structural elements is limited to a maximum of 20%. The additional building functions that generally fit in this building are: office and education, meaning that this option can in theory freely switch between five functions.

The BAI of option 2 is 87% larger than that of the baseline. The sacrifice to the rentable area in this case is 24%, which is a setback of this variant. The total material volume is increased with only 7%, due to the use of less columns in the floor plan and less stories, while having an increase of the structural element dimensions of a maximum of 50%. The additional building functions that generally fit in this building are: gathering and shopping, meaning that this option can in theory freely switch between seven functions.

Option 3, with a BAI of 126% larger than that of the baseline, sacrifices less of the rentable area due to the use of split stories. In the case that no split stories are used, the rentable area is less than half of the baseline, but in the case that the stories are split, this is approximately the same as in the baseline, namely 97%. However, due to the additional capacity of the structural elements, the increase of the structural element dimensions by a maximum of 60% means that the total material use of option 3 with split stories is 38% more than the baseline. The additional building functions that generally fit in this building are: healthcare, industrial, and sport, meaning that this option can in theory freely switch between all ten functions.

It is concluded from Figure 45 and Table 16 that for option 1, a significant increase of the BAI can be achieved with little repercussions. Option 2 has relatively many disadvantages compared to option 1 and 3, due to the large element dimensions and large decrease of rentable area, but also with a significantly increased BAI. Option 3 again has relatively little repercussions, due to the use of split stories. The BAI can be greatly increased, leading to full functional flexibility, at the cost of 60% larger element dimensions, while the rentable area can be maintained.

4.3. Economic and Environmental Meaning BAI

Using the results from the material use, it is investigated what the consequence to the economic and environmental impact is. With this investigation, it can be determined whether the investment of the extra material use to increase the BAI of a building is profitable. This indicates the economic and environmental meaning of the BAI. The following research question is posed for this investigation:

Are there alternative designs which are interesting from a:

1a. Microeconomics point of view?

1b. Macroeconomics point of view?

2. Circularity point of view?

In this chapter, a distinction is made between the micro- and macroeconomic meaning of the BAI. From a microeconomics point of view, it is investigated how the BAI influences the cost and benefits for one investor or company, which is a bottom-up approach. From a macroeconomics point of view, it is investigated what actions from policy makers influence the choice of an investor to invest in a larger BAI, which is a top-down approach [91].

4.3.1. Microeconomic Analysis

From a microeconomics point of view, the meaning of the BAI is investigated by analysing the alternative designs from Chapter 4.2. As mentioned before, the microeconomic analysis concerns the costs and benefits of the alternative designs. Hermans et al. [47] have constructed an overview of the income and expenses of a building during its life span, which is shown in Figure 46.

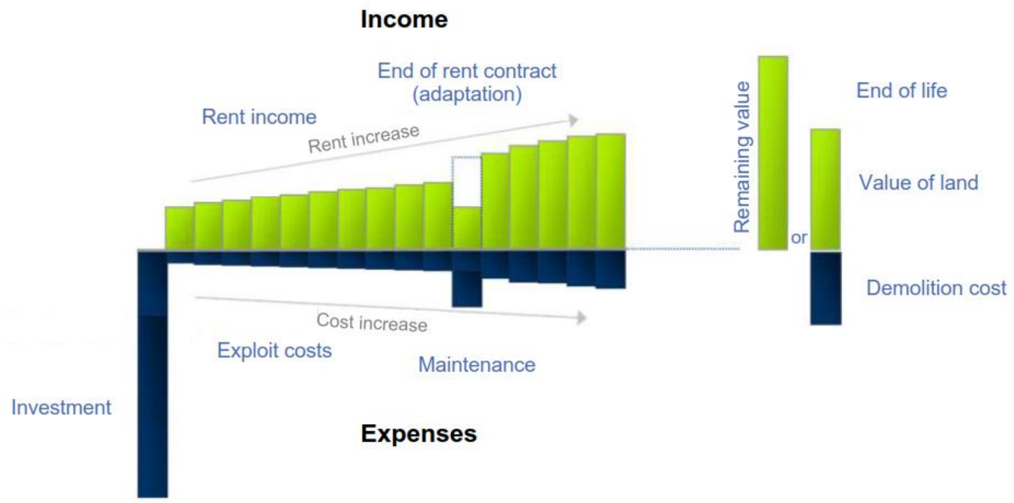


Figure 46: Overview of income and expenses of the owner of a building.

On the expenses side of Figure 46, it is seen that the owner of a building will have to pay an initial investment, yearly exploit costs, and maintenance costs. On the income side is the yearly rent income. At the EoL stage of the building, two scenarios are possible: one where the building is reused and one where the building is demolished. In the case of reuse, the building will have a remaining value, which can be increased by retrofitting the building to accommodate a new function. In the case of demolition, the income will be the remaining value of the land, while there will be expenses for the demolition. An overview of the income and expenses is given in Table 17.

Table 17: Overview of income and expenses for building owner.

Reuse		Demolition	
Income	Expenses	Income	Expenses
Rent income	Initial investment	Rent income	Initial investment
Remaining value	Exploit costs	Value of land	Exploit costs
	Maintenance costs		Maintenance costs
	Retrofitting costs		Demolition costs

Some of the income and expenses in Table 17 take place in the future. This means that the future value of these flows should be calculated by taking into account the inflation. Additionally, this research uses the Net Present Value (NPV) to determine the net value of the building, which indicates whether the investment will be worth it. However, to understand the NPV, first a distinction is made between the technical life span and the economic life span.

The technical life span is the time that a building is operational, while the economic life span is the time that a building can be used responsibly from an economic point of view. It is possible that a building is still operational, but will not be economically interesting. This means that its technical life span is in that case higher than its economic life span. In the calculation of the NPV, the economic life span is used to determine the time at which adaptation of the building could be necessary.

This means that the future values of the flows should be converted to a present value using the following formula [84]:

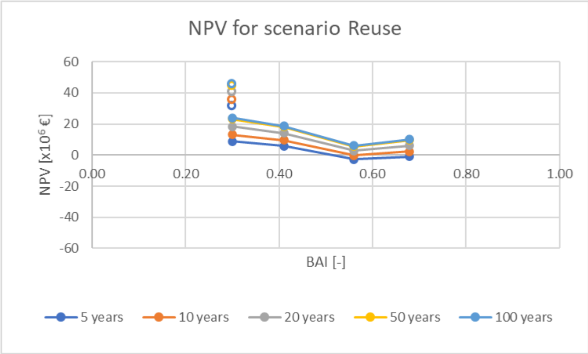
$$PV = \frac{FV}{(1+WACC)^n} \quad (4)$$

Where:

PV	=	Present value
FV	=	Future value
WACC	=	Weighted average cost of capital (WACC)
n	=	Economic life span

It should be noted that in this research, several factors that influence the NPV are estimated by the author for simplicity. For example, the calculation of the WACC is a tedious procedure that is often carried out by financial experts. In this research, the WACC of our fictitious investor is estimated at 10 %. Furthermore, it is estimated that the rent, exploit costs, remaining value, and value of land increase at the same rate as the inflation, which is taken as 3% per year.

Using the present value of the income and the expenses, the NPV can be calculated for the scenario of reuse and the scenario of demolition. This will be done for each alternative design from Chapter 4.2. The calculation for the NPV of the baseline is shown in Appendix D.1. In this calculation, several standard values of income and expenses have been used, for which the sources are mentioned in the calculation. This leads to the NPV of the two scenarios: reuse or demolition, shown in Figure 47. Some additional results from the microeconomic analysis are shown in Table 18.



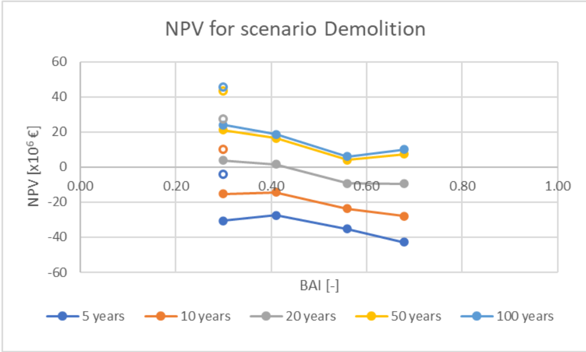


Figure 47: Overview of NPV for different scenarios: Reuse or Demolition at different years after completion.

Table 18: Additional results microeconomic analysis.

	Existing design	Baseline	Option 1	Option 2	Option 3
BAI	0.30	0.30	0.41	0.56	0.68
Initial investment [x10^6 €]	23.3	51.6	45.4	51.3	63.2
Yearly rent [x10^6 €]	5.7	6.3	5.3	4.8	6.1

As is seen from Figure 47, the NPV of the four levels of the BAI are shown, corresponding to the four alternative designs. Following the method of Hermans et al. [47], it is chosen to not only investigate the NPV at the technical life span of the building, but also for other economic life spans. It could be possible that the building becomes obsolete before its technical life span, as is happening with some office buildings in the Netherlands as mentioned before. For this reason, the NPV of the building is calculated for different economic life spans n, as used in Equation 4. This gives insight in the possible scenarios of when the building becomes obsolete, whether that is at the technical life span of 50 years, or perhaps earlier or later.

It is concluded that reuse will almost always lead to a positive NPV, meaning that the investment will be worth making. In the scenario of demolition after 5 or 10 years, the NPV has a negative value. This means that premature demolition is undesirable from a microeconomics point of view. This is because the income in the case of demolition consists only of the received rent and the remaining value of the land. This means that the investment of a to be demolished building takes longer to be earned back, meaning that demolition before earning back the investment is not worth it, as Figure 47 shows.

From Figure 47 it is also concluded that a decrease in the number of stories, as a consequence of increasing the FtF height, leads to a decrease of the NPV for the designs with a large BAI. The reason for this is that the yearly rent income is significantly lower, because of the lower amount of rentable area. Additionally, the investment in the larger element dimensions lead to lower NPVs for a higher BAI, see Table 18. However, in the case that split stories can be used, namely in option 3, the decrease of the NPV is limited. This is due to the extra rentable area of the split stories, which leads to a higher income.

Finally, it is shown in Figure 47 that the existing design has the highest NPV in all scenarios. This is due to the significantly lower initial investment, because concrete is a cheaper construction material than timber. This means that from a microeconomics point of view, the existing design is most interesting, while buildings with a high BAI are less interesting. However, the alternative designs with a higher BAI could still be interesting from a macroeconomics or circularity point of view. This is investigated in Chapter 4.3.2 and 4.3.3.

Concluding, the scenario of premature demolition is undesirable, because the investment has not yet been earned back at such a short exploit time. Option 2 of the alternative designs has a relatively low yearly rent income with a high initial investment. This means that the NPV of this option is low. Due to the use of split stories, the use of option 3 could be interesting for investors with circularity ambitions. It leads to a high amount of adaptability, which means the probability of reuse is higher, which influences the environmental impact. In general, the baseline, option 1 and the existing design prove to be most interesting from a microeconomics point of view. In the case of the baseline, due to the large amount of rentable area, the yearly rent income is high and the NPV therefore too. In the case of option 1, the design of the floor plan is more material efficient, leading to a lower initial investment. The existing design results in the largest NPV, due to the low material costs of concrete. In general, from a microeconomics point of view, there is little incentive to invest in a significant increase of the BAI for a timber building. Investors need an additional motive for this investment.

4.3.2. Macroeconomic Analysis

From a macroeconomics point of view, the meaning of the BAI concerns not only one company or investor, but an entire community or country. The macroeconomic approach is a top-down approach, which means that the choices by policy makers have an influence on the entire economy. An example of this is the use of taxes and subsidies to steer the economy towards the desired product.

In this research, this same approach of steering the construction industry can be used. It is desired that investors have a motive to invest in buildings with a high BAI and a low environmental impact. As seen in Chapter 4.3.1, from a microeconomics point of view an investor will not be keen on investing in a high BAI. By giving out subsidies on buildings with a large BAI, policy makers can increase NPV of these buildings and thus create a motive to invest in adaptable buildings. With this policy, future demolition can be prevented, meaning that the environmental impact of the construction industry can be lowered. This indicates the importance of politics in shifting towards a circular economy, as discussed in Chapter 2.1.

Currently, the Dutch government rewards owners of newly constructed buildings that have an environmental impact of less than €0.50/m^2/year [81]. These investors pay less tax over their investment, leading to a lower expense flow and thus a larger NPV for these buildings. However, this calculation of the environmental impact does not yet implement adaptability of the building. Therefore, the implementation of the DfA strategy in the calculation of the environmental impact is desired, to also reward investors that construct adaptable buildings.

Concluding, by implementing the DfA strategy in the calculation of the environmental impact of a building, the Dutch government can steer building owners to invest in adaptable buildings. This will lead to more buildings with a large adaptability, meaning that future demolition is decreased, leading to less pollution and material waste.

4.3.3. Circularity Analysis

As mentioned before, several methods of analysing the circularity of a building are known. One of these methods is the calculation of the environmental impact in terms of shadow costs per rentable area per year. This method takes into account the material use of the building, for which the environmental impact is determined. In this research, this same method is used to analyse the circularity of the alternative designs. However, in this research the adaptability, implemented through the BAI, is also taken into account. This will be explained at a later point.

The environmental impact as used in this research is determined by using standard values of shadow costs for the different materials. These shadow costs apply only to the product stage of the materials, meaning that it applies to the raw material supply, transport, and manufacturing, see Figure 18. The standard values of the shadow costs, with their sources, are shown in the calculation of the shadow costs of the baseline design, shown in Appendix D.2.

From the calculation in Appendix D.2, the resulting shadow cost of the different alternative designs is shown in Table 19. Using the total shadow cost, the environmental impact can be calculated, using the rentable area and the life span of the building. However, as mentioned before, this research implements the BAI in the calculation of the environmental impact. To understand how this works, the influence of the BAI on the environmental impact is explained first.

The environmental impact is dependent on the life span of the building. A higher BAI means that a building is more adaptable and therefore more likely to have a second life span. This second life span can be used in the calculation of the environmental impact, meaning that an adaptable building will have less environmental impact. The probability of adding a second life span to a building is in this case taken equal to the value of the BAI. This means that, for the baseline with a BAI of 0.30, it is assumed that the probability of a second life span is 30%. In the case studies of Chapter 3.3 and Appendix B, it is shown that the BAI is correlated with the probability of reuse. For simplicity it is assumed that the BAI is equal to the probability of reuse. For future research, it is recommended to do a more extensive study on the correlation between the BAI and the probability of reuse.

Using the BAI as a probability of a second life span, the environmental impact is calculated. Similar to the microeconomic analysis, the environmental impact is calculated for different economic life spans. This is because it is possible that the building will become obsolete before the technical life span. It is assumed that the second economic life span will always be 50 years, which leads to the following calculation of the environmental impact:

$$Environmental\ impact = \frac{Shadow\ cost}{A \times (n + 50 \times BAI)} \tag{5}$$

Where:

A = Rentable area

n = First economic life span

Table 19: Results environmental impact.

		Existing design	Baseline	Option 1	Option 2	Option 3
	BAI	0.30	0.30	0.41	0.56	0.68
	Shadow costs	€ 412,000	€ 287,000	€ 262,000	€ 259,000	€ 295,000
Environmental impact	n = 5	€ 0.86	€ 0.55	€ 0.46	€ 0.40	€ 0.30
	n = 10	€ 0.69	€ 0.44	€ 0.39	€ 0.34	€ 0.26
	n = 20	€ 0.49	€ 0.31	€ 0.29	€ 0.27	€ 0.22
	n = 50	€ 0.27	€ 0.17	€ 0.17	€ 0.17	€ 0.14
	n = 100	€ 0.15	€ 0.10	€ 0.10	€ 0.10	€ 0.09

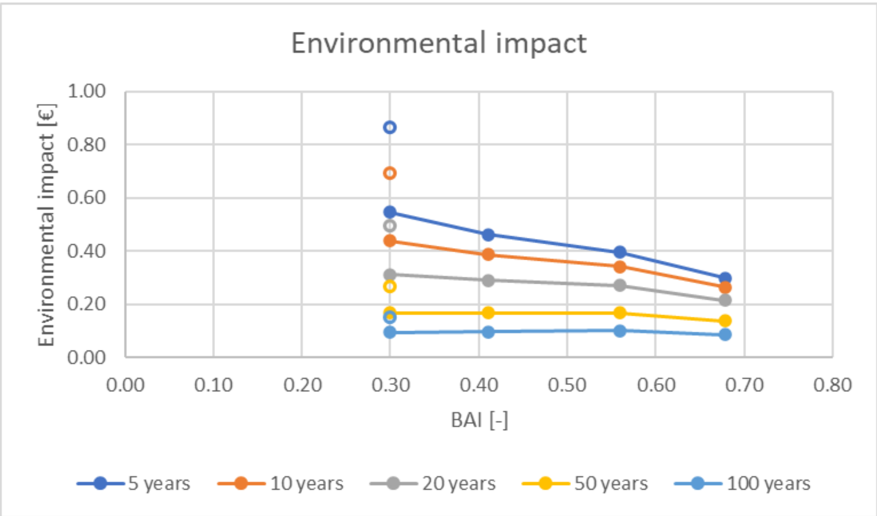


Figure 48: Influence of BAI on environmental impact through life span extension.

