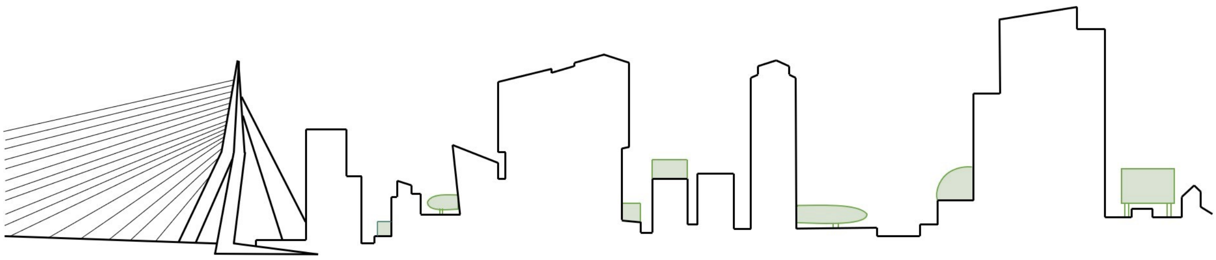
Delft University of Technology

Faculty of Civil Engineering and Geosciences

Timber Upward Extension

Exploration of the use of parametric modelling and machine learning for initial building extension design



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May, 2021

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Exploration of the use of parametric modelling and machine learning for initial building extension design

by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Friday May 21, 2021

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Preface

This research project was carried out to fulfill the requirements to obtain a Master of Science degree in Civil Engineering, Building Engineering track with specialisation of Structural Design.

First, I would like to thank the graduation committee members for their guidance and support from developing an interesting topic to dealing with unexpected challenges and obtaining satisfying results. I am grateful to Dr. ir. H. R. Schipper for leading as the committee chair and providing accurate remarks, to Ir. A. C. B. Schuurman for the help developing ideas and answering structural design questions (and mentioning the words “machine learning” in the first place), to Ir. P. Eigenraam for assistance with parametric modelling and to Dr. B. Basharirad for the help and advice when learning about machine learning.

Special thank you to my family for their endless support and to my friends for making these study years an unforgettable experience.

G. Bikulčiūtė
Delft, May 2021

Abstract

The concept of sustainability currently is of great importance as it aims to develop while protecting the environment. One of the major issues it takes into account is urbanisation which causes a phenomenon of urban sprawl. In order to fight it, the strategy of urban densification is introduced which focuses on saving the non-urban areas and better management of already developed areas. Building upward extension is one of the methods applied to densify already busy city centers, however, investigating the feasibility of placing an extension on top of an existing building requires a significant amount of time and effort from structural engineers. Therefore, this research aims to explore computational tools that would simplify the initial exploration process and make the option of extension more appealing.

Theoretical background part of the thesis is intended to analyse conditions and limitations for building reuse, upward extension and use of timber. It is found that the main requirements for building reuse are either historic or architectural value of a building or good condition of its structure. In order to place an extension on top, there are three predominant methods: using the remaining structural capacity, changing the stability system or separating the old and the new structures. The choice of which method is optimal depends on the structural assessment of the existing building. Lastly, timber as a structural material for an extension is found to be the most advantageous due to its lightweight, quick and quiet construction process and sustainability.

The practical part of the research aims to explore parametric modelling and machine learning (ML) in order to produce a proof of concept ML tool which predicts how much an existing building can be extended based on its parameters. The main issue for the development of a legitimate ML model is the lack of data - there are not many realised timber extension projects in the Netherlands, moreover, information about them is difficult to be obtained. As a solution, a fictional project database is created by employing parametric modelling.

For the first step, information is collected about seven realised upward extension projects in the Netherlands. This data together with the knowledge acquired in the theoretical background part defines the object for the parametric model: existing building has initial industrial function and concrete rigid frame structure while a timber extension is placed on top mainly making use of the structural reserve with strengthening of the existing structure or changing the stability system.

The parametric model is built using Rhino plug-in Grasshopper by dividing it into two parts. Model 1 analyses existing structures with the goal to establish structural reserve while model 2 examines extensions and helps to determine how many additional storeys can be constructed. Six parameters defining existing buildings are chosen for iteration: ratio between the length and the width of the building, its floor height and number of floors, stability type, concrete strength and column cross-section size. By changing these parameters, a database of 8 652 fictional projects is generated.

For the ML, the data is analysed and used for supervised learning where regression task is performed. Multiple linear regression (MLR) algorithm is initially applied to make predictions which are validated using 5-fold cross validation (CV) and evaluated by calculating errors: mean

error (ME), root mean square error (RMSE), the largest errors and the amount of unacceptable predictions. However, all checks show a large error which on average makes up around 47%. To find the cause for the error, the parameter analysis is carried out which concludes that it is a combination of four parameters: number of floors, stability type, concrete strength and column size. The probable reason for it is nonlinear relation between these parameters and the output. As Grasshopper, also used for creation of ML model, does not allow customisation of the MLR component, the data is used for nonlinear regression (NLR) which shows a large improvement of the performance of the model as the average error reduces to around 10%. This proves that including nonlinear contribution of parameters that cause the error in MLR model would improve it.

Finally, the research presents a possibility and an example of using ML for extension exploration. The use of ML model during the initial stage of upward extension projects seems very appealing due to the quick feedback with limited information provided. A useful database of realised projects with a selection of structural parameters, the analysis indicates that the most important are stability type, concrete strength and element size, together with the incorporation of non-structural ones and a customised ML model should provide accurate predictions. However, the current problem of lack of data about realised extension projects needs to be solved. In addition, the research shows that parametric modelling can be useful during the initial extension exploration stage as well. Even though building a parametric model for a specific project requires more time and information, it provides structural analysis and extension alternatives can be explored more in detail.

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1 Introduction

1.1 Motivation

This master thesis is a research on building reuse with the focus on transformation of spaces by building upward using lightweight timber structures and exploration of the feasibility by the use of computational tools.

The initial idea rises from the concept of sustainability which nowadays seems to be conveyed in every aspect of life. The world society after analysing the future prospects has decided to take action in order to make the planet a better place to live in not only for the present but also for the future generations. This leads to new regulations and guidelines in industrial sectors, especially the ones with a significant environmental impact as the construction industry.

One of the major issues is urbanisation and, from the construction point of view, the possibilities for building new structures in the future are declining while the need to learn using what is already created is growing. The architect Carl Elefante stated that "The greenest building is ... one that is already built", noting the need to preserve, conserve, restore, and adapt (Elefante, 2018) which is the main inspiration for this thesis topic.

By now, there are quite a few theses written by students of Delft University of Technology regarding building reuse focusing on assessing existing buildings and vertical extensions as well as high-rise timber structures. This research aims to explore timber upward extensions and introduce them to a new field by the use of computational tools, parametric modelling and machine learning, which would make the reuse of existing buildings a more appealing choice.

1.2 Research background

1.2.1 Urbanisation, urban sprawl and urban densification

The concept of sustainability recognizes values of human existence and growth potential for future generations and, therefore, establishes criteria for economic development. One of the major problems the doctrine of sustainability takes into account is urbanisation. Cities grow due to population shifting from rural areas to urban areas and more area and volume of buildings are needed to accommodate the increasing number of inhabitants (Pelczynski and Tomkowicz, 2019).

Consequently, a phenomenon of urban sprawl occurs, which was defined by Nilsson et al. (2014) as "the low-density expansion or 'leapfrog development' of large urban areas into the surrounding rural landscape". One driving force behind this expansion is population growth and the trend towards urban sprawl is clear in dense areas with evident growth as the Netherlands.

Figure 1.1 below shows the growth of population in the Netherlands in the last ten years and Figure 1.2 presents the growth of urban population during almost the same time period. Total Dutch population increased more than 4% in the last decade while urban population was growing by around 1% each year. This leads to a growth of urban population by almost 10% which is more than a million people who migrated from rural regions to the cities.

The Netherlands, with 508 people living in each square kilometre in 2020 (Worldometers.info, 2020), is a country with one of the highest densities in Europe and an issue of housing shortage.

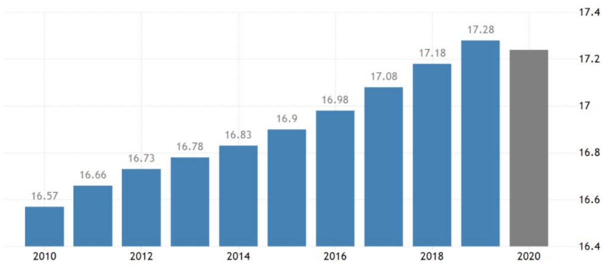


Figure 1.1: *Population growth in the Netherlands 2010-2020 (Trading Economics, 2020b)*

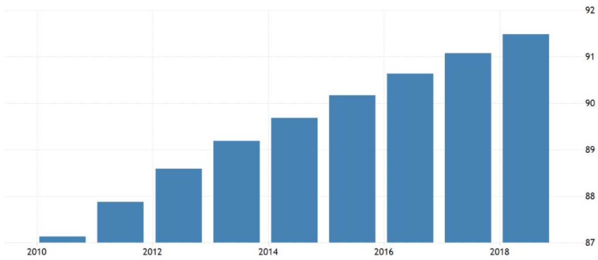


Figure 1.2: *Urban population growth in the Netherlands 2010-2019 (%) (Trading Economics, 2020a)*

Moreover, urban sprawl is a global problem which occurs in regions with declining populations too. Haase et al. (2013) explains it by a growing number of households as one-person households become more popular and an increase in per capita living space which is related to positive income development and changing quality of life standards as preference for more spacious living arises. To sum up, urban sprawl is a result of population and economy growth as well as changing ways of living which causes it to be a worldwide problem.

The PLUREL project (Nilsson et al., 2014), which is one of the recent research projects carried out on urban issues, identified the most important negative aspects of urban sprawl:

- Consumption of land, loss of highly productive agricultural land
- Destruction of biotypes and habitats with fragmentation of landscape structure and decline of ecosystem services
- Less open space, longer distances to attractive recreational areas
- Increased dependency on private car use, traffic congestion, longer commuting times and distances, climate change emissions, noise and air pollution

As a solution, the strategy of urban densification is introduced. It focuses on saving non-urbanised areas, better management and intensified exploitation of already developed areas with attention to quality of life in cities. Four methods of urban densification are distinguished (Pelczynski and Tomkowicz, 2019):

- increasing the use of existing buildings (change of function)

- intensification of existing development (building up on free spaces)
- downward and upward extensions
- replacement of existing buildings (demolition and new construction)

The main idea of these methods is to increase efficiency of use of natural resources. Moreover, transformation projects lead not only to an increase of usable space but also give an opportunity to improve the existing situation. Another positive side effect - economic simulation, created additional value activates sources of funds. (Pelczynski and Tomkowicz, 2019)

On the other hand, densification can cause several problems as air pollution, heat islands, wind discomfort, heritage neglect, daylight and solar access reduction, pressure on urban infrastructure (Amer et al., 2017). In order to counteract, densification should focus on neighborhoods with best location and urban services, for example, public transportation routes, which is usually included in urban planning (Amer et al., 2017).

While all densification methods mentioned above have their advantages and disadvantages, adaptation of unused space (change of function) is the most sustainable option as it does not require many new resources. The least efficient method is replacement of existing buildings due to the largest expenses and effect on the environment.(Pelczynski and Tomkowicz, 2019)

Probably the most optimal method is upward extension as it not only gives an opportunity to adapt a space to satisfy emerging new needs but also allows to create another layer of a city. Especially if only one or two storeys are added, there is no significant effect on daylight access while a new life is given to an unoccupied space. (Pelczynski and Tomkowicz, 2019)

Some studies concerning roof stacking have been already made in European capitals. The results show that Brussels Capital Region in Belgium could accommodate more than 59,000 additional inhabitants, which represents approximately 30% of the expected increase in population by 2040 (Amer et al., 2017), by only increasing the height of the existing buildings. In addition, a study in Vienna, Austria, identifies a number of 3,600 residential units to be realized via rooftop extension until 2035 (Rissetto et al., 2018) while a study in the Netherlands notes a capacity for between 100,000 and 300,000 homes within the existing cities (Donkers et al., 2018).

1.2.2 Existing buildings stock

At the beginning of 2020, the total building stock in the Netherlands was over 9 million. The major part of it, 87% which is almost 8 million, was housing and the rest, 13% or over 1 million, was non-residential building stock. Although, it is important to note that here the term 'housing' covers all objects with at least a residential function and possibly one or more other utilisation functions and non-residential buildings are objects with one or more utilisation functions but without a residential function. (CBS, 2020)

Nevertheless, there is a high demand for affordable homes in the country while around 50 million square meters of non-residential function space is vacant. In the near future this number might increase to between 75 and 100 million. (Donkers et al., 2018) Therefore, there is a high potential for building reuse and transformation.

The year of construction can say a lot about the condition of the building. It gives an indication of the material quality and methods of construction. For instance, homes built before 1920 are less solidly built while the quality from the period after that is very high. After the World War II the quality dropped down due to the major housing shortage as the focus was on producing many homes instead of high-quality homes. In the 70s and 80s the focus on the quality of buildings was brought back and in 1990 the Building Decree was introduced, which significantly increased the quality and luxury of buildings. (Atlas Leefomgeving, 2018)

Figure 1.3, Figure 1.4 and Figure 1.5 present fragments of maps of buildings by year of construction in Amsterdam, Rotterdam and The Hague which are the largest cities in the Netherlands. These figures show that the majority of the buildings in the main parts of the cities were built between 1900 and 1950 with the exception of Rotterdam which was mostly rebuilt after the World War II. Moving further from the city centers the buildings get more recent, mostly built after 1975, revealing the urban spread.

Figure 1.3: *Buildings by year of construction, Amsterdam (3D Geoinformation Group, 2020)*

Figure 1.4: *Buildings by year of construction, Rotterdam (3D Geoinformation Group, 2020)*

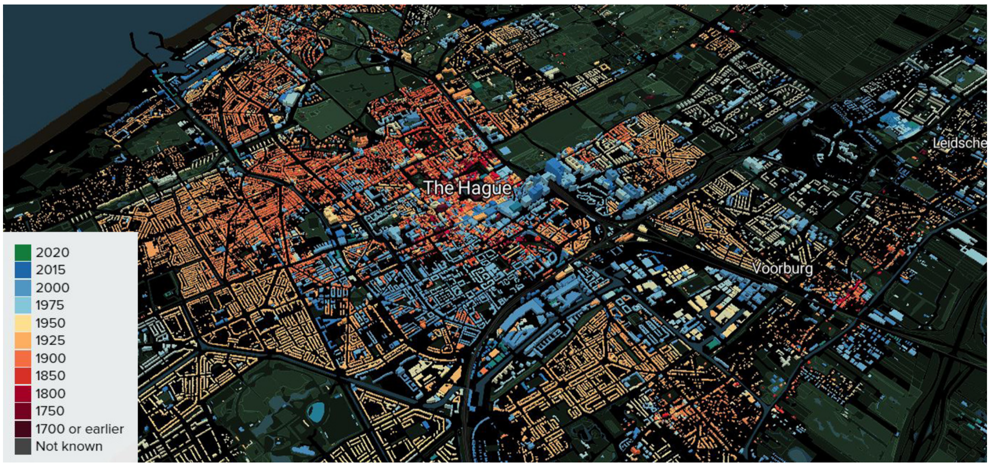


Figure 1.5: *Buildings by year of construction, The Hague (3D Geoinformation Group, 2020)*

As mentioned above, knowing the construction year of a building helps to assess its current state and potential. One of the aspects to be taken into consideration is building regulations followed for the design.

The history of building standards in the Netherlands starts with the Housing act in 1902 which focuses on the improvement of living conditions (Lurvink, 2019). The overview of the standards for structural safety in use with the different Building Regulations is presented in Table 1.1.

Table 1.1: *Overview of the standards for structural safety in use with the different Building Regulations (Lurvink, 2019)*

1902	1992	2012
Municipalities set minimum requirements through local building ordinance, which (may) refer to Standards	National building regulations containing minimum requirements, refers to Standards	See 1992
GBV 1912 N1055:1949 NEN 3850:1972 VB 1974	NEN 6700-series	Eurocodes + National Annexes

Table 1.2: *Evolution of standards (Lurvink, 2019)*

N1055:1949	NEN 3850:1972	NEN 6700:1990	EN 1990:2005
24 pages Contained: Basis of design Actions Materials	Introduction of semi-probablistic approach Parts for: Basis of design Actions Materials	Assumed series would be replaced by Eurocodes in due time Parts for: Basis of design Actions Materials Getechnics Bridges	Parts for: Basis of design Actions Materials Geothechnics Bridges Other structures Seismic design
Did not include concrete, which was in a separate standard	Bridges were available in separate, loosely connected standards	Series was written to comply completely to building regulations in terms and definitions	Developed and published to allow easier exchange of services and goods through Europe

The first building regulations were GBV 1912 (in Dutch: Gewapend Beton Voorschriften meaning Reinforced Concrete Regulations), released in 1912, introducing regulations for reinforced concrete in the field of technology, execution and calculation (Gijsbers, 2012). It was followed by GBV 1918, GBV 1930, GBV 1950 and GBV 1962. Each of them being more informative and extensive. The last edition, GBV 1962, showed a significant improvement after GBV 1950 and a rapid development of the technique after the World War II with the most research done. After GBVs, a series of VBs (Concrete Regulations) followed that included rules from practice and very detailed explanations.

Table 1.2 presents evolution of standards in the Netherlands mentioned in Table 1.1 as well. First technical foundations for building regulations TGB 1949, or N1055:1949, were released in 1949 containing parts for basis of design, actions and materials and used by engineers together with GBVs. These regulations were followed by the second edited edition TGB 1955, in 1955, and TGB 1972, or NEN 3859:1972, in 1972. The latter one was the first to include safety margins as research in the fields of safety assessment was done. (Nederlands Normalisatie Instituut, 1972)

In 1983 the idea was born to deregulate the regional differences through a national building regulation, which became active in 1992 (Table 1.1). Moreover, the Dutch standards for structural safety were updated too and the NEN 6700-series were published, a suite of standards which in layout was similar to the Eurocodes (Table 1.2). It even included an explanation that Eurocodes would replace Dutch standards in the future which eventually happened in 2012 when all the National Annexes were completed. (Lurvink, 2019)

Knowing the year of construction and the building regulations that were followed for the design are the initial keys in determining the existing structural potential of the building. The difference between the past and present methods of construction, types of structures and minimum requirements for strength and safety assists in analyzing if the structure is capable to hold extra floors brought by vertical extension.

1.2.3 Upward extension

Upward extension is one of the building transformation and urban densification methods, however, not very popular yet. In case of the Netherlands, there is a high percentage of vacant office buildings which is the main driver for transformation projects, therefore, the regulatory system encourages these processes in terms of costs, reducing obstacles and constraints. (Olivadese et al., 2017)

Furthermore, there already is a number of projects that have been realized and one of the interesting examples is De Karel Doorman building in Rotterdam (Figure 1.6). The challenge in this project was to keep the existing building, built in 1951, as original as possible due to its architectural value and add 16 stories of apartments on top, using the existing load bearing system of columns and the pile foundation. Luckily, the existing building was well documented and the tests carried out showed larger capacity of foundations than expected and high confidence in quality of the original construction. (Hermens et al., 2014)

(a) *Original building 'Ter Meulen' (Hermens et al., 2014)*

(b) *De Karel Doorman new building (van Duivenbode, 2012)*

Figure 1.6: *De Karel Doorman transformation*

Another example is Fenix I (Figure 1.7), a former warehouse built in 1922 in Rotterdam. The goal for the transformation project, realised in 2019, was to build 230 apartments and one parking garage within the plot. However, the existing structure was not capable to bare the new requirements which lead to a design of a steel table structure that was realised above the existing building and placed on steel columns with new foundation. (Rietbergen, 2019)

Figure 1.7: *Fenix I, Rotterdam (Goodwin, 2019)*

These projects seem quite exceptional having different problems and original solutions. Therefore, it peaks an interest in how to find some generalized guidelines that structural engineers could follow when starting to work on reuse projects with upward extension possibility, so that challenges awaiting would look more appealing.

1.3 Problem definition

A phenomenon of urban sprawl caused by rapid urbanisation is a global issue as explained in section 1.2.1, although a solution, urban densification, has been introduced. The implementation of it is already partly being done by urban planning, however, upward extension projects, as one of the densification methods, are still quite rare. Furthermore, the realised projects are usually called original and unique, even though due to the sustainability problems being solved, they should become a lot more common.

The current construction sector is used to creating new structures and now it is a traditional way for building, moreover, we learnt how to do it well and fast. Working on the reuse projects, on the other hand, can be a lot more time consuming and attention requiring as the assessment of the existing situation takes a significant part of it. A current state needs to be evaluated and possible previous mistakes to be fixed as well as ways for improvement to be found. It is challenging and might be intimidating, especially for engineers with little experience.

Nevertheless, having high goals for sustainability requires improvements in every sector and making these changes simpler, more understandable and easy to implement can motivate to seek for even better solutions.

1.4 Research questions

The main question of this research is:

How to explore the feasibility of a timber upward extension on top of existing buildings?

This thesis aims to find a way to make the exploration of building reuse by upward extension using timber more appealing for developers and designers. The question asks for a quick evaluation tool, a starting point that the vertical extension design could be based on.

In order to find the answer to the main question, the following sub-questions were raised:

(Q1) How to determine if the building is good enough for reuse?

(Q2) When upward extension is a reasonable solution?

(Q3) When timber is the best choice for extension structure?

(Q4) How machine learning can be used to explore feasibility of extension?

(Q5) How to create a useful database of projects?

The first three questions (Q1-Q3) focus on setting the requirements for an existing building and a design in order to describe the feasibility of a timber extension. The last two questions (Q4-Q5) are related to the creation of a computational tool that would allow a simple initial analysis. The goal is to determine possibilities of machine learning in the scope of the research topic.

1.5 Methodology

The research is composed of four parts: introduction, theoretical background, computational tool design and conclusions.

Introduction:

The first part of the thesis aims to explain the motivation and background of the research and set the goals to be achieved. It includes initial literature review and research definition.

Theoretical background:

The second part consists of a literature review on three subjects: building reuse, upward extension and the use of timber for extension structures. The goal of this part is to gain knowledge about existing buildings and the design of extensions.

Computational tool design:

In this part, the database for the machine learning tool is created by collecting data from realized upward extension projects as well as generating data with the help of parametric design and structural analysis. Moreover, a research on machine learning theory and models is presented. Consequently, a machine learning model is built and trained with the prepared data in order to predict a number of additional floors that could be added on top of any existing building.

Conclusions:

In the final part all the findings and conclusions are summarized and results as well as the completion of the goals are discussed. Some recommendations for the future research are presented to suggest how the results could be improved.

Figure 1.8 presents the general outline of the research.

Figure 1.8: *Research outline*

2 Theoretical background

2.1 Building reuse

2.1.1 Introduction

The building sector is responsible for 40% of the global energy and resource consumption and it is infamously known as a forty-percent sector (Assefa and Ambler, 2017). Moreover, the waste produced by construction and demolition make up the largest waste stream in European Union in terms of mass. Even though large amounts of waste is reintroduced into the economy, due to the past building practices and the lack of generation of high-purity materials, elements from demolition works are not suitable for reuse. (EEA, 2020)

Building reuse is a sustainable alternative to the waste stream coming from demolition and it is included in building sustainability certifications such as BREEAM. Besides, majority of the buildings needed for upcoming decades in many developed countries are already built which brings a focus on improving the performance of existing building stock (Assefa and Ambler, 2017).

This leads to a concept of adaptive reuse, in this thesis represented by the term reuse. It is best described as "a process that changes a disused or ineffective item into a new item that can be used for a different purpose" (Bullen and Love, 2010) and it is conventionally described as "a process of retrofitting old buildings for new uses" (Clark, 2008), which allows existing structures to maintain their historic value and meet modern needs. For example, Figure 2.1 presents a project by Mei architects and planners where a former Gouda cheese warehouse was transformed into lofts.

Figure 2.1: *Gouda Cheese Warehouse Loft Apartments (van Duivenbode, 2017)*

Therefore, section 2.1 aims to analyze the process of building reuse as well as challenges related to it and answer the first sub-question of the research, determine the conditions for an existing building to be feasible for reuse.

2.1.2 Advantages of reuse

According to Bullen and Love (2010) the shift to reuse has become a trend in the last two decades as sustainability was prioritized. Adaptation can make a significant contribution to the sustainability of existing buildings (Bullen and Love, 2010), moreover, prolonging the useful time of buildings can save material, energy and reduce waste and transport related impacts in comparison to demolition and new construction (Assefa and Ambler, 2017).

Itard and Klunder (as cited in Bullen and Love, 2010) stated that demolition should be considered as an environmentally unfriendly process due to the generation of waste and the use of materials and energy. Adaptive reuse, as an alternative, suggests a more effective and efficient way of dealing with old buildings as "it reduces the amount of disturbance due to hazardous materials, contaminated ground and the risk of falling materials and dust" (Bullen and Love, 2010).

One more benefit of repurposing existing buildings is the avoidance of the development of new land which is especially important for institutions with limited access to land at the same location where they are as universities (Assefa and Ambler, 2017). Furthermore, it lowers the consumption of productive agricultural land for new construction.

Building reuse has a lot of advantages, mostly related to sustainability, therefore, it should always be included into considerations. However, execution of repurposing a building poses challenges, therefore, not every building will be good enough to be reused.

2.1.3 General considerations

The decision making of adaptive reuse is quite a complex process according to Noorzalifah and Kartina (2016) as it involves many stakeholders and each party has a different view and various levels of influence. Those involved in the decision making are the owners, developers, producer, investors, regulators and marketers and they all come from different backgrounds. For example, producer, or a professional team, will base their decision to reuse a building on the original architecture, structure, function, space and others.

As literature suggests lots of aspects to be analyzed, some generalizations need to be made, therefore, the main general considerations when it comes to building reuse in this thesis are: location, function change, historic value and cost.

Location

Many of the existing structures get considered to be reused due to their location. The importance is drawn to the market opportunity as some old buildings are on sites that are very desirable (Bullen, 2007) and land in some areas might be difficult to acquire. Proximity to transport and amenities and cost of land are included in the criteria for decision making as well (Noorzalifah and Kartina, 2016).

In some cases, a building might be chosen for transformation due to its position in a neighbourhood that is being redeveloped or in a very dense surrounding area. New construction requires space for material and equipment storage as well as access for transport while reuse projects already provides an envelope and does not need as heavy equipment. (Bullen and Love, 2010)

Function change

Another element to be considered is the relation between the old and the new functions. The compatibility of newly introduced uses with existing should be reviewed as well as possible contamination of the structure (Noorzalifah and Kartina, 2016). For example, former oil factory might be too polluted to be reused as a residential building.

Moreover, attention to the demand for building after adaptation must be paid (Bullen, 2007). Therefore, the new function has to fulfill modern needs, if no valuable functions can evolve from the old, the building in consideration might not be worth reusing.

Historic value

According to National Trust NSW (as cited in Bullen and Love, 2010), adaptive reuse has been a matter of common sense for centuries in urban areas around the world as it allows the preservation of historic buildings. They make people appreciate their culture and our heritage, they have ”architectural, aesthetic, historic, social, economic, spiritual and symbolic values that are enjoyed in the society and shall be preserved” (Hui and Leung, 2004).

When starting a conservation project, it is important to firstly identify and analyse the values of the historic building and place them according to the priority, so better choices can be done during the decision making in the design. Mostly the architecture and history should be respected as well as the quality of special characteristics preserved (Hui and Leung, 2004).

Table 2.1 presents the typical values of historic buildings.

Table 2.1: *Typical values of historic buildings or monuments (Hui and Leung, 2004)*

Emotional values	Cultural values	Use values
• Wonder • Identity • Continuity • Respect and veneration • Symbolic and spiritual	• Documentary • Historic • Archaeological and age • Aesthetic and architectural values • Townscape • Landscape and ecological • Technological and scientific	• Functional • Economic • Social • Educational • Political

Moreover, not all historic buildings are declared as heritage, national or municipal monuments, however, they still hold importance and research is recommended. For example, such building was the old building in the Fenix I project (Figure 1.7) as it was one of the few surviving the

World War II which made it well known and important for Rotterdam.