The resulting environmental impact is shown in Table 19 and Figure 48. It is seen that the use of timber in the alternative designs leads to a significant decrease of the shadow costs compared to the existing design. This means that investors that value the environment will have a motive to invest in one of the alternative designs, even though its microeconomic value is lower than that of the existing design. Additionally, by limiting the environmental impact to a maximum of €0.50/m^2/year, the investor will get a subsidy on their investment, as discussed before.

Comparing the alternative designs, it is seen that buildings with a higher BAI will directly lower the environmental impact due to the increased probability of a second economic life span. In case the building will fulfil its technical life span, the influence of a higher BAI is limited on the environmental impact. However, in case the building has a low economic life span, it is desirable to have a high BAI to give the building a second life span and therefore limit its environmental impact.

4.3.4. Combination Macroeconomics and Circularity

The previous analyses on what designs are interesting from a macroeconomics and circularity point of view can be combined to determine what subsidies are needed to increase the incentive to use a high BAI. This is done by comparing the environmental impact with the NPV of the designs, which are shown in Figure 49. The different points of one design represent different economic life spans of that option.

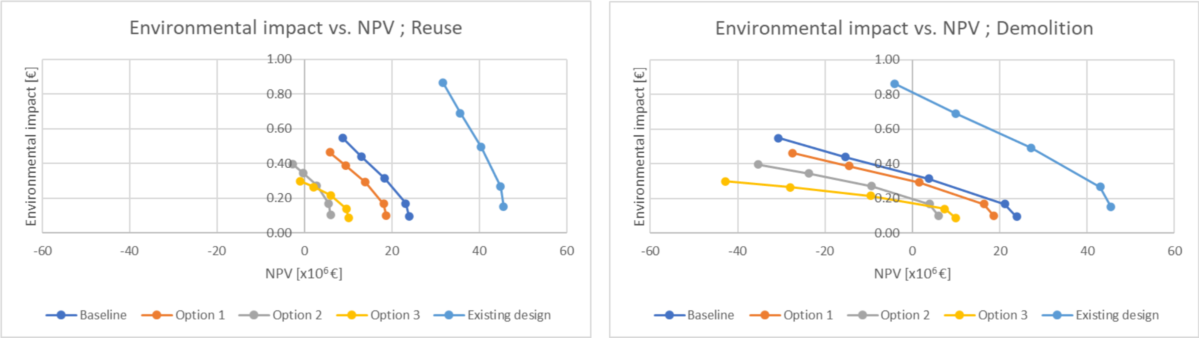


Figure 49: Relation between environmental impact and NPV of scenario Reuse and Demolition.

Figure 49 shows that in general, buildings with a low environmental impact have a low NPV. This can be explained by the fact that a large BAI will lead to a lower environmental impact, but simultaneously increases the material use as per Figure 45. The larger material use leads to a large initial investment, see Table 18, meaning that the NPV of buildings with a low environmental impact is low.

Furthermore, it is concluded that option 2 is less interesting than option 3 in all scenarios, either due to its higher environmental impact or due to its lower NPV for different economic life spans.

From Figure 49, its is concluded that there is no clear optimum for a building with a low environmental impact that has a high NPV. As mentioned before, the existing design is the most interesting from a microeconomics point of view, while option 3 is the most interesting from a circularity point of view.

To close the gap between the existing design and the alternative designs from a macroeconomics point of view, subsidies can be used to increase the NPV of the alternative designs. However, as Figure 49 shows, the gap is of such magnitude, that a subsidy of at least €20 million is needed to make option 1 more interesting than the existing design. This is equal to almost 50% of its initial investment, meaning that this magnitude of subsidy is not realistic.

It is concluded that these particular timber buildings will realistically not be more interesting than the existing design from a macroeconomics point of view. This means that, from a macroeconomics point of view, building investors that do not greatly value circularity will not invest in the alternative designs with increased adaptability. It is recommended that for further research, steel and concrete buildings with a high BAI are investigated on their environmental impact and NPV. This could be used to get a clear overview on what is needed from policy makers to increase the incentive to use a high BAI, which will prevent future demolition.

4.4. Conclusion

In this chapter, the material use of several alternative designs to an existing design is investigated, after which the economic and circular meaning of the BAI is studied.

Due to the low adaptability -a BAI of 0.30- of the existing design, alternative designs are proposed to investigate the feasibility of an adaptive high-rise building. Four alternative designs are proposed, with increasing BAI's. The alternative designs are timber structures with a concrete core, because the use of timber reduces the environmental impact of the building. Comparing the alternative designs to each other, it is seen that the BAI can be increased with 126% with an investment to the material use of 38% and almost losing no rentable area, as is the case for option 3. Additionally, by sacrificing little rentable area and investing in little extra material use, an increase of the BAI with 37% can be achieved, as is the case in option 1.

By analysing the micro- and macroeconomic meaning of the BAI, it is concluded that purely in terms of monetary value the alternative designs cannot compare to the existing design. This is due to the relatively expensive timber in the alternative designs. It is also seen that premature demolition of a high-rise building leads to a low NPV, meaning that the investor will have less profit. Purely from a microeconomic point of view, the investment in a larger BAI cannot be justified, because the large initial investment takes longer to earn back. However, from a macroeconomics point of view, the subsidy by the Dutch government upon limiting the environmental impact could provide the investor a motive to invest in buildings with a higher BAI. For this reason, it is important that the adaptability of a building should become part of the official method of calculating the environmental impact. Investors need the extra nudge to invest in adaptable high-rise buildings, which will prevent future demolition.

From a circularity point of view, the existing design has a significantly large environmental impact and is therefore not interesting. The implementation of the BAI in the calculation of the environmental impact through the addition of a second life span shows that buildings with a high BAI are interesting from a circularity point of view, because the second life span decreases the environmental impact.

Investigating the relation between environmental impact and NPV, it is concluded that buildings with a low environmental impact will generally have a low NPV. It is found that the subsidy that is needed to make the alternative designs more interesting than the existing design, from a macroeconomics point of view, is almost 50% of the initial investment. This means that it is not realistic that building owners will invest in a large BAI from a macroeconomics point of view for these particular timber buildings.

5. Conclusions and Recommendations

5.1. Conclusions

In this research, a Building Adaptability Indicator (BAI) is created to encourage structural designers and building owners to realise adaptable high-rise buildings. The BAI is created by performing indicator studies on how to achieve adaptability in a high-rise structure, after which the economic and environmental meaning of the BAI is investigated through several alternative designs to the existing design of a high-rise building.

In the literature review, it is shown that circularity in civil engineering consists of three main strategies: Design for Disassembly, Design for Adaptability, and Minimum Embodied Carbon. Currently, there are many high-rise buildings that are prematurely demolished. The main reason for these demolition cases is the desire of realising a new building, with improved technologies and perhaps a different building function. A building that is adaptable to these improved technologies or different functions could prevent future demolition. Additionally, to implement circularity in high-rise, it is desired to measure the amount of circularity. Previous research focussed on measuring circularity only at the material level or with the Design for Disassembly strategy for example. It is concluded that there is no circularity measurement tool that focusses on the Design for Adaptability strategy on the scale of an entire building. Therefore, the Building Adaptability Indicator is created. This will help structural designers to quantify adaptability, which will help in encouraging building owners to invest in an adaptable building. This will prevent future demolition, which means that the environmental impact of the building is lowered.

This answers the main research question of this research, because it is concluded that the structural design process of a circular high-rise building is one that implements the Design for Adaptability strategy. To increase the incentive of implementing this strategy, a measurement tool for adaptability at the building level is created.

By performing indicator studies on how to reach adaptability in a high-rise building, together with conducting interviews with structural designers and circularity experts, it is concluded that the adaptability of the structure of a high-rise building is governed by three *sub-indicators*: openness, reserved capacity, and floor-to-floor height. For these sub-indicators, it is investigated which value will lead to a high adaptability. This results in the Module Adaptability Indicators (MAI), which indicate the adaptability of a module of a building. The value of the MAI depends on the number of building functions that fit in the module, which are weighted by their property value and the total area of that function in the Netherlands. The MAI's are combined by using weighting factors for the sub-indicators, which are determined from the interviews, to create the BAI.

By performing case studies from literature and on example projects from ABT, it is concluded that buildings with a low BAI will certainly be demolished in the future. Buildings with a high BAI are more likely to be reused, but can still face demolition if there is no motive to reuse. This means that building owners should be encouraged to reuse their buildings, for example by policy makers. The least thing that structural designers can do is to implement some form of adaptability in their designs.

This research implements the BAI by performing an analysis on an existing design with four alternative design options. This analysis includes the consequence to the economic and environmental impact of the material use of high-rise buildings. It is shown that the existing design is not adaptable and thus not circular. Alternative designs are proposed, by using timber as a construction material due to its low environmental impact. Furthermore, the choice of the stability system is made in such a way, that adaptability is only governed by the sub-indicators of the BAI. It is concluded that for the alternative designs, it is possible to increase the BAI with 126% by investigating a maximum of 60% extra to the structural element dimensions, resulting in an increase of 38% to the total material volume.

From a microeconomics point of view, it is shown that in terms of monetary value, there is no reason to significantly increase the BAI of a building. The increased initial investment and the lower rent income due to a lower amount of stories means that the Net Present Value (NPV) of adaptable buildings is relatively low. However, from a macroeconomics point of view, it is possible that building owners will be encouraged to invest in circular buildings through a subsidy on their investment. Currently, the Dutch government provides a discount on the investment tax for owners of buildings with a low environmental impact. Therefore, it is vital that the adaptability of a building becomes part of the official calculation of the environmental impact, so that investors will have a motive from a macroeconomics point of view to invest in buildings with a high BAI.

From a circularity point of view, it is concluded that the existing design cannot compete with the alternative designs due to the high amount of concrete elements, which have a high environmental impact. It is shown that implementing the BAI in the calculation of the environmental impact through the probability of a second life span decreases the environmental impact of adaptable buildings, meaning that buildings with a high BAI are interesting from a circularity point of view.

At the moment, only investors with great circularity ambitions will invest in buildings with a high BAI. Policy makers can encourage the investors that do not value these circularity ambitions to invest in adaptable buildings as well. This can be done by implementing adaptability in the calculation of the environmental impact, resulting in subsidies for owners of buildings with a high BAI. The required magnitude of the subsidy is of such magnitude that it is not realistic to convince all building investors to invest in timber buildings with a high BAI. Other construction materials should be investigated, as this could shift the construction industry more towards adaptable buildings, which will prevent demolition and lead to a lower environmental impact across the industry.

5.2. Recommendations

Firstly, the measurement tool for adaptability that is created in this research focusses on the structural aspects of building adaptability. However, as is mentioned in the interviews, there are many other factors that influence the choice of demolition or reuse. Therefore, it is recommended to expand the BAI towards more sub-indicators. Possible directions are fire safety, installations, or façades.

Secondly, in the study on the circular meaning of the BAI, the BAI is implemented in the calculation of the environmental impact. The method of this implementation should be investigated more carefully. It is assumed that the probability of a second life span of a building is equal to the BAI. However, it is recommended that a study is performed on the probability of reuse through an extensive data analysis of buildings in practice. This will lead to an accurate prediction of the probability of reuse. This will in turn mean that the BAI can be converted to a probability, after which adaptability can be implemented in the calculation of the environmental impact. This is an important extension of this research, because it could potentially yield subsidies for investors of adaptable buildings, which will prevent future demolition.

5.3. Limitations

Several limitations of this research have been identified. Because the BAI is at its early stage of development, many limitations of the tool have been identified. The author hopes that the development of the BAI is continued, starting by tackling the following limitations:

1. The weighting factors of the MAI's are determined by assigning an estimated factor of 0.8 for the property value factor *a* and 0.2 for the area factor *b*. The basis on which these factors are assigned is to limit the influence of one single building function, namely the residential function. A more extensive study on how to score these weighting factors should be performed.
2. The weighting factors of combining the MAI's into the BAI are estimated by the author based on the interviews with structural designers. By performing the case studies on reused and demolished buildings, the validation of these weighing factors is reinforced. However, because these weighting factors are essential in the creation of the BAI, a more extensive study on how to weigh the MAI's should be performed by expanding the number of case studies and fitting the weighting factors to the results.
3. The structural calculation in this research focusses on the skeleton and foundation of the high-rise structure. However, the inclusion of dynamics, fire safety, and connection details would give a more complete overview of the material use.
4. Only four alternative design configurations have been investigated in this research. This means that there could be designs that have a higher NPV or a lower environmental impact without knowing it. It is recommended that a parametric study is performed on adaptable buildings and investigate their material use, economic value, and circularity value.

5. The analysis on the economic and circular meaning of the BAI focussed on alternative designs which mainly use timber as a construction material. More construction materials such as concrete and steel should be investigated to investigate whether the subsidy on these buildings will shift the industry towards buildings with high a BAI.
6. The calculation of the NPV and the environmental impact are limited to estimations of material cost and shadow prices. For a clearer overview of which designs are interesting, these analyses should be expanded towards a more detailed calculation.

Bibliography

1. Abspoel, R. (2013). *Reader CIE4281 - Building Structures 2: Steel part*. Delft University of Technology.

2. ABT. (2020). *Sustainable Structural Engineering [Presentation]*.

3. Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017). Circular economy in construction: current awareness, challenges and enablers. *Proceedings of the Institution of Civil Engineers - Waste and Resource Management, 170*(1), 15-24. https://doi.org/10.1680/jwarm.16.00011

4. Alba Concepts. (2019). *Een meetmethode voor losmaakbaarheid [An assessment method for disassemblability]*.

5. Ali, M., & Al-Kodmany, K. (2012, 09/01). Tall Buildings and Urban Habitat of the 21st Century: A Global Perspective. *Buildings, 2*. https://doi.org/10.3390/buildings2040384

6. Ali, M. M., & Moon, K. S. (2007, 2007/09/01). Structural Developments in Tall Buildings: Current Trends and Future Prospects. *Architectural Science Review, 50*(3), 205-223. https://doi.org/10.3763/asre.2007.5027

7. Anastasiades, K., Blom, J., Buyle, M., & Audenaert, A. (2020, 2020/01/01/). Translating the circular economy to bridge construction: Lessons learnt from a critical literature review. *Renewable and Sustainable Energy Reviews, 117*, 109522. https://doi.org/https://doi.org/10.1016/j.rser.2019.109522

8. Andjelic, M., Moons, M., & Wiltjer, R. (2018). Amstel Tower siert skyline Amsterdam ['Amster Tower adorns skyline Amsterdam']. *Cement,*. https://www.cementonline.nl/amsteltoren

9. Arcadis. (2020). *Vormfactoren & kostenkengetallen Nederlandse Assets 2019/2020 ['Shape factors & Cost indicators Dutch assets 2019/2020']*. https://www.arcadis.com/nl/nederland/wat-we-doen/onze-capabilities/consultancy/kostenbeheer/planning-van-levenscycluskosten/

10. Baldwin, E. (2019). Precht Designs Timber Skyscrapers with Modular Homes and Vertical Farming. Retrieved 10-12-2020, from https://www.archdaily.com/912058/precht-designs-timber-skyscrapers-with-modular-homes-and-vertical-farming%3E

11. BallastNedam. The CoolTower. Retrieved 04-02-2021, from https://www.ballast-nedam.nl/projecten/the-cooltower/

12. Bertin, I., Lebrun, F., Braham, N., & Le Roy, R. (2019, 2019/09/06). Construction, deconstruction, reuse of the structural elements: the circular economy to reach zero carbon. *IOP Conference Series: Earth and Environmental Science, 323*, 012020. https://doi.org/10.1088/1755-1315/323/1/012020

13. Bitovi. (2020). *Intro to Modular Design*. Retrieved 09-12-2020 from http://styleguidedrivendevelopment.net/course/modular-design/?course_type=content&course_page=1&lecture=1

14. Böhm, M., & Zwaan, W. (2018). *Betondag 2018: Bolted Connections - Design for Disassembly [Concrete day 2018: Bolted Connections - Design for Disassembly]*. Peikko.