Cost

Probably one of the most important factors when considering reuse is cost, especially from the point of view of developer. For a long time reuse projects were seen as a lot more expensive than demolition and new construction due to the interventions and renovation techniques needed in order for it to meet new modern requirements as well as more difficult and costly maintenance. And it is still true that a poor state of a building can cause many technical issues, therefore, it is important to analyse the potential before making the decision for reuse. For example, a deteriorating external fabric of a building can cause significant problems (Bullen and Love, 2010).

On the other hand, if a building is in a good state, there can be many cost advantages to reuse. One of them is lower establishment costs, there is little or no demolition required, land acquisition is less expensive and many of the required utilities and services are already connected and may only need modernization. Moreover, the main structure is already in place. (Clark, 2008)

Consequently, there is a growing perception that it is cheaper to transform old buildings than to demolish and rebuild (Bullen and Love, 2010). According to Ball (as cited in Bullen and Love, 2010), in case of replacement by a new building, the value of the location and quality of a new building will not necessarily be better than the old one. And even if the performance of the transformed building is worse, it can be balanced by the social gains.

In contrary, if a building in consideration for reuse has historic value, the preservation of history and culture most often is the main priority and the costs get lower on the priority list. Even if such building is in a poor state, large amounts will be spent in order to save the building for future generations.

2.1.4 Structural considerations

Commercial and architectural aspects are not the only criteria when deciding on the usefulness of the building. From the structural point of view, the most important factors when considering building reuse are the condition of the structure and available data about the original design.

Impediments for reuse

According to Kendall (as cited in Bullen, 2007) the biggest impediment for reuse is design for a short life cycle. For example, older ordinary office buildings used to be designed for obsolescence. These type of buildings were intended to be more temporary and demolished when they are no longer useful. Moreover, such designs might not include consideration of long term actions and require very attentive and thoughtful maintenance. Low quality materials might have been used as well, because the structures were not expected to be in use for long.

Consequently, the second impediment is low quality construction (Bullen, 2007). In the past, it usually occurred during the time periods of low economy levels or the shortage of living space when the goal was to build fast. Low building quality might also result from financial restraints of developer when high quality is not prioritized.

However, even if buildings are designed for long use with high quality solutions and materials, they all eventually reach the end of their service life (Bullen and Love, 2010). At this point, prolonging their useful life might require too many interventions and replacements in order to bring them to the modern levels of safety and sustainability. Moreover, the evaluation and re-design might become very expensive.

Another reason why reuse should not be considered is obvious deterioration of structural elements (Bullen and Love, 2010). It is partially related to the previous aspect, the end of life of a building, as deterioration shows the end of the service life of separate structural elements (Figure 2.2). In order to reuse the building these elements would have to replaced or strengthened. In case many elements show signs of decay, the structure is no longer valuable enough to be saved.

(a) *Deteriorating reinforced concrete elements (Adobe Stock, n.d.)*

(b) *Corrosion of steel elements (pixabay, n.d.)*

Figure 2.2: *Examples of structural elements deterioration*

Lastly, according to Hilbert-Jan Kuijer, a structural engineer from ABT, (full interview is attached in Appendix A) original drawings and calculations are very important to have. The more structural information is available, the more possibilities there are to fully use the existing building and make interventions in the structure. If only information about the state of existing structure is collected from inspections and non-destructive research methods, it is very hard, almost impossible, to prove that the structure is able to withstand new and additional loads.

To conclude, the main impediments for reuse and reasons why owners should consider buildings to be no longer useful are:

- Design for short life cycle
- Low quality construction
- End of service life
- Deterioration
- Lack of original drawings and calculations

Possible issues

If there are no major impediments for reuse and it comes to more in detail consideration, the main factor to influence this choice is to what extent the program of requirements for a new building matches with the possibilities of the existing structure. These requirements differ for every specific project as they depend on the purpose of the building and choices of the owner, however, the main categories to examine for a structural engineer in most of the projects are the loads, connections, mechanical systems and materials.

Architectural changes and interventions result in the need for the structure to withstand new and additional loads (Ramos et al., 2018). These loads might occur due to penetrations or openings, for example, a need for intervention to install a pipe or a window, as well as impact of mechanical systems, for instance, a modern system might be heavier than the old one. Extra loading can also result due to the change of function and a new function might impose higher live loads in comparison to what was estimated in the original design.

Another aspect related to loads on the structure is the difference between the building codes followed for the original design and the recent eurocodes. The attention must be paid to the minimum requirements set for the elements in the older building regulations and the modern standards. In addition, as the Netherlands have a regulatory system that encourages transformation, there can be some reduction on the modern constraints (Olivadese et al., 2017). Some issues might occur due to the lack of connections in the existing building as was noted by Ramos et al. (2018) while researching an adaptive reuse project of an 18^{th} century infantry barrack. According to recent regulations, a certain amount of staircases and elevators are required for fire safety as well as the use of the disabled. Installing new connections might require cutting large openings which could impose additional loads. Also, availability to install them depends on the solutions of the existing structure, for example, pre-spanned floor slabs would create issues as they loose strength when a perforation is made (Divendal, 2013).

Another problem arising from reuse projects is outdated mechanical systems or even lack thereof in the existing building. In cases, where new installations are needed, for example, ex-industrial buildings, prisons or monasteries, the costs might become a lot higher than expected benefits, therefore, reuse can be financially unfeasible (Olivadese et al., 2017). Moreover, updating these systems could cause additional loads, which has to be taken into account in the reuse project.

Furthermore, complications arise due to the integration of mechanical systems and structure. As mentioned before, installations might be outdated and need to be changed while the structure has to be maintained. Consequently, separating the two becomes very costly or almost impossible. (Divendal, 2013)

The final problem arises from the ability to match existing materials. In order to perform repairs and interventions, additional elements and materials have to be used. Therefore, some testing might have to be done to analyze the compatibility between the original materials and the modern ones as well as the suitability of new elements for their purpose with regard to the effect on the existing situation and the influence in the structural behavior of the order in which the interventions will be performed (Ramos et al., 2018).

Furthermore, as mentioned in section 1.2.2, the regulations for reinforced concrete were changing over the years. These regulations described the technology, execution and calculation, consequently, buildings constructed in different years involve materials with varying properties. Figure 2.3 presents how the mix of reinforced concrete changed throughout the years. Since around 1930, the proportioning started to be based on the ratio of cement volume to concrete volume and water content was based on the required water to cement factor. As for additives, chlorides were only used when casting in the cold weather, later they started to be used as accelerators for prefabricated elements.

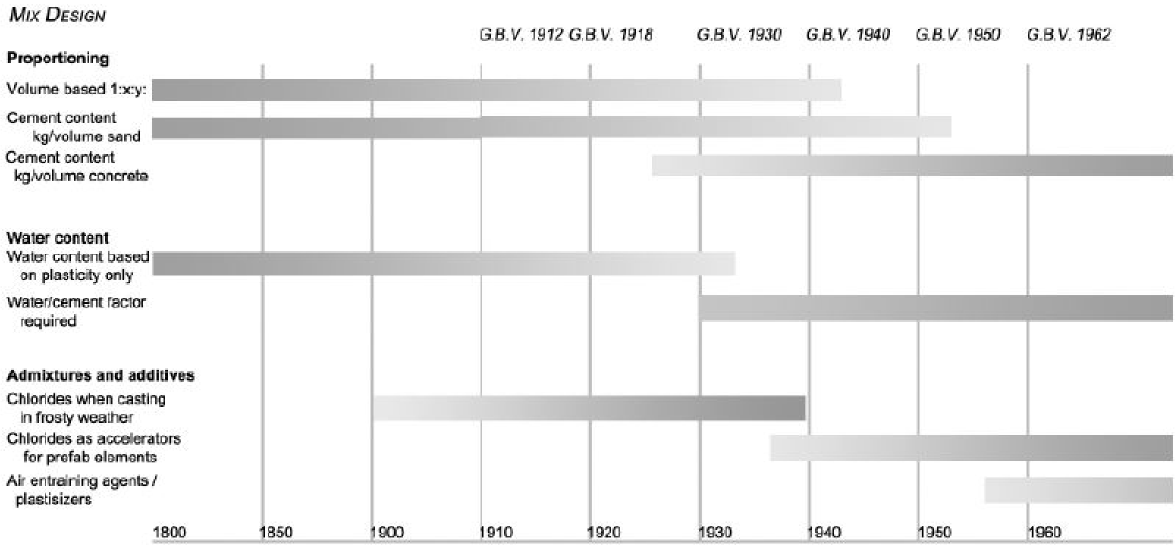


Figure 2.3: *Timeline for reinforced concrete mix design (Florisson, 2013)*

Due to different material properties it might be difficult to determine their strength, therefore, helpful conversion tables were introduced. Table 2.2 presents the conversion of reinforced concrete strength classes in previous building codes to the strength classes according to the eurocodes.

Table 2.2: *Conversion of reinforced concrete strength classes (Florisson, 2013)*

Standard	Composition / Strength class	Average cube strength	Allowable compressive stress	Safety Factor	f_{ck} [N/mm^2]	$f_{ck,cube}$ [N/mm^2]	Strength class
GBV 1912	135 kg | 5 – 6 HL	150	30	5	-	-	-
	135 kg | 4 – 5 HL	200	35	5,7	-	-	-
	135 kg | 4 HL	250	40	6,25	-	-	-
GBV 1918	125 kg | 2 HL	250	40	6,25	-	-	-
GBV 1930	125 kg | 2 HL	200	40	6,6	8	10	C 8/10
GBV 1940	*without bouwcontrôle*	150	40	3,75	8	10	C 8/10
	with bouwcontrôle	200	50	4	11	13	C 11/13
	with bouwcontrôle	250	60	4,16	13.5	16.5	C 13.5/16.5
GBV 1950	B150 *without bouwcontrôle*	150	40	3,75	8	10	C 8/10
	B200 *with bouwcontrôle*	200	50	4,16	11	13	C 11/13
	B250 *with bouwcontrôle*	250	60	3,75	13.5	16.5	C 13.5/16.5
EC 2		80 - 1500	-	2,8 – 3,1			

Conservation engineering

Structural technology can be current, archaic or obsolete. Archaic structural technology meets current requirements, however, in a form which is no longer used in new construction. For example, riveted connections in steel frames are becoming an archaic solution due to their replacement by the high strength bolts as well as the urge to design for reuse as riveted connections are permanent. On the other hand, obsolete structural technology meets the previous requirements but not the current ones and these solutions in their form could not be used in new construction. For instance, unreinforced masonry as old brick walls lack the ductility required in modern designs. (Abdelfatah and Friedman, 2019)

Knowledge about the history of structural technology and previously used structural solutions is crucial when it comes to working on renovation projects, especially with historic buildings. In these cases conservation engineering is brought into play. It can be defined as "the branch of conservation that deals with managing the structural well-being of a building, minimising alteration and extending its life for future generations" (D'Ayala and Forsyth, 2007). In itself it is a mixture of disciplines as structural engineer becomes familiar with the old buildings analysis and the design of their restoration with knowledge of the history of architecture, the history of the locality and technical architectural topics such as waterproofing (Friedman, 2001).

Figures below illustrate the importance of knowledge of general and technical history. Figure 2.4 presents the actual design of draped-mesh slab floor system which was developed in 1890s and was in common use between 1900 and 1930. It uses wire mesh that runs over the top of the floor beams and drapes down between the beams, as a result, the reinforcing wires act as a series of catenaries, carrying the floor loads in tension. (Friedman, 2001)

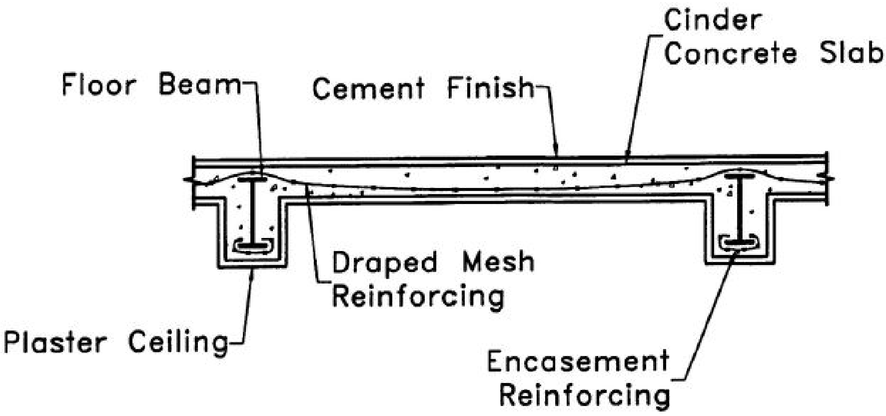


Figure 2.4: *Draped-mesh slab floor system (Friedman, 2001)*

Analysing the draped-mesh slab without the knowledge of the system would lead to incorrect conclusions showing the slab to be under-reinforced according to the modern standards (Figures 2.5 and 2.6). (Friedman, 2001)

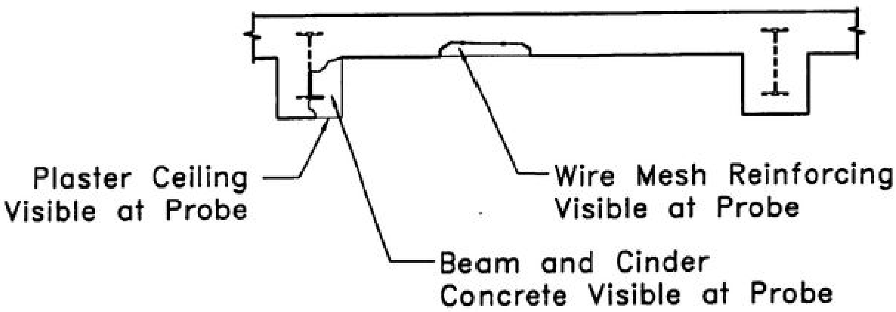


Figure 2.5: *Field observations (Friedman, 2001)*

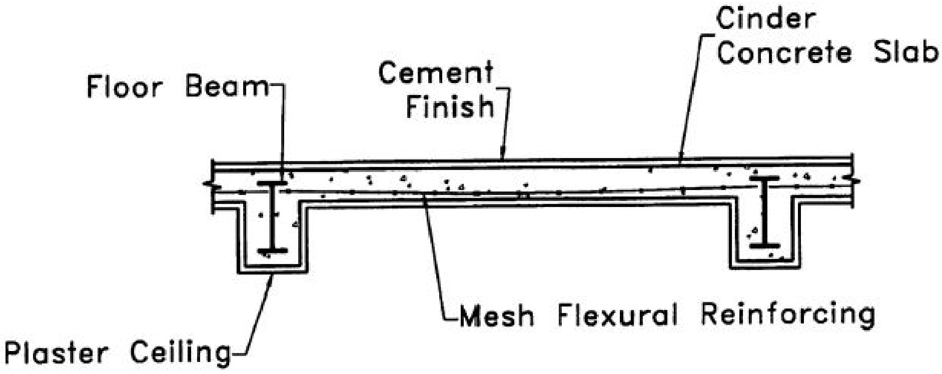


Figure 2.6: *Incorrect conclusion (Friedman, 2001)*

The first step in a conservation engineering project is a field investigation of the structure which includes identification of structural elements and structure types, eras of original construction and previous interventions as well as differentiation between structural and non-structural damage (Friedman, 2001). When working with an existing building it is important to not only make assumptions based on code-compliance and the status of technology used but also examine the structure on the case-by-case basis, especially when an obsolete structure is being analyzed (D'Ayala and Forsyth, 2007).