15. Brand, S. (1995). *How buildings learn: What happens after they're built*. Penguin.

16. Brundtland, G. H., & Khalid, M. (1987). Our Common Future: Report of the World Commission on Environment and Development. *United Nations, Brundtland commission*.

17. Casadata. *Construction costs ; Driven steel tube piles*. Retrieved 20-07-2021 from https://www.casadata.nl/details/bouwkosten/bouwkosten-bouwdelen/funderingspalen-damwanden/funderingspalen/920?a=1

18. CBRE, & Cushman & Wakefield. (2021). *Mondriaan Tower*. Retrieved 04-02-2021 from https://www.mondriaan-tower.nl/

19. Centraal Bureau voor de Statistiek (CBS) [Statistics Netherlands]. (2019). Bevolkingsgroei in 2018 vooral in de Randstad [Population growth in 2018 mainly in the Randstad]. Retrieved 24-11-2020, from https://www.cbs.nl/nl-nl/nieuws/2019/01/bevolkingsgroei-in-2018-vooral-in-de-randstad

20. Central Bureau of Statistics. (2021). *Housing stock ; mean area ; housing type, year of construction, region*. https://opendata.cbs.nl/statline/#/CBS/nl/dataset/82550NED/table?ts=1626082070824

21. Coenders, J. (2018). Parametrisch ontwerp? Wat is dat? [Parametric design? What is that?]. (6), 4-9. Retrieved 11-12-2020, from https://www.cementonline.nl/parametrisch-ontwerp-wat-is-dat

22. Coenen, T. B. J. (2019). Circular bridges and viaducts: development of a circularity assessment framework, University of Twente, Faculty of Engineering Technology, Enschede. The Netherlands.

23. CTBUH. (2018). World's Tallest Demolished Buildings. *CTBUH Journal*(II).

24. CTBUH. (2019). *Tall Buildings in 2019: Another Record Year for Supertall Completions*. Retrieved 01-02-2021 from https://www.skyscrapercenter.com/year-in-review/2019

25. CTBUH. (2020). *Compare data*. Retrieved 07-12-2020 from https://www.skyscrapercenter.com/compare-data

26. CTBUH. (2020). Tall + Urban Innovation 2020: Dominant Trends. *CTBUH Journal*(II).

27. De Benchmark Gemeentelijk Vastgoed ["The Benchmark Municipal Real Estate"]. (2020). *Kengetallen gemeentelijk vastgoed 2020 ["Key Figures Municipal Real Estate 2020"]*. Retrieved 19-05-2021 from https://www.republiq.nl/update/kengetallen-gemeentelijk-vastgoed-2020

28. Eberhardt, L. C. M., Birkved, M., & Birgisdottir, H. (2020). Building design and construction strategies for a circular economy. *Architectural Engineering and Design Management*, 1-21. https://doi.org/10.1080/17452007.2020.1781588

29. Ellen MacArthur Foundation. (2017). Circular Economy System Diagram. https://www.ellenmacarthurfoundation.org/circular-economy/concept/infographic

30. Ellen MacArthur Foundation. (2017). What is the circular economy? Retrieved 30-11-2020, from https://www.ellenmacarthurfoundation.org/circular-economy/what-is-the-circular-economy

31. Ellen MacArthur Foundation, & ANSYS Granta. (2019). *Circularity Indicators: An approach to Measuring Circularity*. https://www.ellenmacarthurfoundation.org/resources/apply/material-circularity-indicator

32. Emporis. (2021). *Netherlands's tallest buildings - Top 20* Retrieved 04-01-2021 from https://www.emporis.com/statistics/tallest-buildings/country/100118/netherlands

33. Erasmus MC. (2020). *Sloop oude gebouwen: Ruimte voor nieuwe ontwikkelingen [Demolition Old Buildings: Space for New Developments]*.

34. Everts, B. (2019). *Foundations and Pits: Lecture slides CIE4281*. Delft University of Technology, Department of Geo-Engineering.

35. eVolo Magazine. (2019). Imagine the Future of the Skyscraper: 2020 Skyscraper Competition Call for Entries is Here. Retrieved 11-02-2021, from https://archinect.com/news/article/150169212/imagine-the-future-of-the-skyscraper-2020-skyscraper-competition-call-for-entries-is-here

36. Fivet, C., & Brütting, J. (2020). Nothing is lost, nothing is created, everything is reused: structural design for a circular economy. *Structural Engineer, 98*(1), 74-81.

37. Gan, V. J. L., Chan, C. M., Tse, K. T., Lo, I. M. C., & Cheng, J. C. P. (2017, 2017/09/10/). A comparative analysis of embodied carbon in high-rise buildings regarding different design parameters. *Journal of Cleaner Production, 161*, 663-675. https://doi.org/https://doi.org/10.1016/j.jclepro.2017.05.156

38. Gan, V. J. L., Cheng, J. C. P., Lo, I. M. C., & Chan, C. M. (2017, 2017/01/10/). Developing a CO2-e accounting method for quantification and analysis of embodied carbon in high-rise buildings. *Journal of Cleaner Production, 141*, 825-836. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.09.126

39. Gan, V. J. L., Lo, I. M. C., Ma, J., Tse, K. T., Cheng, J. C. P., & Chan, C. M. (2020, 2020/05/01/). Simulation optimisation towards energy efficient green buildings: Current status and future trends. *Journal of Cleaner Production, 254*, 120012. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.120012

40. Geldermans, R. J. (2016, 2016/09/01/). Design for Change and Circularity – Accommodating Circular Material & Product Flows in Construction. *Energy Procedia, 96*, 301-311. https://doi.org/https://doi.org/10.1016/j.egypro.2016.09.153

41. Generalova, E., & Generalov, V. (2020, 2020/03/07). Mixed-Use High-Rise Buildings: a Typology of the Future. *IOP Conference Series: Materials Science and Engineering, 753*, 022062. https://doi.org/10.1088/1757-899x/753/2/022062

42. Ghisellini, P., Ji, X., Liu, G., & Ulgiati, S. (2018, 2018/09/10/). Evaluating the transition towards cleaner production in the construction and demolition sector of China: A review. *Journal of*

Cleaner Production, 195, 418-434. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.05.084

43. Ham, P. H., & Terwel, K. C. (2017). *Structural calculations of High Rise Structures*.

44. Havel, G. (2014). Construction Concerns: Hollow Core Precast Concrete Plank. Retrieved 11-02-2021, from https://www.fireengineering.com/fire-prevention-protection/hollow-core-precast-concrete-plank/

45. Heeren, N., & Hellweg, S. (2019). Tracking Construction Material over Space and Time: Prospective and Geo-referenced Modeling of Building Stocks and Construction Material Flows. *Journal of Industrial Ecology, 23*(1), 253-267. https://doi.org/https://doi.org/10.1111/jiec.12739

46. Henry, D., & Lash, H. (2020). JPMorgan sticks with plan to build giant New York headquarters. Retrieved 29-11-2020, from https://www.reuters.com/article/us-jpmorgan-results-realestate/jpmorgan-sticks-with-plan-to-build-giant-new-york-headquarters-idUKKBN26Y2HP

47. Hermans, M. H., Geraedts, R. P., Van Rijn, E., & Remoy, H. T. (2014). *Buildings with future value! The determination of the future value of buildings from the perspective of adaptivity, financial efficiency, and sustainability: Final Report*. D. U. o. Technology. http://resolver.tudelft.nl/uuid:f0555f9d-f2a1-45ad-9fc3-99536caa4fba

48. Herr, C. M. (2017). Student designs for Shanghai's high-rise future. Retrieved 11-02-2021, from https://www.xjtlu.edu.cn/en/news/2017/11/student-designs-for-shanghais-high-rise-future

49. Hoenderkamp, J. C. D. (2008). Second outrigger at optimum location on high-rise shear wall. *The Structural Design of Tall and Special Buildings, 17*(3), 619-634. https://doi.org/https://doi.org/10.1002/tal.369

50. Hossain, M. U., & Ng, S. T. (2018, 2018/12/20/). Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: An analytical review. *Journal of Cleaner Production, 205*, 763-780. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.09.120

51. Hossain, M. U., Ng, S. T., Antwi-Afari, P., & Amor, B. (2020, 2020/09/01/). Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction. *Renewable and Sustainable Energy Reviews, 130*, 109948. https://doi.org/https://doi.org/10.1016/j.rser.2020.109948

52. Jonkers, H. M. (2019). *Reader CIE4100 - Materials and Ecological Engineering*.

53. Kasarda, M. E., Terpenny, J. P., Inman, D., Precoda, K. R., Jelesko, J., Sahin, A., & Park, J. (2007, 2007/12/01/). Design for adaptability (DFAD)—a new concept for achieving sustainable design. *Robotics and Computer-Integrated Manufacturing, 23*(6), 727-734. https://doi.org/https://doi.org/10.1016/j.rcim.2007.02.004

54. Kelly, J. (2012). How do you demolish a skyscraper? Retrieved 29-11-2020, from https://www.bbc.com/news/magazine-20535821

55. Khan, F. R. (1967). Current trends in concrete high-rise buildings. In *Tall Buildings* (pp. 571-590). Elsevier.

56. Kirchherr, J., Reike, D., & Hekkert, M. (2017, 2017/12/01/). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling, 127*, 221-232. https://doi.org/https://doi.org/10.1016/j.resconrec.2017.09.005

57. KPF. (2021). *Hudson Commons 441 Ninth Avenue*. Retrieved 17-05-2021 from https://www.kpf.com/projects/hudson-commons

58. Kroessler, J. A. (2018). Losing Its Way: the Landmarks Preservation Commission in Eclipse. https://academicworks.cuny.edu/jj_pubs/245/

59. Lankhorst, G. (2018). Sustainable structural design of high-rise: Life-cycle assessment of main load bearing structures of high-rise buildings in the Netherlands. http://resolver.tudelft.nl/uuid:bd8090bf-47ff-45be-88cc-2168ac4609b5

60. Leiden, U. o. (2020). *Duurzame sloop hoogbouw faculteit Wiskunde en Natuurwetenschappen [Sustainable Demolition High-Rise Faculty of Science]*. Retrieved 16-12-2020 from https://www.universiteitleiden.nl/dossiers/bouwprojecten/duurzame-sloop-oude-laboratoria

61. Lever Architecture. (2017). *Resilient rocking wall design*. Retrieved 30-06-2021 from https://leverarchitecture.com/research/clt_wall_panel_structural_testing

62. Matsuda, A. (2021). JPMorgan Chase will embrace "flexible" design for 270 Park HQ. Retrieved 17-05-2021, from https://therealdeal.com/2021/04/19/jpmorgan-chase-will-embrace-flexible-design-for-270-park-hq/

63. McCall, V., & Mooney, G. (2018, //). The Repoliticization of High-Rise Social Housing in the UK and the Classed Politics of Demolition. *Built Environment, 43*(4), 637-652. https://doi.org/10.2148/benv.43.4.637

64. McFarland, D. E., Ross, B. E., & Albright, D. (2021). Quantifying Adaptability of College Campus Buildings. In *Sustainability in Energy and Buildings 2020* (pp. 75-87). Springer. https://doi.org/https://doi.org/10.1007/978-981-15-8783-2_6

65. Metsä Wood. (2015). *Environmental product declaration Kerto LVL*.

66. Metsä Wood. (2016). *Kerto Ripa: Technische Richtlijnen ['Kerto Ripa: Technical Guidlines']*. https://docplayer.nl/60911911-Kerto-ripa-technische-richtlijnen-metsa-wood.html

67. Metsä Wood. (2021). *Kerto LVL mechanical properties*. https://www.metsawood.com/global/Tools/kerto-manual/Pages/Kerto-manual.aspx#

68. Metsä Wood. (2021). *Kerto Ripa roof- and floor elements* [Email].

69. Ministerie van Binnenlandse Zaken en Koninkrijksrelaties ['Ministery of the Interior and Kingdom Relations']. (2012). *Bouwbesluit 2012*. https://rijksoverheid.bouwbesluit.com/Inhoud/docs/wet/bb2012

70. Modder, J. (2016). Nederlands perspectief op hoogbouw [Dutch perspective on high-rise buildings]. Retrieved 24-11-2020, from https://www.cementonline.nl/artikel/nederlands-perspectief-op-hoogbouw

71. Mondeel, F. E. (2011). Overdrachtsconstructies: 'een ontwerptool voor wanneer de hoofddraagconstructie niet rechtdoor kan' ['Transition structures: 'a design tool for when the main structure is not straightforward']. *Eindhoven University of Technology,*.

72. Municipality of Amsterdam. (2019). *The determination of value of land for new leaseholds 2019*. https://www.amsterdam.nl/wonen-leefomgeving/erfpacht/nieuw-beleid/archief-grondprijzen/

73. National Geographic. (2019). *Cities of the Future*. Retrieved 01-02-2021 from https://www.nationalgeographic.com/magazine/2019/04/see-sustainable-future-city-designed-for-people-and-nature/

74. Nationale Milieu Database (NMD) ['National Environment Database']. (2021). *Environmental information from products in the National Environment Database*. Retrieved 21-07-2021 from https://viewer.milieudatabase.nl/

75. NEN. (1998). *NEN5080: Personenliften in woongebouwen - Afmetingen en functionele eisen ['NEN5080: Passenger elevators in residential buildings - Dimensions and functional requirements']*.

76. NEN. (2011). *EN 1991-1-4+A1+C2 - Eurocode 1: Actions on Structures - Part 1-4: General Actions - Wind Actions*.

77. NEN. (2012). *EN 1993-1-9+C2: Eurocode 3: Design of steel structures - Part 1-9: Fatigue*

78. NEN. (2019). *EN1990+A1+A1/C2: Eurocode: Basis of structural design*.

79. NEN. (2019). *EN 1991-1-1+C1+C11 - Eurocode 1: Actions on structures – Part 1-1: General actions – Densities, self-weight, imposed loads for buildings*

80. NEN. (2019). *EN 15804+A2: Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products*

81. Netherlands Enterprise Agency. (2021). *Brochure and Environment list 2021*. https://www.rvo.nl/subsidie-en-financieringswijzer/miavamil/ondernemers/publicaties-miavamil

82. Niessink, R. J. M., Menkveld, M., & Sipma, J. M. (2017). *Verkenning Utiliteitsbouw ['Exploration Utility buildings']*. https://publicaties.ecn.nl/ECN-E--17-059

83. NLTimes. (2019). Number of 100-meter plus high rise apartment buildings to double by 2025. Retrieved 12-01-2021, from https://nltimes.nl/2019/09/18/number-100-meter-plus-high-rise-apartment-buildings-double-2025

84. P. de Vroe. (2019). *Net Present Value (NPV) explained* [Video]. https://www.youtube.com/watch?v=N-lN5xORIwc

85. Palau Hernandez, J. P. (2020). Environmental Impact of the Structural System of High-Rise Buildings in the Netherlands: A research of the influence of the structural systems of high-rise buildings on their environmental impact, by means of Life-Cycle Assessment. http://resolver.tudelft.nl/uuid:5975c2eb-8333-43a5-b80c-040ac4c52a03

86. Pararius. (2021). Rent decreasing again in free sector. Retrieved 20-07-2021, from https://www.pararius.nl/nieuws/opnieuw-dalende-huurprijzen-in-vrije-sector

87. Pasterkamp, S. (2016). *Concrete Building Structures: Reader CIE4281*.

88. Pavarini McGovern. (2019). *Pavarini McGovern Presents: Hudson Commons [Video]*. Youtube. https://www.youtube.com/watch?v=y3tVrUOyXHw

89. Platform CB'23. (2020). *Leidraad Meten van circulariteit: Werkafspraken voor een circulaire bouw - Versie 2.0 [Guidline Measurement of Circularity: Agreements for circular construction - Version 2.0]*.