However, the new Dutch standard NEN 8700 on assessment of existing structures in case of reconstruction and disapproval applies to all existing buildings, regardless of their age. A building is classified as an existing building after it has been completed (Scholten and Vrouwenvelder, 2009). This standard shows how an opinion on the structural safety of the existing building can be determined together with the 58 Eurocodes as well as establishes the lowest limits of safety levels.

2.1.5 Conclusions

Building reuse has a lot of advantages, most of them related to sustainability which has become a priority in the present world, especially in the construction industry. Reuse is a beneficial alternative to demolition and new construction due to the reduction of material use, energy, waste.

However, there are conditions that apply for existing buildings in order to be considered worth saving. General considerations include building location, function change, historic value and cost. Buildings can be chosen for transformation based on their position in the city, relation between the old and the desired new functions as well as the costs required for the project, nevertheless, if a building has historic or architectural value it might be chosen for reuse despite not complying with other general conditions showing the importance of this value for society.

From a structural point of view, the main aspects for reuse are the condition of the structure and available information about the original design. Therefore, the biggest impediments for reuse are design for short life cycle, low quality construction, end of service life, deterioration and lack of original drawings and calculations. These factors signal that the structure in question is most likely no longer useful. If there are no major drawbacks of the structure, other aspects need to be examined: loads, available connections, mechanical systems and materials. Moreover, when working with existing buildings, especially archaic and obsolete structures, it is highly recommended to have some general and technical history knowledge in order to understand how those structural systems work.

To conclude, taking into account all the considerations, there are two main conditions showing that reuse of the building is useful and should be considered in more detail: (1) building has historic or architectural value as the society appreciates the heritage or symbolic meaning, it is important for future generations; (2) structure is in good condition as it is high quality with available data about the original design.

2.2 Upward extension

2.2.1 Introduction

As introduced in section 1.2.1, the Netherlands is a country with increasing population, especially urban population, which means that a number of inhabitants in urban areas, cities, is constantly growing. Moreover, the area of existing residential buildings is not capable to accommodate all the people which will increasingly become an even bigger issue. Unfortunately, building reuse provides the same area of the already existing buildings which will not be enough in the near future.

Therefore, the question is how to increase density in urban areas and provide more residential space while saving the existing buildings and contributing to the reduction of waste as well as use of materials and energy. The solution is one of the urban densification methods - upward extension. It means placing one or more additional stories on top of already existing structures which allows to create another layer of the city (Figure 2.7).

According to Bergsten (2005), extensions of existing buildings are "a natural way of the urban development and rebuilding process". Making use of new surfaces gives an opportunity to enrich urban structure and urban functions (Pelczynski and Tomkowicz, 2019).

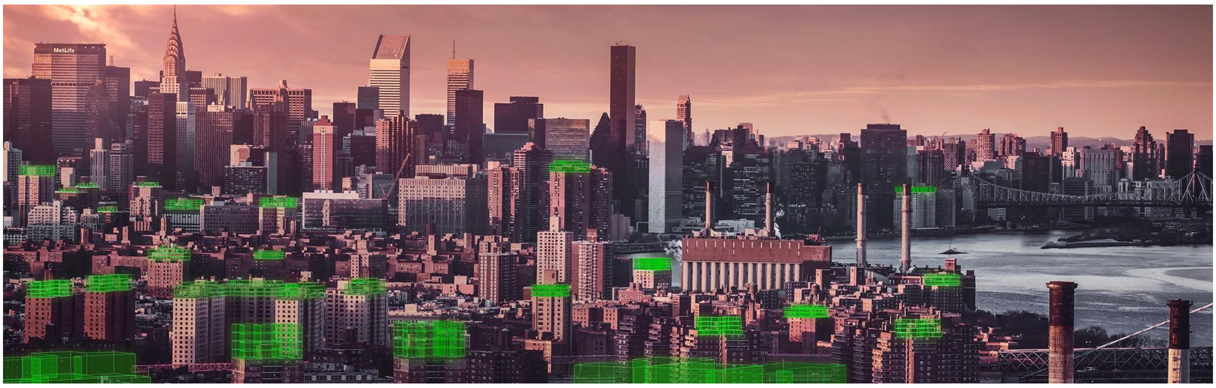


Figure 2.7: *The city above the city (MetsaWood, 2016)*

The goal of section 2.2 is to analyze possibilities of upward extension and answer the second sub-question of the research, set the criteria for when extension is a reasonable solution. For this purpose, in addition to literature research a short case study as well as some interviews with experienced engineers, H. Kuijer and K. Terwel, and a realtor J. Gibbons were carried out. Full interview transcripts can be found in Appendix A.

In this thesis, the terms vertical extension, upward extension and top up are used interchangeably.

2.2.2 Advantages of upward extension

The main advantage of upward extension - urban densification - was already introduced. Adding new layers to existing buildings helps accommodate the population growth as well as counteract the urban sprawl and save highly productive agricultural land and ecosystems. It also means that space occupied by the city is used more efficiently: soil consumption is reduced by using already developed land and the use of new land is minimised (Bertolazzi et al., 2019; Bergsten, 2005; Pelczynski and Tomkowicz, 2019), also, the potential for green spaces and recreational function is kept (Amer et al., 2017).

Another advantage is the use of already existing technical and service infrastructure, for example, sewerage, water, telecommunications, also, schools, roads and building structures are already in place (Bergsten, 2005; Pelczynski and Tomkowicz, 2019). In comparison, new built projects often require expansion of already existing systems which uses a lot of energy and materials. Pelczynski and Tomkowicz (2019) also suggest that one or two-storey extensions do not reduce sunlight and daylight to surrounding buildings, however, they benefit from great availability of these resources.

Existing buildings can benefit from extension as well since it can be combined with renovation and conversion (Bergsten, 2005). This could lead to improvement of technical status and aesthetic quality of existing building (Pelczynski and Tomkowicz, 2019) as well as more efficient use of load bearing capacity of structure (Bergsten, 2005). There is also a possibility to reduce energy consumption by implementing advanced energy-efficient technologies, improving energy and environmental performance of a building (Pelczynski and Tomkowicz, 2019; Amer et al., 2017).

As quality of existing buildings is enhanced, the value of properties increases (Pelczynski and Tomkowicz, 2019), especially since extension projects are carried out in highly developed areas, city centres. This can bring a financial advantage to the building owner as additional space created can be leased or sold and received profit can cover the renovation costs (Soikkeli, 2016).

Finally, upward extension suggests a lot of advantages in the areas of sustainability, saving resources, creating additional value for building owners and society.

2.2.3 Reasons to top up

In addition to all the advantages listed in the previous section, it is important to note that vertical extension projects are only reasonable in developed urban areas, where the need for additional space is high, therefore, cities and especially city centres. According to Amer et al. (2017), the increase of density should be focused in areas that are best located and equipped with urban services. For example, densification along the public transport nodes encourages inhabitants to choose public transport instead of private vehicles. Moreover, the bigger part of population lives close to main recreation and service points, less commute is necessary in general.

Living in city centres is becoming increasingly more attractive and demand for apartments is constantly growing. Due to the scarce space, building extensions can be financially interesting to present building owners (K. Terwel, Appendix A), therefore, one of the reasons to top up is commercial, creating additional area that could be sold (H. Kuijer, Appendix A).

The need to expand might become a reason to design a vertical extension as well, for example, a growing company that owns an office building in the city center. This solution arises due to the lack of space in such busy areas. The same factor causes many challenges during construction processes, therefore, a smaller scale project as vertical extension is a lot more appealing in comparison to demolition and new construction.

Another reasons for upward extension mentioned by H. Kuijer are sustainability and historic importance of existing buildings. They mostly play a role when densification of specific plot or area is needed. As mentioned in previous sections, reuse and extension reduce the consumption of many resources and reuse of historic buildings has emotional, cultural and use values.

Therefore, extending existing buildings vertically can be a great option in busy urban areas with good accessibility to already existing service systems. The motivation behind such projects can be gaining additional profit from already owned real estate, sustainability goals or preservation of historically important buildings.

2.2.4 Types and shapes of extensions

This section is aimed at getting a better insight on what are the possibilities for an extension structure and for this reason some case studies are analysed. These include Fenix I, Las Palmas and De Karel Doorman projects in Rotterdam.

Fenix I

The following information regarding the Fenix I project was obtained from the interview by the author with a structural engineer of ABT, ir. Hilbert-Jan Kuijer, full interview transcripts are presented in Appendix A. Moreover, some additional information, figures and drawings were provided by the interviewee as well.

Figure 2.8: *Fenix I, Rotterdam (ABT, 2019)*

The original building, San Francisco loods, was designed and built in 1916-1922, at the time it was the largest warehouse in the world. However, at the end of the World War II large parts of it were destroyed in the fire which lead to a rebuilding project in 1954. The former warehouse was divided into two parts and named Fenix I and Fenix II relating to their rise from the ashes.

In 2019, Fenix I went through another transformation when a vertical extension structure was added (Figures 1.7 and 2.8). The main team of this project was: Heijmans (client and contractor), MEI architects (architect), ABT (structural engineer) and LBP Sight (building physics consultant). Their goal was to create a living space of 212 apartments and a parking garage while saving the existing building which has historic importance to the city of Rotterdam.

The existing structure contained of two floors that were built in cast in-situ concrete. Four-spanned portals were placed every 8.6 m along the length of the building and stability was provided by their rigid connections. The strength of the concrete was determined to be C12/15, however, the reinforcement from the rebuilding period in 1950s was not known. The low strength of the existing structure created the first challenge in the extension project as it was not able to carry any additional load.

The decision was made for vertical load transfer not to place the extension structure directly on top on the existing. A steel table structure, called incision layer, placed over the existing building, called substructure, carries the extension of 6 to 9 floors, superstructure (Figure 2.9).

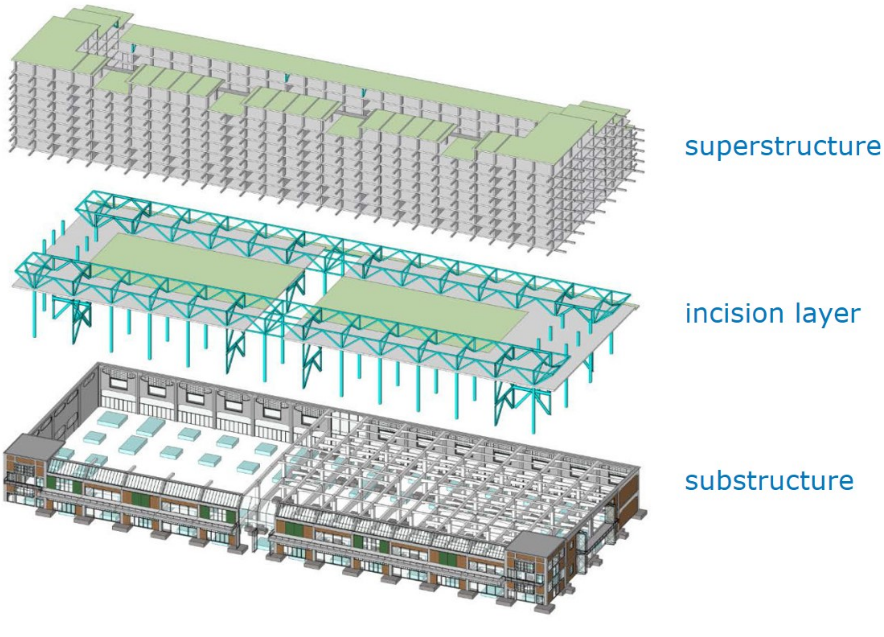


Figure 2.9: *Different structure layers of Fenix I (ABT, 2019)*

The incision layer formed by two longitudinal 2D trusses with a perpendicular truss every 8.6 m alternating with a concrete wall was rested on top of steel columns which pierce through the substructure. They are arranged with the same span as existing columns, 8.6 m, however, with an offset of 4.3 m. The layout is shown in Figure 2.10.

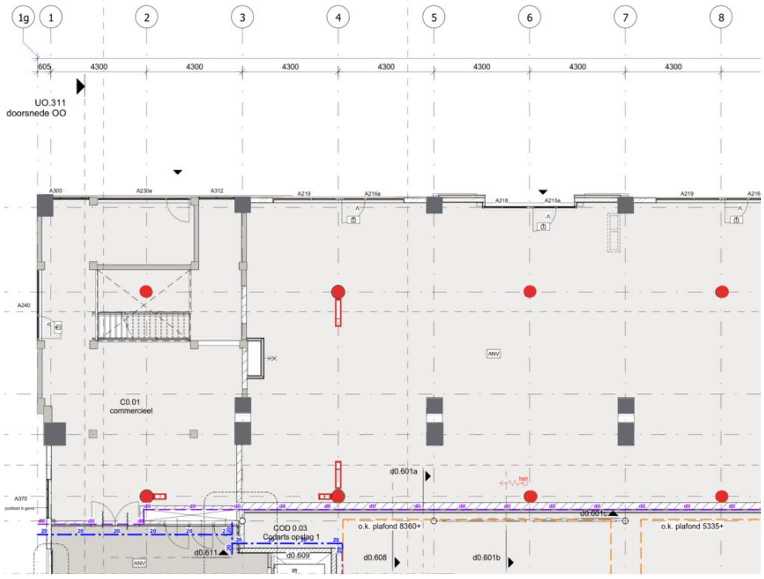


Figure 2.10: *Layout of steel columns (in red) supporting the incision layer (ABT, 2019)*

Another challenge of Fenix I transformation project was stability of the new structure. Due to addition of 9 new floors on the side of the harbour, horizontal loading increased a lot. This issue was solved by adding steel bracings through the existing structure as well as concrete stability walls in superstructure.