90. Pomponi, F., & Moncaster, A. (2017, 2017/02/01/). Circular economy for the built environment: A research framework. *Journal of Cleaner Production, 143*, 710-718. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.12.055

91. Potters, C. (2021). Microeconomics vs. Macroeconomics: What's the Difference? Retrieved 19-07-2021, from https://www.investopedia.com/ask/answers/difference-between-microeconomics-and-macroeconomics/

92. Potting, J., M. P., H., E, W., & Hanemaaijer, A. (2017). *Circular Economy: Measuring Innovation in the Product Chain*. Planbureau voor de Leefomgeving (PBL). https://dspace.library.uu.nl/handle/1874/358310

93. Precht. (2019). *The Farmhouse*. Retrieved 16-12-2020 from https://www.precht.at/the-farmhouse/

94. Reid, R. L. (2020). Skinny 'Scrapers. Retrieved 04-02-2021, from https://www.asce.org/cemagazine/skinny-scrapers/

95. Rios, F. C., Chong, W. K., & Grau, D. (2015, 2015/01/01/). Design for Disassembly and Deconstruction - Challenges and Opportunities. *Procedia Engineering, 118*, 1296-1304. https://doi.org/https://doi.org/10.1016/j.proeng.2015.08.485

96. Risen, C. (2015). How to Heat and Cool a Supertall. *Architect Magazine*. https://www.architectmagazine.com/technology/how-to-heat-and-cool-a-supertall_o

97. Robinson, M. (2016). Vertical cities could be the future of architecture. Retrieved 01-02-2021, from https://www.businessinsider.com/vertical-cities-future-of-architecture-2016-4?international=true&r=US&IR=T

98. Rockow, Z. R. (2020). Qualitative & Quantitative Analyses of Existing Buildings' Adaptability. https://tigerprints.clemson.edu/all_dissertations/2670

99. Sanghvi, A. (2020). *The high-rise in 2030* [Interview]. https://www.mckinsey.com/business-functions/operations/our-insights/the-high-rise-in-2030

100. Sarkisian, M. (2016). *Designing Tall Buildings: Structure as Architecture* (2nd ed.). Routledge.

101. Sauvé, S., Bernard, S., & Sloan, P. (2016, 2016/01/01/). Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research.

Environmental Development, 17, 48-56. https://doi.org/https://doi.org/10.1016/j.envdev.2015.09.002

102. Scheublin, F. (2008). *Tall Buildings in the Netherlands: Constraints to Innovation*

103. Schueller, W. (1990). *The Vertical Building Structure*. Van Nostrand Reinhold.

104. Silverstein, S. A. (2009). Applying "Design for Disassembly" to connection design in steel structures. *Massachusetts Institute of Technology, Department of Civil and Environmental Engineering*. http://hdl.handle.net/1721.1/53071

105. Slooten, E. (2018). Feasibility study of a wood-concrete hybrid super tall building and optimization of its wind-induced behaviour: A case study on a skyscraper in the city-centre of Rotterdam. http://resolver.tudelft.nl/uuid:01da1849-6478-46c9-8a59-e6c7c2e4fb47

106. Soh, S. L., Ong, S. K., & Nee, A. Y. C. (2014, 2014/01/01/). Design for Disassembly for Remanufacturing: Methodology and Technology. *Procedia CIRP, 15*, 407-412. https://doi.org/https://doi.org/10.1016/j.procir.2014.06.053

107. Sonego, M., Echeveste, M. E. S., & Galvan Debarba, H. (2018, 2018/03/01/). The role of modularity in sustainable design: A systematic review. *Journal of Cleaner Production, 176*, 196-209. https://doi.org/https://doi.org/10.1016/j.jclepro.2017.12.106

108. Steficek, G., & Vancura, P. (2015). Reinventing Woolworth: Adaptive Reuse of a Historic Skyscraper. *CTBUH Journal*(IV).

109. Stirane, A. (2020). Tall Building Solutions. *Peikko*.

110. Strelitz, Z. (2011, 2011/10/01). Tall building design and sustainable urbanism: London as a crucible. *Intelligent Buildings International, 3*(4), 250-268. https://doi.org/10.1080/17508975.2011.606362

111. Ter Haar, R. (2012). *Het bepalen van een gewenste liftinzet ['Determination of a desired elevator capacity']* Eindhoven University of Technology]. Zenderen.

112. Teunizen, J. (2020). *Building Circularity Index*. Alba Concepts. Retrieved 12-12-2020 from https://albaconcepts.nl/building-circularity-index/#slide-4-informatie

113. The Ministry of Infrastructure and the Environment, & The Ministry of Economic Affairs. (2016). *A Circular Economy in the Netherlands by 2050: Government-wide Programme for a Circular Economy*. www.government.nl/circular-economy

114. Treels, R. (2019). Berekeningsmethoden dynamische responsies hoogbouw ['Calculation methods dynamic responses high-rise']. *Cement,, 6*. https://www.cementonline.nl/berekeningsmethoden-dynamische-responsies-hoogbouw

115. Turner, K. HINES: A ground-breaking vision for the high-rise of the future. Retrieved 01-02-2021, from https://www.discoverfranceandspain.com/hines/

116. United Nations Environment Programme (UNEP). (2019). *2019 Global Status Report for Buildings and Construction: Towards a zero-emissions, efficient and resilient buildings and*

construction sector. https://www.unenvironment.org/resources/publication/2019-global-status-report-buildings-and-construction-sector

117. Van Leeuwen, D., & Verwoerd, F. (2020). *De Nederlandse Kantorenmarkt [The Dutch Office Market]*. Colliers International.

118. Veljkovic, M. (2016). *Sustainable Steel Buildings: A Practical Guide for Structures and Envelopes*. John Wiley & Sons.

119. Veljkovic, M. (2020). *CIE5126, Introduction to Fatigue of Steel Structures*. S. a. C. S. Delft University of Technology.

120. Verberne, J. J. H. (2016). Building circularity indicators: an approach for measuring circularity of a building. https://research.tue.nl/en/studentTheses/building-circularity-indicators

121. Vermond, M. (2015). The influence of the structural possibilities on the transition point between demolition and transformation of multi-story concrete office building structures. http://resolver.tudelft.nl/uuid:d328ba02-6e62-4cbb-b2dc-fdadf2754832

122. W/E. (2013). *Richtsnoer 'Specifieke gebouwlevensduur' [Guideline 'Specific building life cycle']*.

123. Webster, M. D., & Costello, D. T. (2005). *Designing Structural Systems for Deconstruction: How to Extend a New Building's Useful Life and Prevent it from Going to Waste When the End Finally Comes* Greenbuild Conference, Atlanta, GA.

124. Williams, A. (2015). Cloud Corridor: High-rise vision for the future of housing in LA. Retrieved 11-02-2021, from https://newatlas.com/future-of-la-housing-cloud-corridor-mad-architects/39292/

125. Wit, J. (2007). Belifting van hoogbouw ['Elevators in high-rise']. *TVVL Magazine, 6*. https://tvvlconnect.nl/thema/gezonde-gebouwen/documenten/1536-belifting-van-hoogbouw

126. WSP. (2018). *Hudson Commons: Innovation at its core*. Retrieved 17-05-2021 from https://www.wsp.com/en-SE/insights/hudson-commons-features-innovation-at-its-core

Appendix A: Interviews Demolition – Reuse

A.1. Summary Interviews

The interviewees have different backgrounds, from structural engineers to architects and circularity experts. These interviewees work at ABT and the Dutch Government Real Estate Company. It should be noted that in some interviews, not all questions have been answered.

From Question 2 and 3, it is concluded that the choice for reuse or demolition is dependent on the factors as they are found in literature: costs, technical quality, adaptability, updated laws, circularity goals, and historic value. From the discussion of example projects in Question 4, it becomes clear that the main factor that influences the choice for demolition or reuse is the costs. This is emphasized by several interviewees. A factor that has a large influence on the cost of reuse is the adaptability of the building. Interviewees mention from Question 5 that the use of a high adaptability is not capable of completely eliminating all demolition, but it can certainly decrease the probability of demolition. It followed from Question 6 that there is no clear governing parameter that influences the choice on demolition or reuse, but it is evident that the identified parameters from the BAI, namely openness, floor-to-floor height, and load capacity, play a large role. In Question 7, it is discussed how these parameters can be ranked in terms of influence on the choice for demolition or reuse, which is further elaborated below.

There were some deviations in the answers from the interviewees on a ranking of the adaptability factors of the BAI. Generally, it is agreed that the load capacity has the lowest impact of the three, because it can be increased by for example retrofitting. It is however mentioned that the increase of the load capacity is an expensive measure. The openness and the floor-to-floor height greatly influence the choice of demolition or reuse according to the interviewees, because once a certain grid lay-out or floor-to-floor height is chosen, it generally cannot be changed. However, one of the interviewees explains that it is possible to remove a part of a wall, to increase the openness in a building. Therefore, the influence of the openness on the choice of demolition or reuse is slightly lower than the influence of the floor-to-floor height. With these results, the author has estimated the weighting factors to determine the BAI, see Table 8. During feedback sessions, the opinion of the interviewees on these weighting factors is taken into account, to adjust the values.

A.2. Interview Questions

1. **What is your profession, can you explain what this entails?**

2. **What are motives for demolition of a building?**

3. **What are motives for reuse of a building?**

4. **I have listed several factors that influence the choice for demolition or reuse. Choose several factors to elaborate, based on personal experience or examples.**
   a. *Costs*

   b. *Technical quality*

   c. *Adaptability (structure / façade / fire safety / installations)*

   d. *Updated laws / Different sense of safety*

   e. *Circularity goals*

   f. *Historic value*

5. **Can an adaptive building have less motives for demolition or perhaps none?**

6. **Which parameters of adaptability are governing in the choice for demolition or reuse?**

7. **Could you, based on experience, come up with arguments on how to rank the importance of these parameters on the choice for demolition or reuse?**

A.3. Notes Interview 1

1. **Wat is je functie, kun je uitleggen wat dit inhoudt?**

Mijn naam is Frank Hofmans, ik ben Adviseur bestaande gebouwen bij ABT. Ik ben met name in de fase betrokken waarbij wordt georiënteerd op de mogelijkheid van herbestemmen. Mijn werkzaamheid is voornamelijk het onderzoek naar deze mogelijkheid. Voorbeelden van projecten zijn Van Unnikgebouw, Erasmus MC en Bajeskwartier.

2. **Wat zijn enkele motieven voor het slopen van een gebouw?**

Vaak is het de uitdaging dat de randvoorwaarden van het bestaande gebouw vraagt om creativiteit, om tot een slimme oplossing te komen waarbij het gebouw zou kunnen worden herbestemd. Hierin zijn de euro's op dit moment nog veelal doorslaggevend: als de randvoorwaarden vragen om een te grote investering voor herbestemming, dan wordt gekozen voor sloop. Ook speelt ontwerpvrijheid hierbij een rol, als randvoorwaarden geen flexibiliteit bieden, dan wordt ook vaak gekozen voor sloop. Ontwerpvrijheid houdt in: Vrije indeelbaarheid, vrije hoogte en de envelop indelen zoals de opdrachtgever zelf wil (vraaggestuurd ontwerpen).

3. **Wat zijn enkele motieven voor het herbestemmen van een gebouw?**

Het feit dat bij herbestemming geen nieuwe hoofddraagconstructie hoeft te worden gerealiseerd scheelt een hoop tijd en geld. Dit zijn factoren die vaak doorslaggevend zijn. Daarnaast spelen factoren zoals de milieu-impact van sloop-nieuwbouw en de CO_2 besparing van herbestemmen een steeds grotere rol in de besluitvorming van opdrachtgevers. Tot slot is het ook van belang wat de ambitie is van de opdrachtgever en tevens de adviseurs. Een bepaalde creativiteitsambitie, waarbij men wil laten zien wat er met beperkte randvoorwaarden mogelijk is, kan de motieven voor herbestemmen versterken.

4. Hieronder staan enkele factoren die de keuze voor sloop of herbestemming beïnvloeden. Kun je enkele factoren uitkiezen en hier wat meer over vertellen, bijvoorbeeld aan de hand van voorbeeldprojecten of ervaringen?

a. Kosten

De kosten zijn momenteel nog veelal doorslaggevend in de keuze voor sloop of herbestemmen, is keuze van opdrachtgever.

b. Technische kwaliteit

Een goede basis technische kwaliteit zijn de randvoorwaarden van het bestaande gebouw, wat is de kwaliteit van de hoofddraagconstructie bijv.?

c. (Gedateerd uiterlijk)

Een gedateerd uiterlijk komt veelal tot uitdrukking in de gevel. Als deze onderdeel is van de hoofddraagconstructie beperkt dit de mogelijkheden om het uiterlijk van het gebouw aan te passen. Een draagbare gevel beperkt ook de aanpasbaarheid van het bouwvolume.

d. Adaptiviteit (constructie/installaties/brandveiligheid/gevel)

Brandveiligheid is een essentieel onderdeel van de adaptiviteit van hoogbouw. Er zijn extra strenge eisen aan gebouwen in NL van hoger dan 70 m. De ontsluitingswegen zijn maatgevend in de adaptiviteit van de constructie en het gebouw, besteed hier veel aandacht aan.

e. Nieuwe regelgeving / ander gevoel van wat veilig is

f. Circulariteitsdoelen

g. Historische waarde

Een voorbeeld hiervan is de toekenning van een landmark. Dit heeft een bepaalde rol gespeeld bij het Van Unnikgebouw. Dit is een gebouw wat iconisch is voor de UU.

5. Kan een adaptief gebouw de motieven voor sloop doen verminderen of zelfs verdwijnen?

Verdwijnen zou ik niet durven zeggen. Dat is weliswaar de ultieme wens, maar ik zou eerder willen zeggen dat je de motieven voor sloop aanzienlijk doet verkleinen. Maar we hebben ook geen glazen bol, we kunnen niet in de toekomst kijken. Wellicht is er in de toekomst minder behoefte aan een bepaald bouwvolume, waardoor deze leeg komt te staan. Dan is het interessant om een en ander circulair te verwijderen en het gebouw aan te passen. Een adaptief gebouw vergroot de kans wel aanzienlijk dat er wordt hergebruikt.

6. Welke parameters in adaptiviteit zijn bepalend in de keuze voor sloop of herbestemming?

Vrije hoogte, vloerbelasting, vrije indeelbaarheid, scheiden van lagen Brandt. Misschien zijn er in de toekomst strengere prestatie eisen aan de gebouwschil, dan wil je deze kunnen ontkoppelen van je draagconstructie. Dus zo veel mogelijk ontkoppelbare knopen, droge verbindingen. Dit valt onder het idee IFR: industrieel, flexibel en remontabel bouwen.

7. Wat is de invloed van belastingscapaciteit, verdiepingshoogte, stramienmaat en wanden-/kolommenstructuur op adaptiviteit?

De stramienmaat is gekoppeld aan de huisvestingsbehoeften van de toekomst. Het lijkt er nu op dat er in de toekomst meer behoefte is aan eenpersoonshuishoudens, in hoeverre is de stramienmaat daarin maatgevend? Als een plattegrond bijvoorbeeld een woning van 50 m2 toe laat, dan is dat veelal richtinggevend. De stramienmaat is daarin van andere orde dan de vrije hoogte. De vrije hoogte heeft meer te maken met de ruimtelijke beleving. In de financiële context is de stramienmaat meer richtinggevend, doordat dit je business case bepaalt. De belasting is een afgeleide van de functie en dus indirect van de vrije hoogte en de stramienmaat.

Dus deze parameter is vooral integraal. Fundering is dan weer minder aanpasbaar, daar kan niet zonder intensieve ingrepen capaciteit aan worden toegevoegd.

A.4. Notes Interview 2

1. **Wat is je functie, kun je uitleggen wat dit inhoudt?**

Mijn naam is *************** , ik ben constructeur en ontwerpleider bij ABT. Als constructeur ben ik vaak aan de voorkant betrokken bij het ontwerp. Ik ben daarna tot en met de uitvoering betrokken. Als ontwerpleider fungeer ik als bewaker van het integraal project, waarbij ik meerdere secties aanstuur. Hierbij ben ik ook verantwoordelijk voor het financiële plaatje.

2. **Wat zijn enkele motieven voor het slopen van een gebouw?**

Een lage technische kwaliteit zorgt er vaak voor dat de keuze op sloop valt. Een gedegradeerde constructie maakt het herbestemmen van een gebouw lastig, aangezien hiervoor ingrijpende maatregelen nodig zijn. De mate van degradatie is afhankelijk van het materiaal van de bestaande bouw. Een betonconstructie in een binnenklimaat is vaak in goede staat, een houtconstructie die is blootgesteld aan vocht is vaak van lage kwaliteit. Een andere reden kan zijn dat er een compleet andere bestemming gewenst is dan het bestaande. Bijvoorbeeld een stadion in plaats van een kantoorgebouw.

3. **Wat zijn enkele motieven voor het herbestemmen van een gebouw?**

Het slopen-nieuw bouwen van een gebouw kost vaak meer geld dan het hergebruiken van de hoofddraagconstructie. Het slopen van de hoofddraagconstructie kost veel tijd en geld, welke kunnen worden bespaard op het moment dat er wordt gekozen voor herbestemming.

4. **Hieronder staan enkele factoren die de keuze voor sloop of herbestemming beïnvloeden. Kun je enkele factoren uitkiezen en hier wat meer over vertellen, bijvoorbeeld aan de hand van voorbeeldprojecten of ervaringen?**

   a. *Kosten*

b. Technische kwaliteit

c. Adaptiviteit (constructie/installaties/brandveiligheid/gevel)

De adaptiviteit van de constructie is een diskwalificatie in de keuze voor sloop of herbestemming. Op het moment dat de constructie niet voldoende adaptief is, wanneer de wensen niet mogelijk zijn, dan moet er worden gesloopt. Als het niet past, dan kan er niet worden herbestemd.

d. Nieuwe regelgeving / ander gevoel van wat veilig is

Er is een norm opgesteld voor verbouw, waardoor er drie niveaus zijn in bestaande bouw: afkeur, verbouw of nieuwbouw. Dit zorgt ervoor dat er meer wordt herbestemd dan voorheen. Voor verbouw zijn de belastingfactoren lager, namelijk 1.15 permanent en 1.3 variabel (1.4 voor wind).

e. Circulariteitsdoelen

f. Historische waarde

5. Kan een adaptief gebouw de motieven voor sloop doen verminderen of zelfs verdwijnen?

6. Welke parameters in adaptiviteit zijn bepalend in de keuze voor sloop of herbestemming?

7. Wat is de invloed van belastingscapaciteit, verdiepingshoogte, stramienmaat en wanden-/kolommenstructuur op adaptiviteit?

De verdiepingshoogte is een diskwalificatie, op het moment dat de verdiepingshoogte te laag is en de wensen van de opdrachtgever niet passen, dan zal moeten worden gesloopt. Dit is de minst adaptieve waarde. De stramienmaat is ook een diskwalificatie, maar kan enigszins worden aangepast. Een voorbeeld hiervan is het uitslopen van een wand, om de ruimtelijkheid te vergroten. De reservecapaciteit kan worden vergroot door middel van speciale technieken, bijvoorbeeld een wapeningsstrip of opspuiten constructie zoals in Hudson Commons. Hierbij zijn de kosten wel vaak hoog, wat ervoor zorgt dat niet altijd wordt gekozen voor versterken.

A.5. Notes Interview 3

1. **Wat is je functie, kun je uitleggen wat dit inhoudt?**

Mijn naam is Willem Klaverveld, ik ben Adviseur constructies bestaande bouw bij ABT. Hiervoor ben ik betrokken bij de constructieve achtergrond van bestaande bouw, maar ik fungeer ook als integraal adviseur of projectleider. Ik verzorg het klantcontact en stuur intern aan, niet alleen op constructies maar ook op gebied van installaties en brandveiligheid bijvoorbeeld.

2. **Wat zijn enkele motieven voor het slopen van een gebouw?**

Het meest voorkomende motief is economisch, aangezien alles in geld wordt uitgedrukt. Een voorbeeld hiervan is het European Patent Office (EPO). De opdrachtgever had een bestaand gebouw wat in goede staat was en mogelijkheden gaf voor hergebruik. De opdrachtgever wenste echter een nieuw gebouw met een hoog comfort en de nieuwste technieken. Geld speelde hierin geen rol, gezien de financiële kracht van de opdrachtgever.

3. **Wat zijn enkele motieven voor het herbestemmen van een gebouw?**

Het op de agenda zetten van de duurzaamheidsambitie. En dan niet alleen naar de buitenwereld, maar ook daadwerkelijk deze ambitie naleven. Vaak zie je dat er wordt gepronkt met nieuwbouw van de hoogste duurzaamheidsklasse, maar waarvoor wel een gebouw is gesloopt met alle gevolgen van dien. Dit is natuurlijk niet wat duurzaam is, vaak is herbestemming beter. Hierbij speelt ook het streven van de ingenieur een rol. Hoe slimmer de oplossing van de ingenieur, hoe goedkoper de oplossing en hoe eerder er wordt herbestemd, dit is duurzamer.

4. Hieronder staan enkele factoren die de keuze voor sloop of herbestemming beïnvloeden. Kun je enkele factoren uitkiezen en hier wat meer over vertellen, bijvoorbeeld aan de hand van voorbeeldprojecten of ervaringen?

a. Kosten

b. Technische kwaliteit

Een voorbeeld hiervan is Lindoduin in Scheveningen. Dit complex uit de jaren 60 staat dicht bij de kust. Hierdoor is de technische kwaliteit van het gebouw aangetast, het zout van de zee degradeert de kwaliteit van het beton. Door toepassen van geavanceerde technieken zoals bijvoorbeeld Diana, kunnen slimme oplossingen worden gevonden. Dit zorgt ervoor dat de investering lager is en dus de drempel voor herbestemming ook. Het is vaak makkelijk als constructeur om te zeggen dat het niet voldoet, maar soms moet ook de grens van de norm worden opgezocht om aan de ambitie te voldoen, zo lang er wel verantwoord kan worden dat de situatie veilig is. Een conservatieve constructeur zal eerder de bestaande bouw afkeuren, terwijl dit niet altijd terecht is, waardoor veel gebouwen die nog van een prima kwaliteit zijn worden gesloopt.

c. Adaptiviteit (constructie/installaties/brandveiligheid/gevel)

Voor veel gebouwen is het zo dat de installaties er uit gaan. Dit maakt het makkelijk in de zin van adaptiviteit, aangezien de installaties meestal afgeschreven zijn. Constructief gezien is dat natuurlijk anders, de constructie is robuuster en kan niet zomaar worden vervangen. Ook is de gevel vaak verouderd en wordt eraf gesloopt.

d. Nieuwe regelgeving / ander gevoel van wat veilig is

Sinds ongeveer 10 jaar is er de norm opgezet voor verbouw. Hierdoor zijn er drie niveaus voor bestaande bouw: afkeur, verbouw en nieuwbouw. Dit maakt het makkelijker om een bepaalde kwaliteit, die niet voldoet aan de nieuwbouwnorm, wel te laten voldoen op gebied van verbouw.

Dit zorgt voor een betere verantwoording op juridisch vlak. Voorheen had je vaak geen poot om op te staan, waardoor er vaak voor werd gekozen om niet het randje op te zoeken.

e. Circulariteitsdoelen

f. Historische waarde

Een voorbeeld hiervan is het Binnenhof in Den Haag, welke wordt gerenoveerd. Dit is een project wat veel aandacht oplevert, ook in de media. Er is een bepaald gevoel wat hierbij leeft. Daarom is er ook voor gekozen om een uitkijkpunt op te zetten, waardoor de inwoners van Den Haag kunnen meekijken met de renovatie.

5. Kan een adaptief gebouw de motieven voor sloop doen verminderen of zelfs verdwijnen?

6. Welke parameters in adaptiviteit zijn bepalend in de keuze voor sloop of herbestemming?

7. Wat is de invloed van belastingscapaciteit, verdiepingshoogte, stramienmaat en wanden-/kolommenstructuur op adaptiviteit?

A.6. Notes Interview 4

1. **Wat is je functie, kun je uitleggen wat dit inhoudt?**

R: Mijn naam is Rutger Snoek, ik ben adviseur constructies bij het Rijksvastgoedbedrijf (RVB). Ik fungeer daarbij als constructief ontwerper en voer daarnaast ook werkzaamheden uit als technisch manager. Als technisch manager definieer ik de technische kwaliteit, met de aanbesteding en bewaking daarvan.

B: Mijn naam is Bert Albers, ik ben adviseur circulair bouwen bij het RVB. Ik begeleid projecten, maar ben ook betrokken bij de ontwikkeling van een materiaalpaspoort, meetbaarheid van circulariteit en ook marktplaatsen.

2. **Wat zijn enkele motieven voor het slopen van een gebouw?**

R: Wanneer het gebouw niet meer nodig is of de wensen van de opdrachtgever niet meer kunnen worden vervuld met het huidige gebouw. Een ander motief kan zijn dat het gebouw het einde van de levensduur heeft bereikt.

B: Daar sluit ik me bij aan. Wanneer een gebouw onderdeel is van een leegloopgebied, bijvoorbeeld een gevangenis die niet meer nodig is. Of als de grond verkocht moet worden.

3. **Wat zijn enkele motieven voor het herbestemmen van een gebouw?**

B: Als het gebouw voldoende basiskwaliteit heeft, niet alleen technisch maar ook ruimtelijk. Daarbij heb ik het over de randvoorwaarden of de kenmerken van het object. Sluit het bijvoorbeeld aan op de toekomstige behoefte? Ik ben zelf ooit betrokken geweest bij het ontwikkelen van een tool voor adaptiviteit, bij Brinkgroep. Toen heb ik ook gehamerd op het People-aspect van circulariteit: menselijke waardering, bruikbaarheid, beeldkwaliteit, gezondheid en robuustheid. De waardering van deze aspecten heeft grote invloed op het motief voor herbestemmen, want van een lelijk, ongezond en niet functioneel gebouw willen mensen al gauw af. Een gebouw met een hoge waardering heeft een grotere kans om te worden herbestemd.

R: Ja, dat is het denk ik. Als er nog potentie in het gebouw is en de locatie het toe laat, is herbestemming mogelijk. Altijd zal de afweging van de kosten gemaakt worden, maar je kunt niet alleen naar de kosten kijken. De kwaliteit van het materiaal is bijvoorbeeld ook heel belangrijk.

4. Hieronder staan enkele factoren die de keuze voor sloop of herbestemming beïnvloeden. Kun je enkele factoren uitkiezen en hier wat meer over vertellen, bijvoorbeeld aan de hand van voorbeeldprojecten of ervaringen?

a. Kosten

B: Bij de keuze tussen sloop / herbestemmen kijk je simpelweg of je programma ruimtelijk, functioneel en technisch goed past in een bestaand pand. Liefst toekomstbestendig. De kosten van de noodzakelijke aanpassingen bepalen in relatie tot de eindkwaliteit versus de kosten van sloop-nieuwbouw met bijbehorende eindkwaliteit bepalen de keuze. Als het gaat om de afweging in welke mate bij nieuwbouw moet worden geïnvesteerd in adaptiviteit, geldt in het algemeen dat het voor (veel) opdrachtgevers lastig is om de waarde van een meerinvestering in adaptiviteit in te schatten. De opbrengsten liggen in de onvoorspelbare toekomst en de investering moet je nu doen. Het meest aannemelijke toekomstige gebruik van het gebouw en/of haar onderdelen zou bepalend moeten zijn voor de keuze van de circulariteitsstrategie: kun je bijvoorbeeld beter adaptief of remontabel bouwen?

In een recent project zochten we naar generieke stramienen, bouwhoogten en gebouwdiepten voor een drietal gebruiksfuncties. Al snel bleek dat voor het eerst beoogde gebruik de investeringskosten snel opliepen. Toen rees de vraag of we niet beter gebruiksfunctiespecifiek konden optimaliseren en levensduur konden borgen door verplaatsbaarheid.

R: De kosten zijn essentieel, want het gaat eigenlijk altijd over geld. Daarbij, een oplossing met een hogere mate van flexibiliteit is vaak ook duurder om te realiseren. Bij de overheid gaat dat ook anders dan op de commerciële markt. Een voorbeeld hiervan is de Zalmhaventoren. Dit is een woontoren met lage verdiepingshoogte en een wandenstructuur, waar alleen een woonfunctie mogelijk is. Dit zorgt voor de meest kostenefficiënte methode, terwijl het totaal niet adaptief is. Er zit ook verschil tussen of het koopwoningen of sociale huurwoningen zijn. Koopwoningen zullen niet snel aangepast worden naar een andere functies, omdat dit om verschillende eigenaren gaat. Een gebouw met allemaal huurwoningen is sneller onderhevig aan een functiewisseling, omdat er sprake is van 1 gebouweigenaar die zelf bepaalt wat hij met zijn gebouw doet.

Een ander bijzonder aspect is dat een gipswand duurder is dan een in-situ betonwand, waardoor woningbouw eigenlijk altijd een wandenstructuur heeft, welke niet adaptief is. Utilitaire torens zijn automatisch al adaptiever, door de ruimtelijke indeling van de functies.

b. *Technische kwaliteit*
c. *Adaptiviteit (constructie/installaties/brandveiligheid/gevel)*

B: Een ander voorbeeld is de nieuwbouw voor het RIVM. Deze zijn van een campus in Bilthoven verhuisd naar een ‘postzegellocatie’ in Utrecht, waarbij het programma door ruimtelijke beperkingen in één bouwmassa moest worden gehuisvest. De behoefte aan flexibiliteit is groot en de verhuizing dermate complex en kostbaar, dat je wel moet investeren in adaptiviteit, simpelweg omdat de huisvesting voor de komende ‘100 jaar’ de processen optimaal moet ondersteunen.   Bijvoorbeeld de (gedeeltelijke) uitwisselbaarheid van kantoren en laboratoriums is hierin meegenomen. Dit zorgt voor een gebouw met een op lange termijn hoge gebruikswaarde.

Wat in de toekomst mogelijk kan helpen, is de waardering van een langere levensduur in de MPG.. Meer materiaal ten gunste van adaptiviteit leidt tot hogere milieulasten, terwijl de levensduur er potentieel mee wordt verlengd. Of die levensduur daadwerkelijk wordt benut weet je nooit, maar als je rekenkundig zou mogen belonen voor de potentie van een langere levensduur, zijn de schaduwkosten per m2 mogelijk lager ondanks meer materiaalgebruik.

d. Nieuwe regelgeving / ander gevoel van wat veilig is

e. Circulariteitsdoelen

f. Historische waarde

5. Kan een adaptief gebouw de motieven voor sloop doen verminderen of zelfs verdwijnen?

R: Ja dat is wel de bedoeling, maar je kunt niet in de toekomst kijken. Er zijn gebouwen die gewoon echt niet meer nodig zijn, dan spelen er andere belangen dan dat je had voorzien. Het is dus best mogelijk dat een adaptief gebouw alsnog gesloopt wordt.

B: Dan kom je weer terug bij het feit dat adaptiviteit niet overal het antwoord op is. Soms is een andere strategie logischer om de beoogde doelen te behalen.

6. Welke parameters in adaptiviteit zijn bepalend in de keuze voor sloop of herbestemming?

7. Wat is de rangorde van belastingscapaciteit, verdiepingshoogte, stramienmaat en wanden-/kolommenstructuur op adaptiviteit?

R: Als je je verdiepingshoogte slim kiest, dan past er al heel veel in. De kans dat je een toren hebt met een industriefunctie, met daaronder bijvoorbeeld woningen is heel klein. Bij bijvoorbeeld 3.5 of 4.0 meter passen de meeste functies al. Daarna is dus ook vrij weinig te behalen met vrij grote aanpassingen. De stramienmaat is lastig, want met een kleinere stramienmaat kun je ook heel veel behalen. Wat wij vaak doen is een hogere belasting uitvragen, om enige mate van flexibiliteit toe te voegen. Er bestaat soms bijvoorbeeld de wens om een bijeenkomstruimte toe te voegen aan een kantoor. De vraag daarbij is of het nodig is om het hele gebouw daarop uit te leggen. Misschien is het beter om juist lokaal te versterken, omdat de overmaat niet overal benodigd is.

B: Ik weet niet of er een rangorde is. Volgens mij moet je kijken naar het meest aannemelijke toekomstige gebruik en daar stem je het ontwerp op af. Daarbij maak je de afweging of je voor-investeert of een upgrade achteraf mogelijk maakt. Als je in de toekomst een hogere belastingscapaciteit nodig verwacht te hebben, moet je je afvragen of dat lokaal of generiek zal zijn. Daarnaast moet je afwegen of je die capaciteit nu realiseert of de upgrade faciliteert, door bijvoorbeeld voldoende verdiepingshoogte.