The final big challenge in the project was accommodating all the cultural functions which had different requirements. This lead to demolishing several floors, cutting beams and even removing some columns resulting in almost total recalculation of the structure.

The Fenix I building originally was a typical industrial building with a rigid frame structure. The aim to preserve the historic existing building and create a large additional residential area resulted in quite an exceptional extension project. Smart engineering solutions of constructing a transitional steel table structure and adding stability walls allowed the existing building to carry additional 6 to 9 floors.

Las Palmas

The following information about the Las Palmas project was provided by Sara Florisson in her master's thesis "Assessing Existing Structures 1910-1950" (2013).

Las Palmas was constructed in 1953 in de Kop van Zuid in Rotterdam and it was used as a departure hall for Holland America Line for almost 20 years. After the service line between Holland and the United States was cancelled, the building lost its function as well.

After 2000, a wide range of cultural initiatives took advantage of the empty industrial building to place their activities in and, finally, in 2003, Las Palmas was transformed into an art and culture centre with an office extension on top (Figure 2.11). The team working on this project was OBR Ontwikkelings Bedrijf Rotterdam and OVG Projectontwikkeling (client), Benthem Crowel Architekten (architect) and DHV (structural advisor).

Figure 2.11: *Las Palmas, Rotterdam (Bart van Damme, 2013)*

The existing building of Las Palmas had a basement and four floor layers with high ceilings averaging around 5.5 m. The load bearing structure consisted of floor plates supported by mushroom columns working as a rigid portal. The original design was well documented and suggested that structure has more capacity than was being used. Firstly, the former structural designer accounted for two additional floors to be placed on top. Secondly, engineers from DHV were expecting that the strength of concrete will have increased over time. Therefore, technical assessment was performed with column samples taken from each floor level. The results showed that the strength values had increased three to six times in comparison to the original design.

These findings were followed by a design of an egg-shaped office building to be constructed on top on the existing building. As the original structure accounted for two more floor layers and one of them was already erected during the construction phase, there was still capacity for one more cast in-situ storey. The decision was made to use lightweight steel structure, which allowed for two more additional layers. The columns of the new structure were placed on top of the existing columns for direct vertical load transfer since calculations showed that no interventions were needed for existing mushroom columns and foundation in order to be able to carry additional load.

Stability was not a big problem in this project as well. The wind load situation belonging to the original design with two possible additional layers were compared to the new design. The results showed that the first situation is governing, therefore, no additional checks needed to be made. However, in the transition between the new and existing structures horizontal forces are generated by the wind load. It was proven that the roof structure of the existing building is able to carry those forces, so, no additional structural members were required.

Finally, the Las Palmas extension was a result of great documentation and availability of original design, good quality of concrete and high overcapacity of the load bearing structure.

De Karel Doorman

The main source of information about the De Karel Doorman project was a conference paper "Ultra Light Weight Solutions for Sustainable Urban Densification" by Maurice Hermens, Michiel Visscher, John Kraus (2014).

The original building called Ter Meulen (Figure 1.6a) was built in 1951 during the period when the city center of Rotterdam was rebuilt after the World War II. It was designed by architects Van den Broek and Bakema in the famous Dutch modernistic style. Ter Meulen was housing shops, offices and a canteen. The original structural design was taking into account an expansion of one more floor and, in 1970s, two instead of one floors were constructed on top. However, in 1990s, the retail market changed and the building became mostly empty.

Eventually, the owner asked architect Ibelings van Tilburg to investigate the future possibilities of the existing building and the decision to preserve it with an addition of a large block of apartments above was made (Figure 2.12). Royal HaskoningDHV was asked to join the team as a structural consultant.

Figure 2.12: *De Karel Doorman, Rotterdam (Van Duivenbode, 2012)*

The original building had a basement and three floor layers with two more layers added at a later stage. The load bearing system was completely made of cast in-situ concrete and lateral stability was ensured by rigid frame action of columns and beams. The intended compression strength of the columns was comparable to C14/17 strength according to present Eurocode, however, tests showed that the quality of construction was very good and actual concrete strength was reaching even 40.9 N/mm^2. Similar findings came from the existing foundation where documentation suggested great densification of soil. New cone penetration tests were made and the results indicated that the bearing capacity of piles was 1600 up to 2000 kN, which was a lot higher than the original 900 kN.

The main challenge for the structural enginners was to keep the existing building as original as possible, by adding the new 16 stories with apartments truly on top of the existing building, using the existing load bearing system of columns and pile foundation. The solution was found by following three approaches.

First, analysing the existing load bearing system in order to find its existing and hidden capacities. Fortunately, the original design was well documented and on site tests showed great confidence in the drawings and quality of the construction. Moreover, as previously mentioned, the structure turned out to be a lot stronger than expected.

Second, using an ultra-lightweight structure for the extension building. This structure was built up of steel columns and beams, wooden floors with a 55 mm concrete topping, a double separated metalstud and gypsum wall system between the apartments, a wooden façade and glass cladding on the outside. The system is roughly $1/5^{th}$ of the weight of standard Dutch concrete apartment buildings which required great attention to acoustic isolation and floor vibration.

Third, separating the vertical load bearing from the horizontal load bearing for both, new expansion as well as existing building. For this purpose, two concrete stability cores were added and rigidly connected to the floors. Consequently, the load bearing system changed from a system with rigid frame action to a system with supported columns, where the columns only had to carry vertical loads (Figure 2.13). This resulted in the increase of load bearing capacity from 5000 kN to 10000 kN without any structural modifications of the elements.

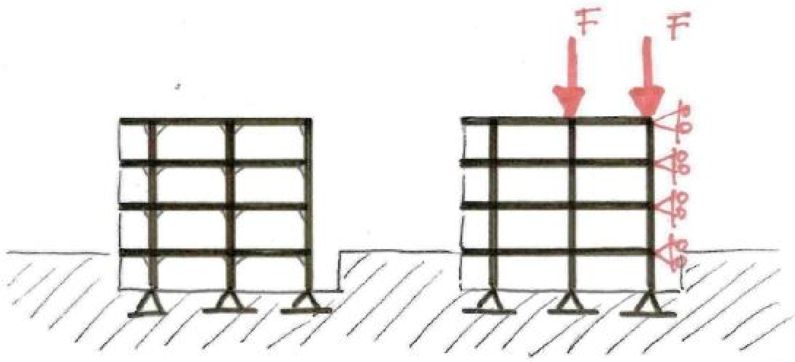


Figure 2.13: *Stability systems before and after (Hermens et al., 2014)*

Additional check was made regarding the differences in settlements as the new block was placed on only two out of three existing columns rows. This caused settlements up to 25 mm between the columns which implied that deformations would create bending moments in the beams and columns. The calculations showed that these bending moments were smaller than required minimum and did not reduce the vertical capacity.

De Karel Doorman project is a great example of how a combination of good quality construction and documentation of original structure and smart engineering solutions can lead to extraordinary results. In this case, even 16 additional floors could be added on top of the existing building.

Summary of case studies

The main information regarding extension types and shapes of realised projects are presented in Table 2.3 below. In addition to the projects previously described in more detail, information about a few other extension projects are included in the table as well.

Table 2.3: *Description of extensions in the realised projects*

Project	Existing stability system	Additional floors	Main solution	Extension shape
Fenix I, Rotterdam	Rigid frame	6 to 9	Steel table structure	Stair-shaped
Las Palmas, Rotterdam	Rigid frame	2	Structural reserve, high quality construction	Egg-shaped, smaller area
De Karel Doorman, Rotterdam	Rigid frame	16	Changing stability system, high quality of construction	Stair-shaped, smaller area
De Gekroonde P, Rotterdam	Rigid frame	3	Structural reserve	Rectangular
Groot Willemsplein, Rotterdam	Rigid frame	3	Structural reserve, changing stability system	Rectangular
Zeemanshuis, Rotterdam	Rigid frame	3	Steel table structure	Rectangular
St. Jobsveem, Rotterdam	Rigid frame	1	Structural reserve	Rectangular, smaller area
Styrpinnen 15, Stockholm	-	3	Structural reserve	Rectangular

Majority of analysed projects were located in Rotterdam, moreover, the stability of existing buildings were provided by rigid connections between structural elements: columns and beams. In regards to extension structures, available structural reserve of existing buildings usually allows an addition of 1 to 3 new storeys, however, bigger investments into smart designs as changing a stability system of existing building or separating existing and new structural systems by placing a steel table structure on top expands the possibilities of existing situation.

As for the shape of extensions, a rectangular addition is the most common, although, a stair-shaped structure with two or more different roof levels is designed as well. Also, the area of extension floor can be chosen to be the same as existing floor area or smaller.

2.2.5 Structural feasibility

Even though vertical extension of existing buildings has a lot of advantages, it raises challenges as well which might not always make extension possible. The following section analyses different factors that influence the structural feasibility and should be considered when planning a top up.

General considerations

Before going more into detail of structure, there are some architectural and organisational factors that need to be taken into account. Structural engineers are usually not responsible for these effects, however, it is useful to know about other factors that may shape a project.

First, the height and size of an existing building and the possibility to increase it should be determined. Usually, the maximum allowed height of buildings is regulated by urban planning laws and must be reviewed in cooperation with a municipality a project belongs to. This may lead to findings that an existing building is already at the maximum allowed height and a higher extension is not possible unless the regulations for a plot change. Moreover, the daylight and sunlight accessibility is monitored as well. A new extended building has to receive a minimum set amount of light as well as not block daylight or cast shadows onto surrounding buildings which may set a limit to an extension height.

Second, top up projects often have more constraints than projects in areas that are not as exploited as city centres. According to Bergsten (2005), in addition to the usual factors as in all building projects, the complexity of an extension project also depends on the lack of space on site, inner city traffic, disturbance to the surroundings and communication with the affected people. This requires a detailed and strict logistics planning to, from and on site in order to deal with site boundaries for material storage and possible transport issues due to busy streets. Also, the construction plan has to be clearly communicated to the affected people, not only living nearby but through the neighbourhood, in order to avoid conflicts arising during the construction process which could stall or even stop the project.

Structural considerations

The first step when considering an upward extension from a structural point of view is the assessment of an existing building. The objective is to fully understand the behaviour of a structure and to determine the quality of construction. Florisson (2013) developed an assessment protocol which assists the structural engineer in visualizing the structural possibilities for multi-story industrial heritage constructed between 1910 and 1950 and it is presented in great detail in her thesis explaining the steps to take and what to expect. The main outline of the protocol is presented in Table 2.4.

Quality	The historic assessment The visual assessment The technical assessment Evaluation
Design possibilities	The preliminary assessment
Structural safety	The [refined] structural safety assessment Strengthening assessment

Table 2.4: *Main purpose individual assessment steps (Florisson, 2013)*

The goal when using the protocol is to establish future possibilities for an existing building. The goal of this thesis, on the other hand, is exploration of a specific possibility - upward extension, therefore, the focus is on the first part of the protocol, indicating the material and structural quality. This purpose requires four individual assessment steps: historic assessment, visual assessment, technical assessment and evaluation.

The historic assessment includes collecting documentation which would help a structural engineer gain knowledge about the original design as well as bridge the gap between the construction year and today. The main sources to be analysed are original architectural drawings, original structural drawings, original reinforcement drawings, piling and foundation plans and original structural calculations (Florisson, 2013). As accentuated by H. Kuijer as well, the more structural information is available, the more possibilities open to fully make use of the existing building and add interventions in the structure.

The visual assessment is composed of the visual inspection of load bearing system, the verification of original documents, the non-destructive research and taking of samples for the technical assessment. The information resulting from this assessment step contains the clarification of load bearing system quality, stating the areas and level of deterioration, the verification of original drawings and creation of new drawings if needed, the results gathered from the non-destructive research, the indication of samples taken for the technical assessment and the indication of the remaining life span of a structure. (Florisson, 2013)

The technical assessment is performed in the laboratory and it is based on destructive research techniques. The samples taken during the visual assessment are analysed in order to further elaborate on the cause of damage found during the visual assessment, visualize the non-visual damage, indicate the future damage (Florisson, 2013) and inspect actual material properties.

The evaluation step concludes the previous assessments summarising findings and stating solutions on possible repair and strengthening techniques which are elaborated on in one of the following sections.

A more general existing structures assessment guide is presented in standard NEN-ISO 13822 explaining the data needed for the assessment, carrying out the structural analysis and verification, as well as documentation and dealing with heritage structures. The ultimate goal of the standard is to limit the interventions to a strict minimum which complies with the principles of sustainable development.

When designing a vertical extension, main obstacles are correctly assessing the remaining strength of the structure as well as exactly calculating the increase of vertical and horizontal loads (Bertolazzi et al., 2019). Due to the increase of loads, one of the critical structural elements is foundation as strengthening methods are quite expensive and labour intensive. Moreover, the type of foundation highly depends on the soil type which, in the Netherlands, tends to be soft and loose with water tables at the grounds surface (Papageorgiou, 2016). If foundation does not have any additional structural reserve to carry additional building layers, a solution might be separating existing and extension structures as it was done in Fenix I and Zeemanshuis projects (section 2.2.4).

Another point to check is local strength of attachment points between the existing building and the extension (Bergsten, 2005). Due to the former function as a roof layer, elements might not be strong enough to carry typical floor loads. If needed, the attachment points should be strengthened or full top layer could be demolished and rebuilt to accommodate higher loads.

Another great challenge when designing a top up is providing stability for a higher building which receives larger wind loads.

Loads and level of safety

The major factor when it comes to a structural analysis of an existing building in an extension project is a change and increase of loads. First, high vertical loads are added on top due to the placement of new floors. However, it is important to keep in mind the difference between former and new functions, for example office and residential, as this difference might allow an addition of one or more floors without changing the acting forces on critical structural elements (Vermond, 2015).