Kan je spreken van een rangorde? Alle aspecten staan in dienst van ander potentieel gebruik. Als er 1 niet klopt, kan je het beoogd gebruik niet accommoderen, tenzij je de tekortkomingen kan herstellen. Je zou je kunnen afvragen: wat is het lastigst te herstellen of op te waarderen? Als een bestaande verdiepingshoogte net niet klopt voor beoogd gebruik, is een vloer verwijderen (en bijna dubbele hoogte creëren) wel heel rigoureus. Hoogte is dus belangrijk, maar staat niet op zichzelf. In de plint van een toren worden dikwijls gebiedsgerichte (of groeps-) functies gepland die meer hoogte, grotere vrije overspanningen en een andere vloerbelasting vragen. Voor een adaptieve opzet van een toren zou ik daar zeker rekening mee houden.

Appendix B: Example Projects ABT

To increase the number of data points on the influence of a high BAI on the choice of demolition or reuse, example projects from ABT are studied, which are shown in Appendix B.1-B.4 below. The properties of the case studies are shown in Table B.1.

Table B.1: General properties of demolished or reused example projects.

Project name	PI Over Amstel	Van Unnikgebouw	GAK-kantoor	De Lens
Location	Amsterdam	Utrecht	Amsterdam	Utrecht
Year of completion	1978	1969	1960	2000
Year of demolition/reuse	2019	2021	2016	2019
Life span	41	52	56	19
Demolished or Reused?	Demolished	Reused	Reused	Demolished
Height [m]	50	76	46	35
Number of floors	14	21	12	9
New height [m]	-*	76	46	-*
New number of floors	-*	21	12	-*
Original function	Prison	Educational	Office	Office
New function	-*	Office	Residential	-*
FtF height [m]	2.80	3.40	3.25	3.3
New FtF height [m]	-*	3.40	3.25	-*
Grid size [m]	2.70	7.20	7.25	4.2
Columns or walls?	Walls	Columns	Columns	Columns
New grid size [m]	-*	7.20	7.25	-*
BAI	0.00	0.50	0.51	0.21

*It is not yet known what buildings will replace the demolished buildings, which is why these values are unknown.

B.1. Penitentiary Institution Over Amstel [Demolished]

The PI Over Amstel was a complex of six towers with a prison function. The Dutch Governments' Real Estate Company decided that the towers should be sold, because they did not fulfil their purpose anymore. A study by ABT on the possibility of reusing the six towers was conducted, which lead to the following conclusions.

The position of the stability walls in the floor plan have a large influence on the possible building functions for reuse. As discussed in Chapter 3.1.2, buildings with a wall grid generally can only adapt to a prison, lodging or residential function. Furthermore, with the current structural load capacity of 1.5 kN/m^2, the capacity is entirely used up by the current function of the towers. The use of a FtF height of merely 2.8 meters means that the BAI of the towers is at the lowest value of 0.00, which means that the buildings are completely unadaptable, which resulted in the demolition of the towers.

B.2. Van Unnikgebouw [Reused]

The Van Unnikgebouw, part of the campus of University Utrecht, is a high-rise tower that is one of the most recognisable buildings at the campus. Due to the presence of asbestos and partly vacancy of the building, ABT was asked to perform a study on the feasibility of reusing the tower and its basement.

It is concluded from this study that the main load bearing structure of the building is in good condition and ready for a new lifespan of 50 years. Due to the good condition of the structure with load capacity for an educational function, several reuse functions are deemed to be possible: office, residential, and (partly) education. The open structure and the available load capacity lead to the relatively high BAI of this project, leading to the possibilities of reusing the building. Attention should still be paid to the fire safety and installation plan of the building, but due to the capacity in the core size, this should not lead to problems in reuse.

B.3. GAK-Kantoor [Reused]

The former GAK-kantoor, or GAK-office in English, has been transformed to apartments. Due to the available adaptability and the ambitions of the parties involved, reuse has been made possible. The ambition of the parties originated from the current lack of housing for students and young families. The out-of-use GAK-office proved a building with the sufficient adaptability and floor plan lay out to change to a residential function, which is in high demand in Amsterdam. The fact that the office building could be reused means that the environmental impact of the building is lower than in the case of demolition and building new, which is in line with the ambitions of the municipality of Amsterdam and the other parties involved.

B.4. De Lens [Demolished]

The former municipality office of Nieuwegein, De Lens, has been demolished as part of a reuse project of the rest of the municipality office. De Lens was a 9 story high building in which the municipality of Nieuwegein operated temporarily, awaiting the completion of their new municipality office. Because the part of the municipality office surrounding De Lens is converted to elderly residences, a study on the feasibility of reusing De Lens for this project was conducted by ABT. De Lens has an extraordinary structure, with its eye-shape and welded steel frame, see Figure B.1. This resulted in a low amount of adaptability in the structure, due to the small grid size. This led to the conclusion that De Lens should be demolished, to make room for the reuse of the surrounding building.

(a) *(b)*

Figure B.1: a: De Lens, with its surrounding office ; b: Interior of De Lens, with welded connections in the façade to provide stability.

Appendix C: Calculations Alternative Designs

C.1. Elevator Calculations

Note: The elevator calculations only serve as an indicative calculation to determine the starting point of the core of the fictive alternative designs. A more elaborative calculation of the elevators is required in real cases.

Elevator calculation Residential

General properties			
Number of stops above ground floor	N	32	
Story height	d_{gem}	3.0	m
Nominal Elevator Capacity	NLB	13	
Velocity	v	1.2	m/s
Acceleration	a	0.8	m/s^2

Term 1			
Time of passenger transfer	$2Pt_p$		
Average number of passengers	$P = NLB \times 0{,}80$		
	P	10.4	
	t_p	1.50	s
Term 1		31.20	s

Term 2			
Time of stops	$(S+1)t_s$		
Average number of stops	$S = N - \left(1 - \frac{1}{N+1}\right)^P \times N$		
	S	8.76	
Time needed to stop	$t_s = t_f(gem) + t_D - t_v$		
	$t_f(gem) = \frac{d_{gem} - \left(0{,}5A \times \left(\frac{V}{A}\right)^2\right)}{V} + \frac{V}{A}$		
Travel time average jump	$t_f(gem)$	3.25	s
Total door time	t_D	7.00	s
Transfer time single story	t_v	2.50	s
	t_s	7.75	s
Term 2		75.67	s

Term 3			
Travel time between stories	$2Ht_v$		
Average highest reached story	$H = N - \sum_{i=1}^{N-1} \left(\frac{N_i}{N+1}\right)^P$		
	H	30.31	
Term 3		151.53	s

Term 4		
Time benefit of unpopulated story	$2t_e$	
Express time	$t_e = \frac{((N-1) - N_P) \times d_f}{V}$	
Number of populated stories	N_p	33
	t_e	-5.00 s
Term 4		-10.00 s

Round trip time		
	$RTT = 2Ht_v + (S+1)t_s + 2Pt_p + 2t_e$	
Round trip time	RTT	248.40 s

Elevator capacity		
Number of elevators	n	3
Interval of waiting time	INT	82.80 s
	$AWT = \left(0.4 + \left(1.8 \times \frac{P}{NLB} - 0.77\right)^2\right) INT$	
Average waiting time	AWT	70.29 s
Maximum allowed waiting time	AWT_{max}	130.00 s
	UC	0.54

Elevator calculation Office

General properties		
Number of stops above ground floor	N	27
Story height	d_{gem}	3.5 m
Nominal Elevator Capacity	NLB	13
Velocity	v	2.5 m/s
Acceleration	a	0.8 m/s^2

Term 1		
Time of passenger transfer	$2Pt_p$	
Average number of passengers	$P = NLB \times 0{,}80$	
	P	10.4
	t_p	1.50 s
Term 1		31.20 s

Term 2		
Time of stops	$(S+1)t_s$	
Average number of stops	$S = N - \left(1 - \frac{1}{N+1}\right)^P \times N$	
	S	8.50
Time needed to stop	$t_s = t_f(gem) + t_D - t_v$	
Travel time average jump	$t_f(gem) = \frac{d_{gem} - \left(0{,}5A \times \left(\frac{V}{A}\right)^2\right)}{V} + \frac{V}{A}$	
	$t_f(gem)$	2.96 s
Total door time	t_D	7.00 s
Transfer time single story	t_v	1.40 s
	t_s	8.56 s
Term 2		81.37 s

Term 3		
Travel time between stories	$2Ht_v$	
Average highest reached story	$H = N - \sum_{i=1}^{N-1} \left(\frac{N_i}{N+1}\right)^P$	
	H	25.70
Term 3		71.95 s

Term 4		
Time benefit of unpopulated story	$2t_e$	
Express time	$t_e = \frac{\left((N-1) - N_P\right) \times d_f}{V}$	
Number of populated stories	N_p	28
	t_e	-2.80 s
Term 4		-5.60 s

Round trip time		
	$RTT = 2Ht_v + (S+1)t_s + 2Pt_p + 2t_e$	
Round trip time	RTT	178.92 s

Elevator capacity		
Number of elevators Interval of waiting time	n INT	5 35.78 s
	$AWT = \left(0.4 + \left(1.8 \times \frac{P}{NLB} - 0.77\right)^2\right) INT$	
Average waiting time	AWT	30.38 s
Maximum allowed waiting time	AWT_{max}	35.00 s
	UC	0.87

C.2. Lateral Stability Calculations

Note: The lateral stability calculations only serve as an indicative calculation to determine the starting point of the core of the fictive alternative designs. A more elaborative calculation of the stability system is required in real cases.

Lateral stability calculation core (wind on long side)

Properties core			
Wall thickness	t	0.50	m
Length core wall	L	12.0	m
Width core wall	W	13.0	m
Height	H	100.0	m
Second moment of area	I	183.1	m^4
Concrete class		C30/37	
Elastic modulus	E_c	33000	MPa
Bending stiffness	EI	6.04E+09	kNm^2

Wind load			
Mean wind pressure	$p_{w;mean}$	1.58	kN/m^2
Mean wind load	$q_{w;mean}$	56.72	kN/m
Bending moment base	M_{base}	283600	kNm

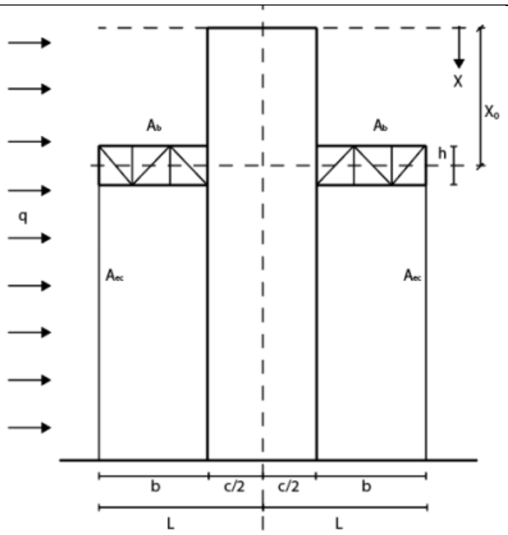
Deflection			
	$u_{top} = \frac{q_{w;mean} H^4}{8EI}$		
Top deflection	u_{top}	0.12	m
	$u_{top;max} = \frac{H}{750}$		
Maximum allowed top deflection	$u_{top;max}$	0.13	m
	UC	0.88	

Lateral stability calculation outrigger* (wind on long side)

*This calculation follows the method of Hoenderkamp [49]

Properties core			
Wall thickness	t	0.35	m
Length core wall	L	9.0	m
Width core wall	W	12.0	m
Height	H	100.0	m
Second moment of area	I	100.8	m^4
Concrete class		C30/37	
Elastic modulus	E_c	33000	MPa
Bending stiffness core	EI_{core}	3.33E+09	kNm^2

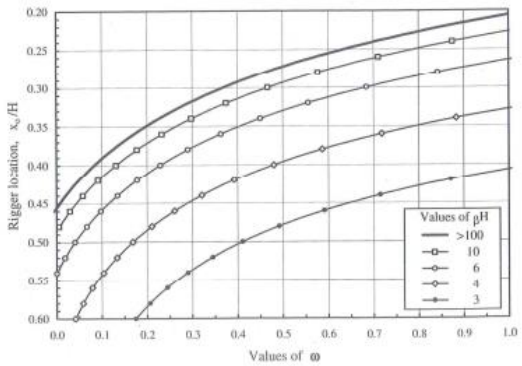
Outrigger properties



Outrigger length	b	5.85	m
Number of outriggers	n	2	
Number of diagonals	j	2	
Outrigger height	h_{out}	3.5	m

Outrigger beams (GL32h)			
Depth	d_b	0.70	m
Width	w_b	0.40	m
Area	A_b	0.28	m^2
Elastic modulus	E_b	13700	MPa
	$EI_{out} = n \times \frac{j^2}{j^2-1}\left(\frac{EA_b h^2}{2}\right)$		
Bending stiffness outrigger	EI_{out}	6.27E+07	kNm^2
Outrigger column distance	a	2.93	m
	$GA_{out} = n \times j \times \frac{2a^2 hEA_b}{\left(\sqrt{a^2+h^2}\right)^3}$		
Shear stiffness outrigger	GA_{out}	9.86E+06	kN

Exterior columns (GL32h)			
Column distance from centre of core	L	12.60	m
Depth	d_{ec}	0.80	m
Width	w_{ec}	0.80	m
Area	A_{ec}	0.64	m^2
Elastic modulus	E_{ec}	13700.00	MPa
	$EI_{ec} = E \times n \times 2 \times L^2 \times A_{ec}$		
Bending stiffness exterior columns	EI_{ec}	5.57E+09	kNm^2

Outrigger location			
	$\alpha = \frac{L}{b}$		
Alpha	α	2.15	
	$S_v = \frac{H}{EI_{core}} + \frac{H}{EI_{ec}}$		
Vertical flexibility parameter	S_v	4.80E-08	kN/m
	$S_h = \frac{1}{\alpha^2}\left(\frac{b}{24EI_{out}} + \frac{1}{hGA_{out}}\right)$		
Horizontal flexibility parameter	S_h	7.20E-09	kN/m
	$\omega = \frac{S_h}{S_v}$		
Omega	ω	0.15	
			
Optimum location	x_0	36.50	m

Wind load			
Mean wind pressure	$p_{w;mean}$	1.58	kN/m^2
Mean wind load	$q_{w;mean}$	56.72	kN/m

Bending moment base			
	$M_r = \left(\frac{q(H^3 - x_0^3)}{6EI_t}\right)\left(\frac{H}{(H - x_0)S_v + HS_h}\right)$		
Restraining moment	M_r	78334	kNm
Non reduced bending moment	M_{base}	283580	kNm
Reduced bending moment base	$M_{red;base}$	205246	kNm

Deflection			
	$u_{top} = \frac{qH^4}{8EI_{core}} - \frac{M_r(H^2 - x_0^2)}{2EI_{core}}$		
Top deflection	u_{top}	0.11	m
Maximum allowed top deflection	$u_{top;max}$	0.13	m
	UC	0.83	

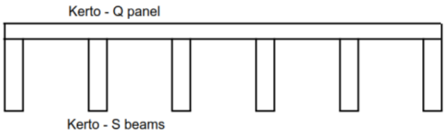
C.3. Structural Analysis Baseline

Building properties			
Building length	L	25.2	m
Building width	W	36.0	m
Building height	H	99.0	m
Building function		Residential	
Number of stories	n_{story}	33	
Number of columns per story	n_{col}	44	

Loads			
Permanent load	G_k	5.00	kN/m^2
Variable load	Q_k	2.55	kN/m^2
Temporary load factor	ψ_0	0.4	
Quasi-permanent load factor	ψ_2	0.3	
	$1.32 \times G_k + 1.65 \times Q_k$		
Load combination 1	LC1	10.81	kN/m^2
	$1.49 \times G_k + 1.65 \times \psi_0 Q_k$		
Load combination 2	LC2	9.13	kN/m^2
	$1.49 \times G_k + 1.65 \times Q_k$		
Maximum possible load	q_{max}	11.66	kN/m^2
Characteristic load	q_{char}	7.55	kN/m^2
Façade load	$G_{façade}$	0.50	kN/m^2

Adaptability parameters			
Grid size		5.4	m
Floor load		1.75 + 0.8	kN/m^2
Foundation load		1.02	kN/m^2
Floor-to-floor height		3.0	m

Calculation floor



Floor properties (Kerto Ripa)			
Span	L	5.4	m
Panel width	w_{panel}	2400	mm
Kerto-Q thickness	t_q	31	mm
Kerto-S height	h_s	300	mm
Kerto-S width	w_s	45	mm
Total floor thickness	t	331	mm

Kerto-Q (from Metsä[67])			
Bending strength flat	$f_{m,0,flat,k}$	36.00	MPa
Size effect parameter	s	0.12	
Tensile strength	$f_{t,0,k}$	26.00	MPa
Compressive strength	$f_{c,0,k}$	26.00	MPa
Shear strength flat	$f_{v,0,flat,k}$	1.30	MPa
Modulus of elasticity	$E_{0,mean}$	10500.00	MPa
Shear modulus	$G_{0,mean}$	120.00	MPa

Material factor	γ_M	1.20
Modification factor	k_{mod}	0.90
Rectangular LVL section	k_m	0.70
	$k_h = \min\left(\left(\frac{300}{h}\right)^{s}; 1.2\right)$	
Size factor	k_h	1.20
	$k_l = \min\left(\left(\frac{3000}{l}\right)^{\frac{s}{2}}; 1.1\right)$	
Length factor	k_l	0.97
Deformation factor	k_{def}	0.60

Bending strength	$f_{m,d}$	32.40	MPa
Tensile strength	$f_{t,d}$	18.82	MPa
Compressive strength	$f_{c,d}$	19.50	MPa
Shear strength	$f_{v,d}$	0.98	MPa

Kerto-S (from Metsä[67])			
Bending strength edge	$f_{m,0,edge,k}$	44.00	MPa
Size effect parameter	s	0.12	
Tensile strength	$f_{t,0,k}$	35.00	MPa
Compressive strength	$f_{c,0,k}$	35.00	MPa
Shear strength edge	$f_{v,0,edge,k}$	4.20	MPa
Modulus of elasticity	$E_{0,mean}$	13800.00	MPa
Shear modulus	$G_{0,mean}$	600.00	MPa

Material factor	γ_M	1.20	
Modification factor	k_{mod}	0.90	
Rectangular LVL section	k_m	0.70	
Size factor	k_h	1.00	
Length factor	k_l	0.97	
Deformation factor	k_{def}	0.60	

Bending strength	$f_{m,d}$	33.00	MPa
Tensile strength	$f_{t,d}$	25.34	MPa
Compressive strength	$f_{c,d}$	26.25	MPa
Shear strength	$f_{v,d}$	3.15	MPa

Section moduli			
	$n_1 = \frac{E_1}{E_2}$		
Elastic moduli ratio	n_1	0.76	
	$w_{eff} = w_{panel} \times n_1$		
Effective panel width	w_{eff}	1826.09	mm
Center of mass from top	z	105.51	mm
Second moment of area	I	1.35E+09	mm^4
Section modulus top	W_{top}	1.28E+07	mm^3
Section modulus bottom	W_{bottom}	6.01E+06	mm^3

Forces			
	$V_d = \frac{1}{2} q_{max} w_{panel} L$		
Design shear load	V_d	75.54	kN
	$M_d = \frac{1}{8} q_{max} w_{panel} L^2$		
Design bending moment	M_d	101.98	kNm

Bending		
Bending stress top	$\sigma_{m,top,d}$	7.95 MPa
	$UC = \frac{\sigma_{m,top,d}}{f_{m,d}}$	
	UC	0.25
Bending stress bottom	$\sigma_{m,bottom,d}$	16.98 MPa
	$UC = \frac{\sigma_{m,bottom,d}}{f_{m,d}}$	
	UC	0.51

Shear		
Area Shear stress	A τ_d	1.42E+05 mm^2 0.53 MPa
	$UC = \frac{\tau_d}{f_{v,d}}$	
	UC_{plate} UC_{beam}	0.55 0.17

Deflection		
Combined Elastic modulus	E_{tot}	13800.00 MPa
	$u_{inst,G} = \frac{5G_k w_{panel} L^4}{384EI}$	
Instant deflection permanent	$u_{inst,G}$	7.11 mm
	$u_{inst,Q} = \frac{5Q_k w_{panel} L^4}{384EI}$	
Instant deflection variable	$u_{inst,Q}$	3.63 mm
	$u_{fin,G} = u_{inst,G}(1 + k_{def})$	
Final deflection permanent	$u_{fin,G}$	11.38 mm
	$u_{fin,Q} = u_{inst,Q}(1 + k_{def})$	
Final deflection variable	$u_{fin,Q}$	5.80 mm
	$u_{tot} = u_{fin,G} + u_{fin,Q}$	
Total deflection	u_{tot}	17.18 mm
	$u_{max} = \frac{L}{300}$	
Maximum deflection	u_{max}	18.00 mm
	UC	0.95

Calculation beam

Beam properties (GL32h)			
Span	L	5.4	m
Height	h_{beam}	500	mm
Width	w_{beam}	250	mm
Second moment of area strong axis	I_y	2.60E+09	mm^4
Second moment of area weak axis	I_z	6.51E+08	mm^4
	$I_t = \frac{1}{12} h_{beam} w_{beam} (h_{beam}^2 + w_{beam}^2)$		
Torsional second moment of area	I_t	3.26E+09	mm^4
Section modulus	W_y	1.04E+07	mm^3

Bending strength	$f_{m,k}$	32.00	MPa
Tensile strength	$f_{t,k}$	22.50	MPa
Compressive strength	$f_{c,k}$	29.00	MPa
Shear strength	$f_{v,k}$	3.80	MPa
Modulus of elasticity	$E_{0,mean}$	13700.00	MPa
Lower 5 percentile modulus of elasticity	$E_{0.05}$	11100.00	MPa
Shear modulus	G_{mean}	850.00	MPa
Lower 5 percentile shear modulus	$G_{0.05}$	693.75	MPa
Density	ρ_{mean}	470.00	kg/m^3

Material factor	γ_M	1.25
Modification factor	k_{mod}	0.90
Rectangular glulam section	k_m	0.70
	$k_h = \min\left(\left(\frac{600}{h}\right)^{0.1}; 1.1\right)$	
Size factor	k_h	1.02
Deformation factor	k_{def}	0.60

Bending strength	$f_{m,d}$	23.46	MPa
Tensile strength	$f_{t,d}$	17.68	MPa
Compressive strength	$f_{c,d}$	20.88	MPa
Shear strength	$f_{v,d}$	2.74	MPa

Forces			
	$V_d = \frac{1}{2} q_{max} L_{floor} L$		
Design shear load	Vd	169.97	kN
	$M_d = \frac{1}{8} q_{max} L_{floor} L^2$		
Design bending moment	Md	229.45	kNm

Bending			
Bending stress	$\sigma_{m,d}$	22.03	MPa
	$UC = \frac{\sigma_{m,d}}{f_{m,d}}$		
	UC	0.94	

Shear			
Area	A	1.25E+05	mm^2
Shear stress	τ_d	1.36	MPa
	$UC = \frac{\tau_d}{f_{v,d}}$		
	UC	0.50	

Stability: Lateral torsional buckling			
	$l_{eff} = 0.9L$		
Effective buckling length	l_{eff}	4.86	m
	$\sigma_{m,crit} = \frac{\pi\sqrt{E_{0.05}I_z G_{0.05}I_t}}{l_{eff}W_y}$		
Critical bending stress	$\sigma_{m,crit}$	250.69	MPa
	$\lambda_{rel,m} = \sqrt{\frac{f_{m,k}}{\sigma_{m,crit}}}$		
Relative slenderness	$\lambda_{rel,m}$	0.36	
	$k_{crit} = 1\ for\ \lambda_{rel,m} < 0.75$		
Critical factor	k_{crit}	1.00	
	$UC = \frac{\sigma_{m,d}}{k_{crit}f_{m,d}}$		
	UC	0.94	

Deflection			
	$u_{inst,G} = \frac{5G_k L_{floor} L^4}{384EI}$		
Instant deflection permanent	$u_{inst,G}$	8.38	mm
	$u_{inst,Q} = \frac{5Q_k L_{floor} L^4}{384EI}$		
Instant deflection variable	$u_{inst,Q}$	4.27	mm
	$u_{fin,G} = u_{inst,G}(1 + k_{def})$		
Final deflection permanent	$u_{fin,G}$	13.41	mm
	$u_{fin,Q} = u_{inst,Q}(1 + \psi_2 k_{def})$		
Final deflection variable	$u_{fin,Q}$	5.04	mm

Total deflection	$u_{tot} = u_{fin,G} + u_{fin,Q}$	
	u_{tot}	18.45 mm
Maximum deflection	$u_{max} = \frac{L}{250}$	
	u_{max}	21.60 mm
	UC	0.85

Calculation bottom column

Column properties (GL32h)		
Length	L	3.0 m
Depth	d	750 mm
Width	w	750 mm
Area	A	5.63E+05 mm^2
Second moment of area y-axis	I_y	2.64E+10 mm^4
Second moment of area z-axis	I_z	2.64E+10 mm^4
Section modulus y-axis	W_y	7.03E+07 mm^3
Section modulus z-axis	W_z	7.03E+07 mm^3

Bending strength	$f_{m,k}$	32.00 MPa
Tensile strength	$f_{t,k}$	22.50 MPa
Compressive strength	$f_{c,k}$	29.00 MPa
Shear strength	$f_{v,k}$	3.80 MPa
Elastic modulus	$E_{0,mean}$	13700.00 MPa
Lower 5 percentile modulus of elasticity	$E_{0.05}$	11100.00 MPa
Shear modulus	G_{mean}	850.00 MPa
Density	ρ_{mean}	470.00 kg/m^3

Material factor	γ_M	1.25
Modification factor	k_{mod}	0.90
Rectangular glulam section	k_m	0.70

Bending strength	$f_{m,d}$	23.04 MPa
Tensile strength	$f_{t,d}$	16.20 MPa
Compressive strength	$f_{c,d}$	20.88 MPa
Shear strength	$f_{v,d}$	2.74 MPa

Forces		
	$N_{sw,i} = (L_{beam} h_{beam} w_{beam} \rho_{beam} + L_{col} d_{col} w_{col} \rho_{col}) n_{story} \times \frac{9.81}{1000}$	
Self-weight on interior column	$N_{sw,i}$	359.46 kN
	$N_{sw,f} = \left(\frac{1}{2} L_{beam} h_{beam} w_{beam} \rho_{beam} + L_{col} d_{col} w_{col} \rho_{col}\right) n_{story} \times \frac{9.81}{1000}$	
Self-weight on façade column	$N_{sw,f}$	308.11 kN
	$N_{c,i,LC1} = L_{floor} L_{beam} n_{story} LC1 + N_{sw,i}$	
Interior column force LC1	$N_{c,i,LC1}$	10759.30 kN
	$N_{c,i,LC2} = L_{floor} L_{beam} \left((n_{story} - 2) LC2 + 2q_{max}\right) + N_{sw,i}$	
Interior column force LC2	$N_{c,i,LC2}$	9195.60 kN

	$N_{c,f,LC1} = \left(L_{floor} \times \frac{1}{2} L_{beam} LC1 + 1.32 \times L_{floor} L_{col} G_{façade}\right) n_{story} + N_{sw,f}$		
Façade column force LC1	$N_{c,f,LC1}$	5860.87	kN
	$N_{c,f,LC1} = L_{floor} \times \frac{1}{2} L_{beam} \left((n_{story} - 2) LC2 + 2q_{max}\right) + 1.49 \times L_{floor} L_{col} G_{façade} n_{story} + N_{sw,f}$		
Façade column force LC2	$N_{c,f,LC2}$	5124.46	kN
Design compressive force	$N_{c,d}$	10759.30	kN
Wind load	q_w	1.26	kN/m^2
Design bending moment	M_d	7.65	kNm

Compression			
Compressive stress	$\sigma_{c,d}$	19.13	MPa
	$UC = \frac{\sigma_{c,d}}{f_{c,d}}$		
	UC	0.92	

Bending			
Bending stress	$\sigma_{m,d}$	0.11	MPa
	$UC = \frac{\sigma_{m,d}}{f_{m,d}}$		
	UC	0.005	

Combined bending and compression		
	$UC = \left(\frac{\sigma_{c,d}}{f_{c,d}}\right)^2 + \frac{\sigma_{m,d}}{f_{m,d}}$	
	UC	0.84

Stability: buckling			
Radius of gyration y-axis	i_y	216.51	mm
Radius of gyration z-axis	i_z	216.51	mm
Slenderness y-axis	λ_y	13.86	
Slenderness z-axis	λ_z	13.86	
	$\lambda_{rel,y} = \frac{\lambda_y}{\pi} \sqrt{\frac{f_{c,k}}{E_{0.05}}}$		
Relative slenderness y-axis	$\lambda_{rel,y}$	0.23	
Relative slenderness z-axis	$\lambda_{rel,z}$	0.23	
Straightness factor	β_c	0.10	
	$k_y = 0.5\left(1 + \beta_c(\lambda_{rel,y} - 0.3) + \lambda_{rel,y}^2\right)$		
Buckling factor y-axis	k_y	0.52	
Buckling factor z-axis	k_z	0.52	

	$$k_{c,y} = \frac{1}{k_y + \sqrt{k_y^2 - \lambda_{rel,y}^2}}$$	
Critical factor y-axis	$k_{c,y}$	1.00
Critical factor z-axis	$k_{c,z}$	1.00
	$$UC = \frac{\sigma_{c,d}}{k_{c,y} f_{c,d}} + \frac{\sigma_{m,d}}{f_{m.d}}$$	
	UC	0.92

Calculation Foundation pile

Pile properties (Vibro pile)			
Length	L	12.5	m
Diameter	D	610	mm
Area	A	292247	mm^2
Circumference	C	1916	mm
Pile class factor tip	α_t	0.7	
Shape factor pile	beta	1.0	
Factor for varying shape	s	1.0	
Pile class factor shaft	α_s	0.014	

Cone penetration test (CPT) result

Level relative to NAP [m]	Ground type	Cone resistance q_c [MPa]
-3.5 to -4.5	Sand	5.0 to 10.0
-4.5 to -6.0	Peat	0.1 to 0.2
-6.0 to -8.3	Clay, weak	0.5 to 1.0
-8.3 to -9.0	Peat	0.1 to 0.2
-9.0 to -14.0	Sand, moderate	6.0 to 14.0
-14.0 to -60.0	Sand, compact	14.0 to 20.0

Source: CPT for existing design

Number of CPT's	n_{CPT}	5	
Stiffness superstructure		Not stiff	
Ground level		3.5 m – NAP	
Pile tip level		16.0 m – NAP	
4D below	4D	2440	mm
8D above	8D	4880	mm
Mean cone resistance I	$q_{c,I,mean}$	17.0	MPa
Mean cone resistance II	$q_{c,II,mean}$	14.0	MPa
Mean cone resistance III	$q_{c,III,mean}$	13.0	MPa
Shaft resistance	$q_{c,z,a}$	13.0	MPa

Pile capacity			
	$q_{t,max} = \frac{1}{2}\alpha_t \beta s \left(\frac{q_{c,I,mean} + q_{c,II,mean}}{2} + q_{c,III,mean}\right)$		
Maximum pile tip resistance	$q_{t,max}$	9.98	MPa
	$q_{s,max} = \alpha_s q_{c,z,a}$		
Maximum pile shaft resistance	$q_{s,max}$	0.18	MPa
	$F_{t,max} = \frac{q_{t,max}}{A}$		
Pile tip capacity	$F_{t,max}$	2915	kN
Length of shaft friction	ΔL	4880	mm

	$F_{s,max} = C\Delta L q_{c,z,a}$		
Pile shaft capacity	$F_{s,max}$	1702	kN
Pile capacity	F_{max}	4617	kN
Correlation factor	ξ_3	1.28	
Correlation factor	ξ_4	1.03	
	$F_p = \min\left(\frac{F_{max}}{\xi_3}; \frac{F_{max}}{\xi_4}\right)$		
Characteristic pile capacity	F_p	3607	kN
Material factor	γ_M	1.2	
	$F_{p,d} = \frac{F_p}{\gamma_M}$		
Design Pile capacity	$F_{p,d}$	3006	kN