Moreover, horizontal wind forces increase due to the bigger height of the building. It results into not only additional forces on top of an existing building but also an increase of wind loads on an existing structure itself. The shape of an extension impacts the wind loads as well. Options to adjust the shape are a sculptured building top, openings at the top of the building, corner modifications, orientation of the extension according to the leading wind direction (Herfst, 2013). In addition, it is important to keep in mind that the regulations for wind load calculations changed a lot compared to previous codes (Papageorgiou, 2016) and in some old projects they might not have been included at all. This might lead to an existing structure not complying to the Eurocodes and interventions are required in order to reuse it.

For an analysis of existing structures a new Dutch standard NEN 8700 was developed in 2009. This standard in conjunction with the 58 Eurocodes assists engineers in determining an opinion about the structural safety of an existing building (Scholten and Vrouwenvelder, 2009). Figure 2.14 presents an overview of the standard structure.

The new standard also establishes lower safety limits for renovation projects. These include renovation, alteration and enlargement of an existing building. Increased safety levels usually mean more costs for an existing building than the one which is still in the design phase. “The safety provisions embodied in safety standards have to be set off against the cost of providing them, and on this basis these costs are more difficult to justify for the existing buildings” (Scholten and Vrouwenvelder, 2009). Therefore, due to economical reasons a lower safety level can be acceptable.

The renovation safety level has lower reliability indices and partial load factors which are determined by reference periods. They are 1 year for buildings in class CC1A and 15 years for buildings in class CC1B, CC2 and CC3. Figure 2.15 show2 how regulations are intended to work based on an example of a building in class CC2 with a service life of 50 years for a new construction and 15 years for renovation. (Scholten and Vrouwenvelder, 2009)

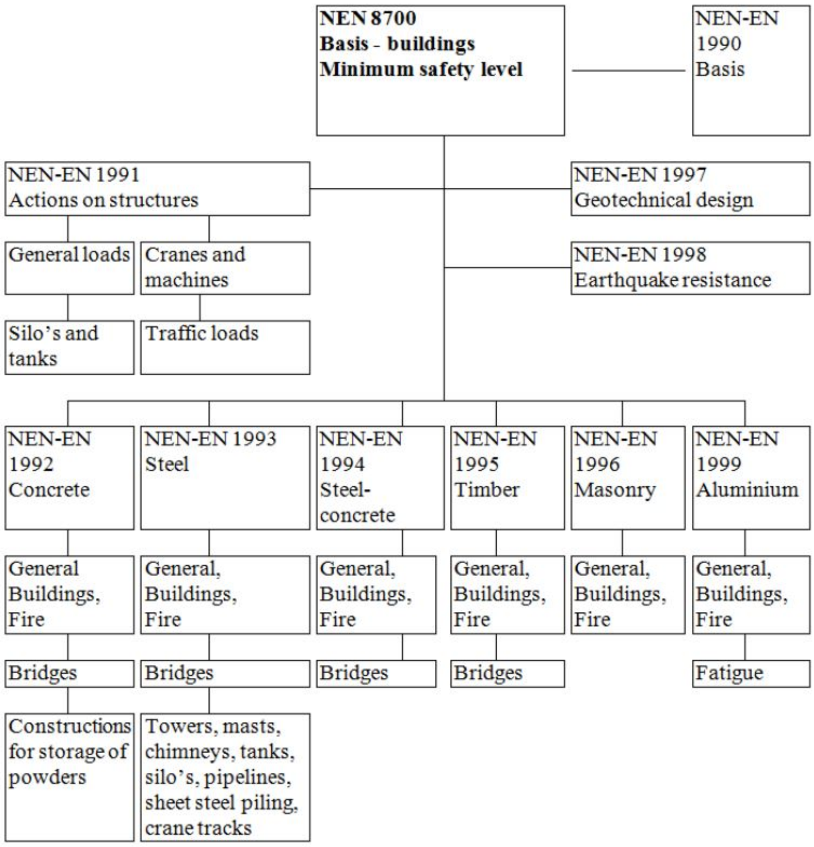


Figure 2.14: *Overview of the standard structure (Scholten and Vrouwenvelder, 2009)*

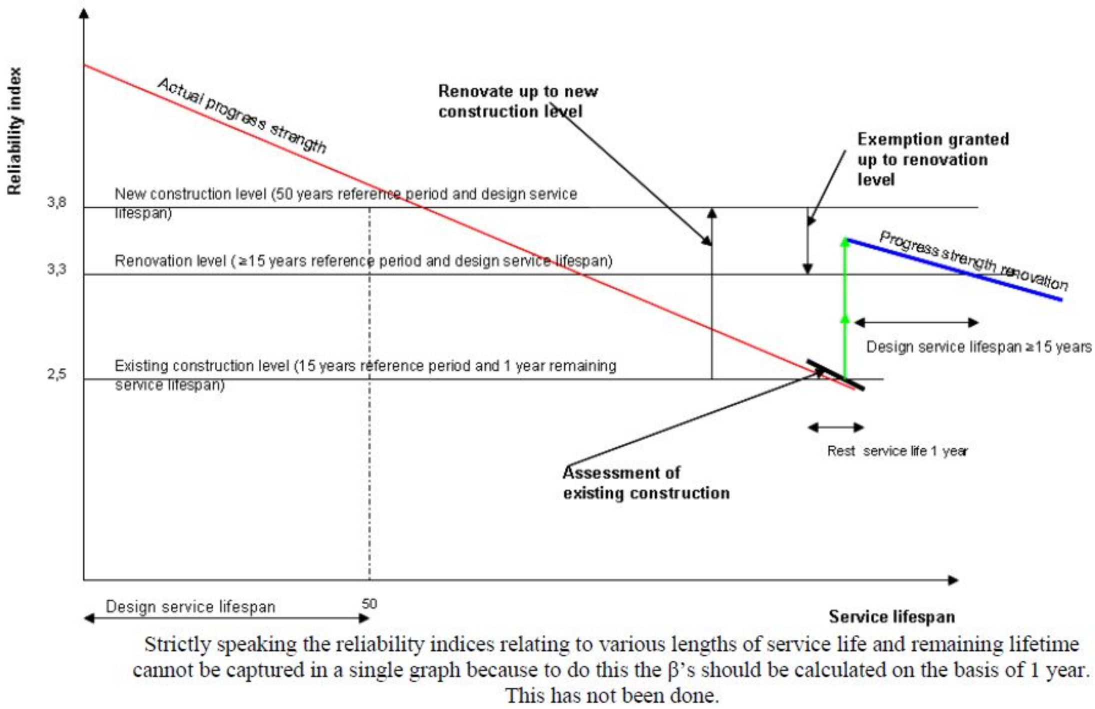


Figure 2.15: *Effect of the regulations on structural safety shown in terms of the required reliability of the building against time (Scholten and Vrouwenvelder, 2009)*

Stability

According to Bažant and Cedolin (2010), "a structure (or any system) is stable if a small change in the initial conditions (input) leads to a small change in the solution (output, response)". For example, a small increase of acting loads on a rigid frame results in an increase of deflections and reaction forces, however, it does not lead to an infinite response of the structure which in this case is a collapse.

The load at which a structure becomes unstable does not depend on the material strength of elements but on the geometry and size, especially slenderness, of a structural system. When a building is extended vertically, a configuration of structural elements, a system is changed which might lead to an unstable structure, especially with an increase of loads. In addition, extension structures are usually designed to be lightweight for an addition of more new floors. Eventually, they lack the mass to counteract the tilting force. Therefore, a stability check is of big importance in upward extension projects.

The methods how stability is ensured in a building depends a lot on the creativity of a structural engineer, however, according to Papageorgiou (2016), there are some principles that can be depended on:

- ensuring continuity of floors and walls acting as diaphragms in the structure,
- increasing the stiffness of vertical elements,
- converting the stability system (Figure 2.16),
- introducing bracings, cores or other stabilising elements to take extra loads and work together with the existing system.

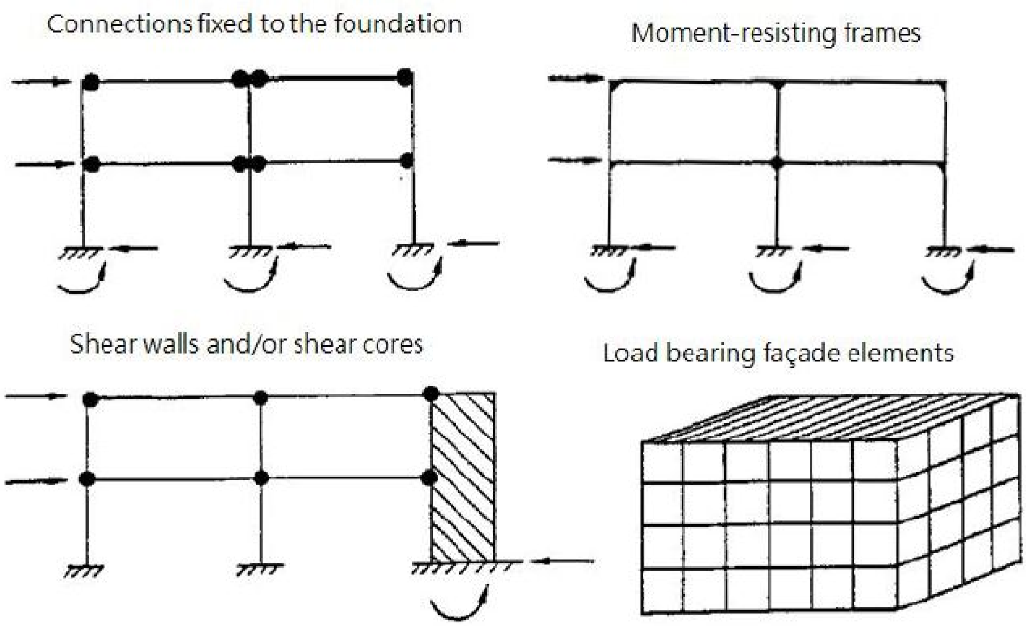


Figure 2.16: *Stability systems (Papageorgiou, 2016)*

Strengthening

Structural assessment of existing building and analysis for extension might show a need to strengthen some of the critical elements of the structure. Therefore, there are a lot of methods and improvements possible based on the material of the structure. Some of the available methods for strengthening a reinforced concrete column, beam and foundation will be introduced in this section.

The most common methods for strengthening columns include concrete jacketing, steel jacketing and fiber reinforced polymer (FRP) strengthening (Figure 2.17).

In traditional concrete jacketing, a new layer of reinforced concrete is applied around over a part or entire length of an existing column. In order to ensure a bond between the old and new layers of concrete, anchor rebars or high-strength bolts are applied. This technique improves the axial strength, flexural strength and ductility, on the other hand, it is expensive and time consuming due to the installation of formwork. Moreover, it increases the cross-sectional area of the column resulting in a larger mass as well which is not always acceptable. Therefore, recently high performance reinforced concrete materials, for example engineered cementitious composites, are used for column jacketing to strengthen the elements without increasing the cross-section. (Bažant and Cedolin, 2010; Islam and Hoque, 2015)

In steel jacketing technique, steel angles or plates are used to confine the column concrete in different configurations, for instance, wrapping circular columns, adding steel plates or steel caging. The gap between steel and concrete is filled with grout. This technique is mostly used for rectangular and square columns and is proven to increase lateral strength, axial load carrying capacity, ductility and shear capacity of structural members. (Islam and Hoque, 2015)

Column strengthening with FRP composites includes external FRP wrapping, FRP encasement, and FRP spraying. Confinement consists of wrapping the column with FRP sheets, prefabricated jacketing, or in situ cured sheets with fiber running in circumferential direction. Due to the confinement, the lateral pressure is applied onto the column which increases axial load capacity and ductility. This method is most effective for circular columns. (Parvin and Brighton, 2014)

Figure 2.17: *Column strengthening: steel jacketing, concrete jacketing, FRP jacketing (Islam and Hoque, 2015)*

Concrete beams need strengthening when the limits of their flexural capacities are exceeded. Earlier strengthening used to be done by addition of beam, post tensioning or propping and supporting (Jamil et al., 2013). However, nowadays, similarly to concrete column strengthening, steel or concrete jacketing methods or various fibrous high performance materials as steel fibre concrete (Radaikin and Sharafutdinov, 2020) or jute fibre strips (Salih et al., 2019) are used.

Methods for strengthening the existing foundation are available too, however, working with the underground part of the building is a lot more time consuming and expensive, therefore, the worth of it should be analysed beforehand. Possible strengthening methods include strengthening of the bed soil by introducing crushed-stone piles (Shishkin and Zachyosov, 2007) or punching piles bellow shallow foundations (Kozakov et al., 1993) but the most effective methods depend on the type of soil and the type of foundation. As previously mentioned, the soil in the Netherlands tends to be soft and loose with high water level, therefore, the most commonly designed foundation type is driven piles, traditionally in timber, following by steel and finally in pre-cast concrete (Papageorgiou, 2016).

According to Tishkov et al. (2013), the methods used to strengthen the foundations of existing buildings can be divided into three groups:

1. By varying the characteristics and properties of the bed soils (grouting, silicification, thermal and electrochemical stabilization, freezing, etc.),
2. By varying the design of the foundation (expansion by the installation of monolithic yokes, reduction, build-up, placement of additional piles beneath the foundations, etc.),
3. By redistributing the active forces (installation of monolithic girdles, unloading frames, transfer of forces onto neighboring components, etc.).

However, Tishkov et al. (2013) discussed that most of the developed methods are very expensive and not that effective. They suggest that the method which makes it possible to increase foundation bearing capacity and reduce deformation is active inclusion of a raft functioning in unison with piles. This is done by opening a pit below an existing foundation raft and concreting its bottom surface while creating the openings for free passage of the existing piles. Wedges are then placed in between the new slab and the old raft which allows a portion of the forces to be transmitted from the piles through the wedges onto the new shallow foundation. After the strengthening, the wedges are replaced by reinforced concrete elements. Figure 2.18 presents the strengthening of columnar pile foundation. The method has shown to be able to increase the bearing capacity of foundation by 50%.

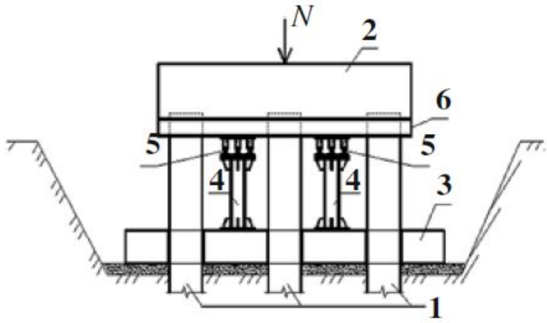


Figure 2.18: *Diagram, showing strengthening of columnar pile foundation: 1) pile; 2) existing raft; 3) complementary raft; 4) pedestal; 5) wedge; 6) strengthening beam. (Tishkov et al., 2013)*

2.2.6 Conclusions

Upward extension is mainly introduced as a solution for urban sprawl and growth of urban population. Placing additional floors on top of existing buildings provides a sustainable way of densifying the highly developed areas. Extending buildings vertically has a lot of advantages but most importantly it leads to creating additional value by reusing resources.

Extension projects are most reasonable in developed urban areas equipped with service systems. Lack of space make it appealing for current building owners to consider upward extension in order to gain additional profit. Moreover, such projects help to achieve sustainability goals and to preserve historic buildings.

Based on the case studies analysed, there are three main methods how an extension can be placed on top. First, making use of the structural reserve if it is available in the existing structure. Usually, older concrete structures allow an addition of 1 to 3 floors without any strengthening required. However, for a higher extension, a change of stability system might be needed in order to increase the residual element capacity. Lastly, if an existing building is not capable to bear any additional loads, a possible solution might be separating existing and new structures by constructing a table structure to carry the new part of a building.

In order to determine which method would be the most suitable, a structural assessment of an existing building has to be carried out. The main output of the assessment are documentation in regards to the original design and construction process, including drawings and calculations; evaluation of a present state of the building, including the verification of original documentation, changes made during the use of the building, areas and state of deterioration; lastly, results from the testing of structure samples elaborating on the damage and actual material properties of structural elements.

When considering an upward extension, the most important elements of the existing building structure to be analysed are foundation, vertical load bearing elements, stabilising elements, roof floor and extension attachment points. They describe the remaining structural capacity of the structure to be able to carry additional loads. Construction of an extension increases not only vertical loads on the existing structure, but also horizontal loads which result from higher wind forces.

Dutch standard NEN 8700 together with all the other Eurocodes help an engineer to come to an opinion about the structural safety of an existing building. The standard establishes a possible lower safety limit for renovation and enlargement projects due to the high costs of reaching the safety level of new construction. According to the renovation safety level, it is allowed to use lower reliability indices and partial load factors when performing the structural analysis on an existing structure.

Extending upwards also results in the change of the structural system geometry which may cause the building to become unstable. Therefore, the stability check is another substantial step in the analysis and assessment of an existing structure. If the stability requirements are not fulfilled, the methods for improvement include increasing the stiffness of vertical elements, converting stability system, introducing stabilising elements as bracings or cores.

Moreover, the structural analysis and assessment may show the need for repair or strengthening of some critical elements. The most common methods for strengthening concrete columns and beams are concrete jacketing, steel jacketing or the use of various high performance fibre materials. Strengthening of foundation is a lot more expensive and time consuming, however, some methods may be used as well, for example, the active inclusion of a raft functioning in unison with piles.

In conclusion, upward extension should be included into considerations regarding reuse of an existing building in areas that require densification due to the sustainability reasons. Moreover, vertical extension is a great option when an existing building is in good state, has hidden structural reserve with documentation about the original design available, especially if strengthening and repair interventions can be applied.

2.3 Timber

2.3.1 Introduction

Evidence of the first timber shelters date to between one million and 300 000 years ago, therefore, people have practiced timber engineering and fire engineering longer than any other construction technologies (Smith and Snow, 2008). Timber was the main structural material until its poor use lead to fire accidents and strict regulations not allowing the use of full potential of timber in construction.

However, if used properly, timber is a high-performance structural material and it has been favorable for ages due to the abundance, high strength to weight ratio and the ability to be shaped easily. Today's tallest trees are about the height of 26 storey buildings as if nature intends timber structures to grow tall and withstand high forces. (Smith and Snow, 2008; Ramage et al., 2017)

Figure 2.19: *Sakyamuni Pagoda of Fogong Temple in China, one of the world's tallest timber buildings, built in 1056 (Charlie Fong, 2019)*

Fortunately, nowadays building codes are changing, allowing engineers to design timber structures more freely and make use of the strengths of this material, especially with the progress of fire prevention technologies as well as the invention of engineered timber. During the manufacturing process, properties and imperfections due to the natural character of the material can be controlled which leads to higher strength and larger and longer members in comparison to traditional solid wood. Moreover, timber is getting more attention also due to the sustainability reasons as it is truly renewable and the production does not necessarily involve destruction of natural ecosystems (Smith and Snow, 2008).

Therefore, this section aims to explore the properties of timber and its use in construction in order to answer the third sub-question of the thesis, establishing when timber is the best structural material for an extension structure.

2.3.2 Reasons to choose timber

To begin with, some case studies of timber upward extension projects and multi storey buildings are analysed in order to determine which reasons lead to the choice of material. Furthermore, the motives of companies passionate about wood building design are studied, concluding in an array of timber properties valued in construction industry.

Four timber extension projects shown in Figure 2.20 are located in Sweden. The information about them are provided by Brandt (2020) in an article focusing on using wood for solving the urbanisation issue.

(a) *Styrpinnen 15, Stockholm (Sigma Civil, 2020)*

(b) *Skellefteå Kraft, Skellefteå (Patrick Degerman, 2020)*

(c) *Quality Hotel Friends, Solna (David Valldeby, 2020)*

(d) *Trikåfabriken, Stockholm (Cristoffer Skogsmo, 2020)*

Figure 2.20: *Timber extension projects in Sweden (Brandt, 2020)*

Two main advantages of timber mentioned in all projects are the lightweight of extension structure and sustainability aspects. The lightness of the additional structure helps solve the problem of settlement of the old building as well as allows an addition of more than one floor. Significantly lower climate impact in comparison to other structural materials is an important factor for the parties involved in the extension projects as they strive for sustainable building.

Other arguments for the use of wood are high prefabrication level and healthier indoor environment. Engineered timber products allow for a high degree of prefabrication which makes assembly more efficient and speeds up the installation time. These aspects are especially important in building extension projects as they are usually located in densely developed areas which creates logistical challenges. As for the healthier environment, timber is seen to create a pleasant atmosphere which assists when selling or renting the premises.

Consequently, three multi storey timber building projects presented in Figure 2.21 are studied. All of them are located in the Netherlands and the information regarding them can be found on official sites.

(a) *HAUT, Amsterdam (Team V Architectuur, 2020)*

(b) *The Dutch Mountains, Eindhoven (Studio Marco Vermeulen, 2020)*

(c) *Patch22, Amsterdam (Luuk Kramer, 2016)*

Figure 2.21: *Timber multi storey building projects in the Netherlands*

The main reason for the choice of timber in these projects is declared to be sustainability, particularly the large storage capacity of CO2. Moreover, timber is a renewable material and consistent with the cradle-to-cradle principle where everything is recycled. Other arguments include the light weight of the structure which makes the construction process quicker and cheaper as well as the environment timber is able to create because it works as a great selling point.

Two companies that are enthusiastic about building in wood chosen for the analysis are the Stable Company in the UK and Folkhem in Sweden. There is no specific reason for the choice as the focus is on the reasons to build in timber of any company that works in the construction field in Europe.

The motive mentioned in both companies is timber being the most environmentally friendly building material. It is not only renewable, but also naturally recyclable and biodegradable. Moreover, it absorbs and stores carbon while carbon emission is one of the main issues in the industry.

The Stable Company also mentions economic and health advantages. First, construction with wood can be up to 10-15 % cheaper than traditional designs and due to the natural insulation properties, energy costs are lower. Moreover, studies show that exposed timber surroundings boost resident's productivity and decrease stress. (The Stable Company, 2020)

The Folkhem company focuses more on the structural performance advantages of timber. First, the light weight makes it well suited for difficult ground conditions and upward extensions. Moreover, it allows for a quick, quiet and clean construction process. The softness of the material does not only create a warm indoor environment, it also reduces the loudness of the installation process. Lastly, timber buildings can be even more fire resistant than steel and concrete constructions as timber elements char on the outside and maintain the ability to support the structure longer. (Samson, 2019)

To conclude, timber properties valued in the construction industry are:

- sustainability
- light weight
- efficient and economic construction process
- healthy indoor environment

2.3.3 Timber in construction

This section aims to look more in depth into the properties mentioned in the previous section.

Structural performance

From the structural point of view, the use of timber for extension structures is mostly favourable due to its light weight, more specifically, strength to weight and stiffness to weight ratios, which makes it a very light and very strong material (Bakker and Baker, 2020). Moreover, some research institutes are investigating the use of performance fiber reinforced timber in order to improve these ratios for more resilient timber structures in seismic zones (Ramage et al., 2017).

Especially lightweight is mass timber. This term is used to refer to a range of modern innovative engineered timber systems. They are made by joining layers of sustainably sourced timber using glues or mechanical fasteners, in this way the quality of material is being controlled. A typical mass timber floor, without acoustic treatment, weighs around 150 kg/m^3 compared to a reinforced in-situ concrete floor weighing around 600 kg/m^2. (Musson, 2020).

Common structural engineered timber products are shown in Figure 2.22.

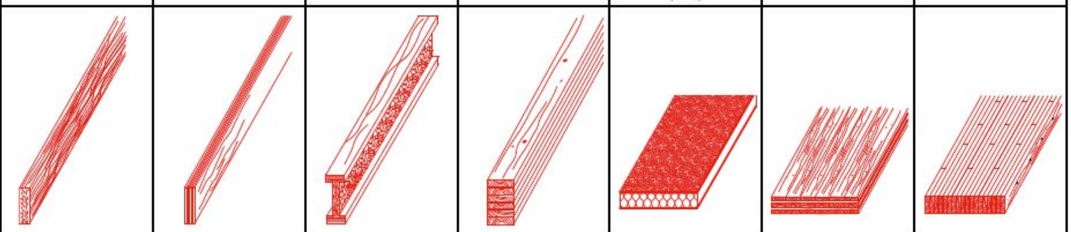
Engineered Timber Product	Parallel Strand Lumber (PSL)	Laminated Veneer Lumber (LVL)	I-Joist	Glulam	Structural Insulating Panel (SIP)	Cross Laminated Timber (CLT)	Brettstappel
Typical Detail							
Application	• Beams • Columns	• Beam • Columns • Cord	• Joist • Beam	• Beam (Long span) • High Loading	• Roof • Wall • Floor	• Roof • Wall • Floor	• Roof • Wall • Floor
Usage	Interior	Interior	Interior	Interior / Exterior	Interior	Interior/ Exterior	Interior/ Exterior

Figure 2.22: *Common structural engineered timber products in Europe (Ramage et al., 2017)*

Figure 2.23 presents compression strength and modulus of construction materials normalised by density. According to Ramage et al. (2017), wood obtained from angiosperms is called hardwood, for example oak or birch, and that from gymnosperms, softwood, for example pine.

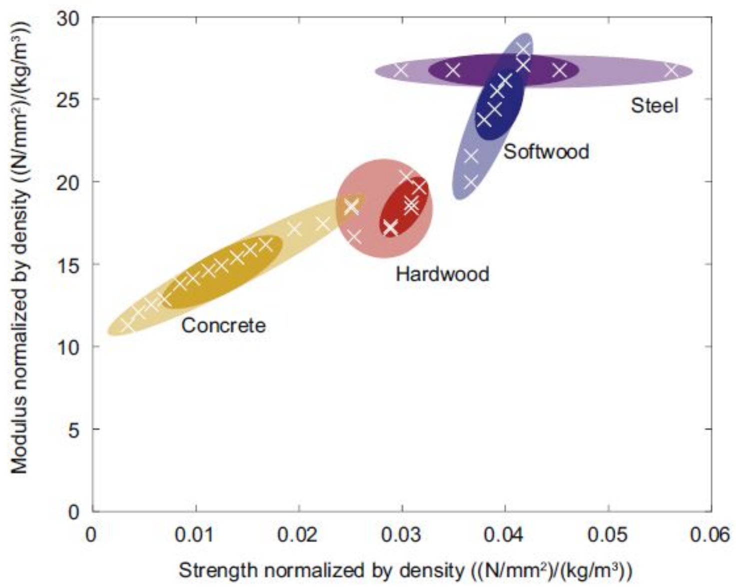


Figure 2.23: *Compression strength and modulus of construction materials normalised by density, according to the relevant design standards – the dark colors represent the more widely used grades of material. Design values of strength and stiffness, including partial factors, are shown, based on the Eurocode design standards for concrete, steel and timber. (Ramage et al., 2017)*

In compression, timber strength parallel to the grain is similar to one of reinforced concrete, however, it does not reach the strength of modern high-strength concrete. As for stiffness, wood is less stiff than both, concrete and steel. On the other hand, timber has the lowest density which, when analysing the stiffness and strength to weight ratios, makes it almost as stiff and strong as steel. These measures suggest that timber is the most efficient in structures where "a high proportion of load to be resisted is the self weight of the structure itself" (Ramage et al., 2017) as elements work mostly in compression.

Moreover, as mentioned in the previous section, timber can be even more fire resistant than other conventional materials. Sufficient resistance can be achieved by assuming a rate at which the timber chars and enlarging the elements accordingly. The remaining cross-section needs to be large enough to carry the acting loads. Smaller elements must be encapsulated in non-combustible material such as gypsum boards or concrete. (Ramage et al., 2017)

As for durability, the mechanical properties and dimensions of timber vary with moisture content and a high moisture content makes the wood vulnerable to fungi or insects. However, when protected well, for example, by impregnation, chemical modification or thermal modification as well as detail design limiting the exposure to wetting or direct sunlight, timber is very durable. (Ramage et al., 2017)

Finally, timber is a very lightweight but strong material. However, due to the lightness, timber structure has less inertia and is more affected by lateral forces as wind. Therefore, from a structural point of view, it is the most efficient in cases where elements work in pure tension or compression. Also, attention must be paid to fire resistance and durability but when designed well, timber structure can last for centuries.