Forces			
	$N_{p,d} = N_{c,d}$		
Compressive force	$N_{p,d}$	10759.30	kN

Number of piles		
Number of piles under governing column	$n_{p;column}$	4
Number of piles under core (assumed)	$n_{p;core}$	100
Number of columns	n_{column}	44
Total number of piles	n_{pile}	276

C.4. Results Alternative Design Configurations

C.4.1. Varying Grid Size

Baseline											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Floor thickness	331.00	100	Bending moment beam	229.45	100	Bottom column load	10759.30	100	Number of piles	276	100
Total volume floors	1571.64	100	Beam height	500.00	100	Column dimensions	750.00	100	Total volume	3958.37	100
			Beam width	250.00	100	Size (2/3)	600.00		Rentable area	26175.6	100
			Total volume beams	753.23	100	Size (3/3)	450.00		BAI	0.30	100
						Total volume columns	1633.50	100			
Grid size 6 m											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Floor thickness	385.00	116	Bending moment beam	314.75	137	Bottom column load	12839.31	119	Number of piles	260	94
Total volume floors	1603.84	102	Beam height	550.00	110	Column dimensions	800.00	107	Total volume	3740.71	95
			Beam width	300.00	120	Size (2/3)	650.00		Rentable area	26175.6	100
			Total volume beams	750.87	100	Size (3/3)	500.00		BAI	0.36	119
						Total volume columns	1386.00	85			
Grid size 6.6 m											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Floor thickness	425.00	128	Bending moment beam	418.94	183	Bottom column load	15535.57	144	Number of piles	292	106
Total volume floors	1969.55	125	Beam height	650.00	130	Column dimensions	900.00	120	Total volume	4404.64	111
			Beam width	300.00	120	Size (2/3)	750.00		Rentable area	26175.6	100
			Total volume beams	887.39	118	Size (3/3)	550.00		BAI	0.41	137
						Total volume columns	1547.70	95			
Grid size 7.2 m											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Floor thickness	437.00	132	Bending moment beam	543.89	237	Bottom column load	18488.61	172	Number of piles	296	107
Total volume floors	2403.22	153	Beam height	650.00	130	Column dimensions	950.00	127	Total volume	5196.42	131
			Beam width	350.00	140	Size (2/3)	800.00		Rentable area	26175.6	100
			Total volume beams	1035.28	137	Size (3/3)	600.00		BAI	0.46	155
						Total volume columns	1757.91	108			
Grid size 8.4 m											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Floor thickness	525.00	159	Bending moment beam	863.68	376	Bottom column load	25165.05	234	Number of piles	280	101
Total volume floors	3239.00	206	Beam height	800.00	160	Column dimensions	1150.00	153	Total volume	6617.31	167
			Beam width	400.00	160	Size (2/3)	950.00		Rentable area	26175.6	100
			Total volume beams	1456.22	193	Size (3/3)	650.00		BAI	0.51	170
						Total volume columns	1922.09	118			

C.4.2. Varying Load Capacity

Baseline											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Floor thickness	331.00	100	Bending moment beam	229.45	100	Bottom column load	10759.30	100	Number of piles	276	100
Total volume floors	1571.64	100	Beam height	500.00	100	Column dimensions	750.00	100	Total volume	3958.37	100
			Beam width	250.00	100	Size (2/3)	600.00		Rentable area	26175.6	100
			Total volume beams	753.23	100	Size (3/3)	450.00		BAI	0.30	100
						Total volume columns	1633.50	100			
Load capacity 2.5 + 0.8 kN/m^2											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Floor thickness	385.00	116	Bending moment beam	253.81	111	Bottom column load	11590.66	108	Number of piles	276	100
Total volume floors	1566.63	100	Beam height	550.00	110	Column dimensions	750.00	100	Total volume	4119.43	104
			Beam width	250.00	100	Size (2/3)	650.00		Rentable area	26175.60	100
			Total volume beams	828.55	110	Size (3/3)	450.00		BAI	0.34	114
						Total volume columns	1724.25	106			
Load capacity 4.0 kN/m^2											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Floor thickness	385.00	116	Bending moment beam	276.55	121	Bottom column load	12702.10	118	Number of piles	320	116
Total volume floors	1566.63	100	Beam height	550.00	110	Column dimensions	800.00	107	Total volume	4300.93	109
			Beam width	250.00	100	Size (2/3)	650.00		Rentable area	26175.60	100
			Total volume beams	828.55	110	Size (3/3)	500.00		BAI	0.37	122
						Total volume columns	1905.75	117			
Load capacity 5.0 kN/m^2											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Floor thickness	385.00	116	Bending moment beam	309.02	135	Bottom column load	15107.80	140	Number of piles	364	132
Total volume floors	1566.63	100	Beam height	550.00	110	Column dimensions	900.00	120	Total volume	4811.49	122
			Beam width	300.00	120	Size (2/3)	700.00		Rentable area	26175.60	100
			Total volume beams	994.26	132	Size (3/3)	500.00		BAI	0.42	141
						Total volume columns	2250.60	138			
Load capacity 5.0 + 0.8 kN/m^2											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Floor thickness	385.00	116	Bending moment beam	335.00	146	Bottom column load	15560.07	145	Number of piles	364	132
Total volume floors	1566.63	100	Beam height	550.00	110	Column dimensions	900.00	120	Total volume	4992.99	126
			Beam width	300.00	120	Size (2/3)	750.00		Rentable area	26175.60	100
			Total volume beams	994.26	132	Size (3/3)	550.00		BAI	0.42	139
						Total volume columns	2432.10	149			
Load capacity 12.0 kN/m^2											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Floor thickness	431.00	130	Bending moment beam	562.34	245	Bottom column load	27492.34	256	Number of piles	540	196
Total volume floors	1960.19	125	Beam height	650.00	130	Column dimensions	1150.00	153	Total volume	7273.24	184
			Beam width	350.00	140	Size (2/3)	950.00		Rentable area	26175.60	100
			Total volume beams	1370.87	182	Size (3/3)	700.00		BAI	0.43	145
						Total volume columns	3942.18	241			

C.4.3. Varying Floor-to-Floor Height

Baseline											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Floor thickness	331.00	100	Bending moment beam	229.45	100	Bottom column load	10759.30	100	Number of piles	276	100
Total volume floors	1571.64	100	Beam height	500.00	100	Column dimensions	750.00	100	Total volume	3958.37	100
			Beam width	250.00	100	Size (2/3)	600.00		Rentable area	26175.6	100
			Total volume beams	753.23	100	Size (3/3)	450.00		BAI	0.30	100
						Total volume columns	1633.50	100			
FtF height 3.3 m											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Floor thickness	331.00	100	Bending moment beam	229.45	100	Bottom column load	9454.40	88	Number of piles	276	100
Total volume floors	1428.77	91	Beam height	500.00	100	Column dimensions	700.00	93	Total volume	3641.75	92
			Beam width	250.00	100	Size (2/3)	600.00		Rentable area	23796.00	91
			Total volume beams	684.75	91	Size (3/3)	450.00		BAI	0.31	104
						Total volume columns	1528.23	94			
FtF height 3.5 m											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Floor thickness	331.00	100	Bending moment beam	229.45	100	Bottom column load	8824.11	82	Number of piles	232	84
Total volume floors	1333.52	85	Beam height	500.00	100	Column dimensions	700.00	93	Total volume	3341.68	84
			Beam width	250.00	100	Size (2/3)	550.00		Rentable area	22209.60	85
			Total volume beams	639.10	85	Size (3/3)	400.00		BAI	0.32	105
						Total volume columns	1369.06	84			
FtF height 4.0 m											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Floor thickness	331.00	100	Bending moment beam	229.45	100	Bottom column load	7878.67	73	Number of piles	232	84
Total volume floors	1190.64	76	Beam height	500.00	100	Column dimensions	650.00	87	Total volume	3059.27	77
			Beam width	250.00	100	Size (2/3)	550.00		Rentable area	19830.00	76
			Total volume beams	570.63	76	Size (3/3)	400.00		BAI	0.33	110
						Total volume columns	1298.00	79			
FtF height 4.5 m											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Floor thickness	331.00	100	Bending moment beam	229.45	100	Bottom column load	6933.23	64	Number of piles	232	84
Total volume floors	1047.76	67	Beam height	500.00	100	Column dimensions	600.00	80	Total volume	2667.95	67
			Beam width	250.00	100	Size (2/3)	500.00		Rentable area	17450.40	67
			Total volume beams	502.15	67	Size (3/3)	400.00		BAI	0.34	114
						Total volume columns	1118.04	68			

FtF height 6.0 m											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Thickness	331.00	100	Bending moment beam	229.45	100	Compression split	10084.69	94	Number of piles	276	100
Volume split	1524.02	97	Beam height	500.00	100	Compression nosplit	5042.35	47	Total split	3736.34	94
Volume nosplit	762.01	48	Beam width	250.00	100	Size (1/3)	700.00	93	Total nosplit	2609.13	66
			Volume split	730.40	97	Size (2/3)	600.00		RA split	25382.40	97
			Volume nosplit	365.2	48	Size (3/3)	450.00		RA nosplit	12691.20	48
						Volume	1481.92	91	BAI	0.40	132
FtF height 9.0 m											
Kerto Ripa		[%]	**Beams**		[%]	**Columns**		[%]	**Total**		[%]
Thickness	331.00	100	Bending moment beam	229.45	100	Compression dbl split	10399.8411	97	Number of piles	276	100
Volume dbl split	1571.6448	100	Beam height	500.00	100	Compression split	6933.23	64	Total dbl split	3958.37	100
Volume split	1047.76	67	Beam width	250.00	100	Compression nosplit	3466.61	32	Total split	3183.41	80
Volume nosplit	523.88	33	Volume dbl split	753.225	100	Size (1/3)	750.00	100	Total nosplit	2408.46	61
			Volume split	502.15	67	Size (2/3)	600.00		RA dbl split	26175.60	100
			Volume nosplit	251.075	33	Size (3/3)	450.00		RA split	17450.40	67
						Volume	1633.5	100	RA nosplit	8725.20	33
									BAI	0.51	171

Appendix D: Calculations Economic and Circular Meaning BAI

D.1. Microeconomic Analysis

Calculation NPV baseline

Standard values				
Inflation		3	%	*Estimated by author*
WACC		10	%	*Estimated by author*
Value of land		800.00	€/m^2	*Source: Municipality of Amsterdam [72]*
Mean rent Amsterdam		20.00	€/m^2/month	*Source: Pararius [86]*
Exploit costs (incl. Maintenance)		37.80	€/m^2/year	*Source: Arcadis [9]*
Demolition costs		45.00	€/m^2	*Source: Arcadis [9]*
Retrofitting costs		22.50	€/m^2	*Estimated by author*
Comment: Retrofitting costs are estimated as half of demolition costs due to lack of literature. Only interior needs retrofitting.				

Material costs				
Kerto Ripa floor		90.00	€/m^2	*Source: Metsä [68]*
Comment: For option 1,2,3 different prices apply, namely: 90 €/m^2 ; 105 €/m^2 ; 110€/m^2 respectively. These prices are indicative.				
Beam GL32h		1,232.63	€/m^3	*Source: Price list ABT*
Column GL32h		1,232.63	€/m^3	*Source: Price list ABT*
Concrete C30/37		124.77	€/m^3	*Source: Price list ABT*
Vibro pile ; 12.5 m, 610 mm		3000.00	€/pile	*Source:Casadata[17]*

Building properties				
Building size	L x W	25.2 x 36.0	m	
Number of stories	n_{story}	33		
Rentable area	A	26175.6	m2	
Economic life span	n	50	years	

Income				
Rent	$Rent = Mean\ rent \times A \times 12\ months$			
		6,282,144.00	€/year	
Exploit costs	$Exploit\ costs = A \times Exploit\ costs$			
		989,437.68	€/year	
Net rent	$Net\ rent = Rent - Exploit\ costs$			
		5,292,706.32	€/year	
Total rent income (PV)	$Total\ rent = \sum_{i=1}^{n} \frac{Net\ rent_{i-1}(1+inflation)^{n_i}}{(1+WACC)^{n_i}}$			
		72,786,467.13	€	
Property value		2,100.00	€	*Source: Table 6*
Comment: Baseline can adapt to prison, lodging or residential. The maximum property value of these functions is taken. For other alternative designs different functions can be possible.				

Remaining value (PV)	$Remaining\ value = \frac{A \times (Property\ value \times (1 + inflation)^n)}{(1 + WACC)^n}$		
		2,052,782.41 €	
Value of land (PV)	$Value\ of\ land = L \times W \times Value\ of\ land \times \frac{(1 + inflation)^n}{(1 + WACC)^n}$		
		27,103.16 €	

Expenses			
Retrofitting costs (PV)	$Retrofitting\ costs = \frac{A \times Retrofitting\ costs}{(1 + WACC)^n}$		
		5,017.01 €	
Demolition costs (PV)	$Demolition\ costs = \frac{A \times Demolition\ costs}{(1 + WACC)^n}$		
		10,034.02 €	
Material costs floor		2,355,804.00 €	
Material costs beams		928,447.73 €	
Material costs columns		2,013,501.11 €	
Material costs core		327,334.10 €	
Material cost piles		828,000.00 €	
Total material costs		6,453,086.93 €	
Initial investment	$Initial\ investment = 8 \times Total\ material\ costs$		
		51,624,695.45 €	
Comment: Total material costs are estimated as 25% of the total construction costs, which are estimated as 50% of the investment costs.			

NPVs			
NPV scenario reuse	$NPV_R = Total\ rent + Remaining\ value - Initial\ investment - Retrofitting\ costs$		
	NPV_R	23,209,537.08 €	
NPV scenario demolition	$NPV_D = Total\ rent + Value\ of\ land - Initial\ investment - Demolition\ costs$		
	NPV_D	21,178,840.83 €	
BAI		0.20	
NPV combined	$NPV_{comb} = BAI \times NPV_R + (1 - BAI) \times NPV_D$		
	NPV_{comb}	21,594,229.90 €	

D.2. Circularity Analysis

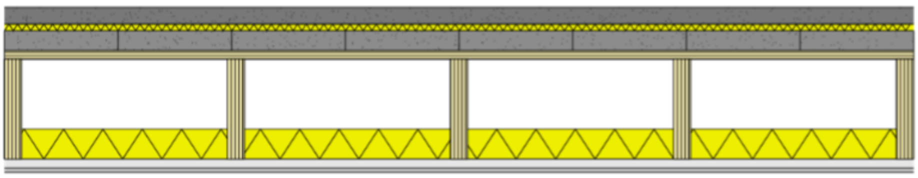
Calculation environmental impact baseline

Standard values floor		
Kerto Ripa floor	13.19 €/m³ LVL	*Source: Metsä Wood [65]*
Finishing floor 50 mm	0.72 €/m²	*Source: NMD [74]*
Gypsum plate 2x12.5 mm	0.60 €/m²	*Source: NMD*
Contact isolation 30 mm	0.22 €/m²	*Source: NMD*
Mineral wool isolation 90 mm	0.66 €/m²	*Source: NMD*
Concrete tiles 60 mm	1.73 €/m²	*Source: NMD*
Steel strips 27 mm	0.32 €/m²	*Source: NMD*

Standard values skeleton		
Beams GL32h	1.25 €/m³	*Source: NMD*
Columns GL32h	1.25 €/m³	*Source: NMD*
Core C30/37	40.74 €/m³	*Source: NMD*

Standard values foundation		
Vibro foundation 12.5 m ; 610 mm	10.52 €/m pile	*Source: NMD*

Shadow cost floor
Using material volumes from Chapter C.3



Source: Metsä Wood [66]

Kerto Ripa floor	20,734.70 €	
Finishing floor 50 mm	18,720.79 €	
Gypsum plate 2x12.5 mm	15,694.89 €	
Contact isolation 30 mm	5,801.39 €	
Mineral wool isolation 90 mm	17,404.16 €	
Concrete tiles 60 mm	45,375.40 €	
Steel strips 27 mm	16,679.09 €	
Total floors	140,410.42 €	

Shadow cost skeleton *Using material volumes from Chapter C.3*		
Beams GL32h	940.96 €	
Columns GL32h	2,040.63 €	
Core C30/37	106,880.34 €	
Total skeleton	109,861.93 €	

Shadow cost foundation *Using material volumes from Chapter C.3*		
Vibro foundation 12.5 m ; 610 mm	36,281.83 €	
Total foundation	36,281.83 €	

Total shadow cost		
Total shadow cost	286,554.18 €