Construction

For the construction process, the light weight of timber makes it stand out from the other materials as well. First, one timber delivery takes place of 5-10 concrete deliveries (Bakker and Baker, 2020) which makes the transportation a lot cheaper, quicker and more sustainable (Nyman, 2020).

Another advantage is high prefabrication level which leads to rapid assembly. Modern timber is largely factory prepared (Ramage et al., 2017), even when meeting specific needs as dimensioning individual elements or integrating components of the facade - doors, windows, cladding (Soikkeli, 2016). According to the research of Rissetto et al. (2018), lightweight and massive timber floor structures take less time to construct in comparison to hybrid steel and timber or concrete floors (Figure 2.24).

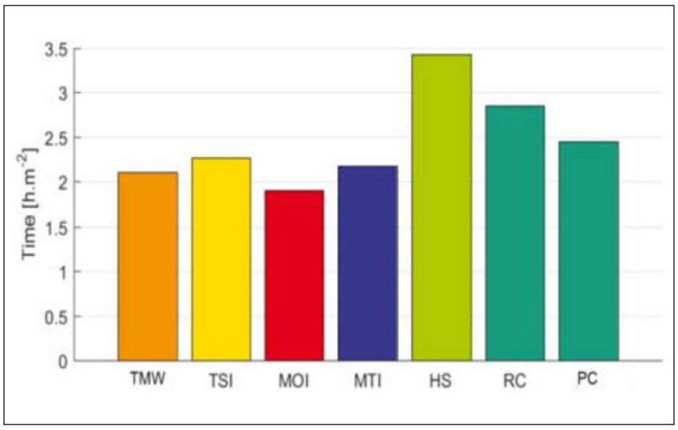


Figure 2.24: *Construction time estimation for each construction per m2, where TMW and TSI - lightweight timber constructions, MOI and MTI - massive timber constructions, HS - hybrid steel and timber construction, RC and PC - concrete constructions (Rissetto et al., 2018)*

Lastly, timber structure allows for a considerably quieter construction process due to the best sound absorbing capability (Nyman, 2020). The echo from drilling and hammering is reduced and not transmitted to the neighbouring buildings. In some cases, existing building might even stay in use (Musson, 2020).

Cost

As a structural material, timber is not the cheapest, especially in the Netherlands where local supply is limited. The direct building cost comparison of different floor types is presented in Figure 2.25 below.

The most commonly used and the cheapest material is concrete (Option 1 in the figure). However, due to its large self-weight it is not the most fit option for vertical extension structures which strive to be lightweight and easily installed. Options 2 and 3 represent lightweight floor types which include steel and timber, although, they get far more expensive than the concrete option when the grid length increases. Nonetheless, Option 3, which represents all timber floor, is more favourable than Option 2 in terms of cost. To conclude, lightweight structural materials as steel and timber are more expensive than traditionally used concrete, however, they are preferred for extension structures. The solution is choosing an optimal grid size in order to find the most economic design.

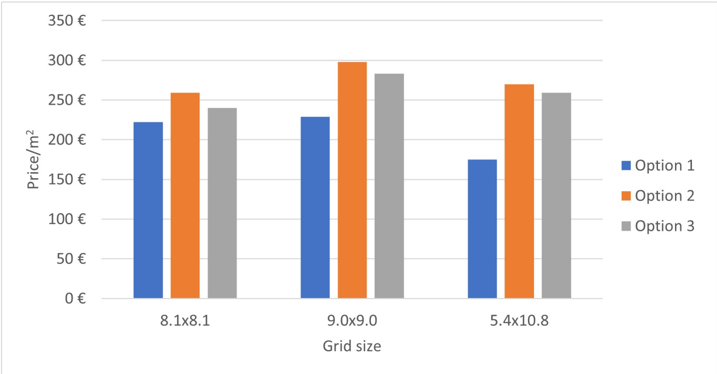


Figure 2.25: *Direct building cost comparison of different floor types in the Netherlands. Option 1 - hollow core concrete slab on steel beams, option 2 - timber floor on steel beams, option 3 - timber floor on timber beams (based on data by A. C. B. Schuurman)*

Moreover, as shown in the previous section describing the construction advantages, timber requires a low amount of deliveries as well as the least time to construct, which also reduces the energy used, makes the building more sustainable and increases the cost-effectiveness of the overall project.

Lastly, for comparison, according to the research on performance of structural timber in central Europe by Rissetto et al. (2018), lightweight timber structures are the most inexpensive. Therefore, measures could be taken to reduce the price in the Netherlands in the future, as establishing local sourcing, making timber a more common structural material.

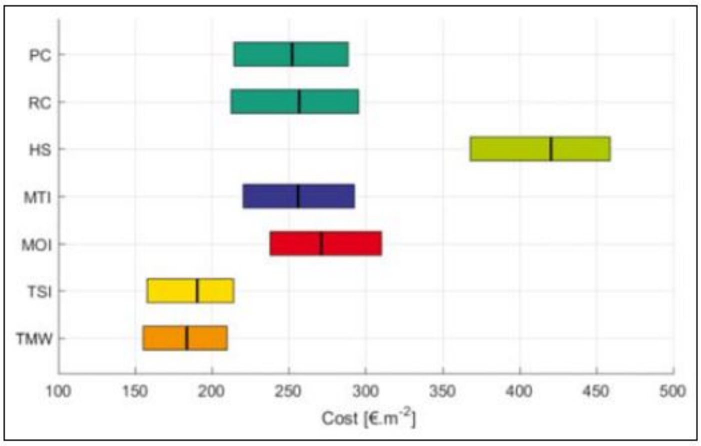


Figure 2.26: *Cost estimation of each construction per m^2 (ranges from minimum to maximum cost, and average indicator), where TMW and TSI - lightweight timber constructions, MOI and MTI - massive timber constructions, HS - hybrid steel and timber construction, RC and PC - concrete constructions (Rissetto et al., 2018)*

Sustainability

Sustainability is probably a feature where timber performs particularly better than other traditional structural materials as steel and concrete. One of the biggest issues in the construction industry is emission of large amounts of carbon-di-oxide (CO2), however, using timber as well as other bio-based materials, these emissions are minimised. A comparison of carbon footprint and shadow price of different floor types are presented in Figure 2.27.

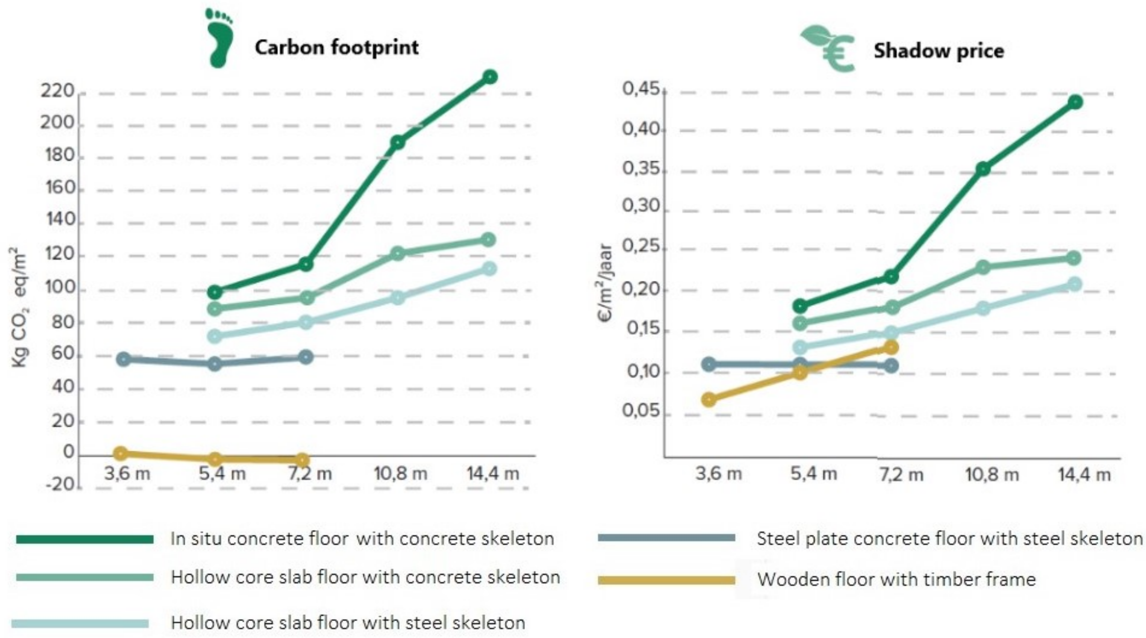


Figure 2.27: *Environmental impact comparison of different floor types (van Haalen, 2018)*

Studio Marco Vermeulen (2019), a design office in the Netherlands, calculated that constructing 1 million homes in a conventional way emits 55 Mton CO2, on the other hand, by choosing bio-based materials these emissions can be avoided, in addition, 45 Mton CO2 can be stored. This leads to even 100 Mton difference. Moreover, the storage creates value in the form of homes as there is a bio-based alternative for most of building parts, such as wood wool for insulation, solid and mass timber for the construction of structural shell.

Another reason which makes timber a lot more environmentally friendly is the production of almost no waste. From harvested wood approximately 50% is recovered as viable board and plank products, "the remaining dust, shavings and fiber byproducts typically are used as biomass fuel or as fiber in engineered timber panel products with a market value" (Ramage et al., 2017). For example, production waste from the Metsa Wood mill in Lohja, Finland, is used for heating of not only the mill but also the town (Nyman, 2020).

Moreover, timber has quite a unique supply chain. While other construction materials require rocks, oils or soils to be mechanically removed from the ground, timber requires that topsoil remains intact. This allows the seedlings to start growing and forests are nurtured before harvesting. (Ramage et al., 2017)

The main issues of the production and use of timber in construction are the use of energy for drying and joining methods that require glue. However, research is already being done on alternative removal of the bound water and welding using high frequency oscillating or linear friction that would be used instead of wet adhesives. Moreover, there is a possibility that in the future new timber species with naturally lower moisture content will be invented. (Ramage et al., 2017)

A problem for the Netherlands is the lack of local timber sourcing. There already is an area of at least 140 000 hectares of forest mostly grown as a production forest for mining. Here trees could provide around 8 m^3 per hectare of wood per year while creating a recreational value. In order to build 210 000 homes from Dutch wood, additional 14 500 hectares are needed, which could motivate the parts of the Netherlands that are struggling with poor soil quality or declining agricultural sector to invest in sustainable forestry. (Studio Marco Vermeulen, 2019)

In Scandinavian and Baltic regions of Europe timber construction is a traditional and culturally accepted way of building which could be a reference to other European countries. During a conference about the European Green Deal, the Minister of Environment in Lithuania, Simonas Gentvilas, stated that leadership of the state is compulsory in order to make timber widely used in construction. This includes change of national reglamentation, investment in local sourcing, involvement in projects triggering the use of timber. Moreover, current European goals promote timber construction, as a result, France is aiming to make timber the main structural material by 2022 while Lithuania strives for all public buildings to have at least 50% of structure built in timber. (Gentvilas, 2020)

Lastly, materials used in renovation and reuse projects should be produced in such a way that only a minimum amount of energy is consumed and as little as possible emissions and waste are created in order for a project to be truly sustainable (Soikkeli, 2016). For this reason, timber is a suitable choice.

Indoor environment

Another property that makes timber superior to steel and concrete is an ability to create a healthier indoor environment as it helps to reduce stress, increase creativity, improve focus and attention (Fell, 2015; Bakker and Baker, 2020).

Studies show that outdoor nature has stress reducing effects, however, an average person spends most of their time indoors. Therefore, a way to bring nature in until now was achieved by introducing plants into the built environment. This sparked interest that wood surfaces might also provide some health benefits. (Fell, 2015)

A study at the University of British Columbia and FPInnovations established that the presence of wood in the built indoor environment reduces sympathetic nervous system (SNS) activation. SNS activation is the way that the body prepares itself to deal with stress. It increases blood pressure and heart rate, inhibits digestion, recovery, and repair functions in the body in order to deal with threats which might lead to more severe health issues. (Fell, 2015)

Therefore, introducing wood surfaces and exposed timber structure into the indoor environment is a way to reduce stress levels and to create healthier surroundings.

2.3.4 Conclusions

Timber is the oldest structural material used in the construction industry, however, building safety regulations have been limiting the use of its full potential. Nowadays designers and builders are researching and incorporating wood in building projects a lot more which leads to it getting discovered again.

According to timber upward extension and multi storey building projects as well as companies that are devoted to building in wood, properties of timber which are mostly valued in the construction industry are its light weight, efficient and economic construction process, sustainability and contribution to a healthy indoor environment.

From the structural point of view, the most valuable characteristic of timber is light weight, particularly strength to weight and stiffness to weight ratios. These ratios show timber parallel to the grain to be almost as strong as reinforced concrete and nearly as stiff as steel. On the other hand, the light weight causes structures to be more affected by lateral forces, therefore, the elements work most efficiently when they are exposed to pure tension or compression. Moreover, despite the natural origin, wood can be even more fire resistant and durable than other conventional structural materials if it is designed well.

Timber is a great option for projects in busy city centers as the construction process is relatively quick and quiet. Furthermore, it is the most cost-effective solution as less deliveries are required as well as energy used for construction is reduced.

Sustainability is probably the most admired property of timber as it is capable of storing CO2 which otherwise would contribute to the industry emissions. Moreover, the production process generates almost no waste as all parts of trees are used in order to create value and unique supply chain allows to save the environment as excavations are not needed. Lastly, European sustainability goals promote the use of timber in construction as it currently shows to be the most sustainable material.

Finally, timber is the only structural material which contributes to formation of healthy surroundings. Exposed wooden elements bring nature indoors and help to reduce stress levels which is especially beneficial in hospitals, offices and homes.

To conclude, for reuse, renovation and extension projects timber is an excellent structural material as it adds to the development of a sustainable project. Moreover, as upward extension projects are usually located in busy and highly developed urban areas, quick and quiet construction process of a timber addition is a huge advantage.

2.4 Conclusions

Table 2.5 presents a summary of the previous sections 2.1, 2.2 and 2.3 stating the main conditions when reuse, upward extension and use of timber are beneficial and disadvantageous.

Table 2.5: *Conclusions of the theoretical background*

	REUSE	EXTEND	TIMBER
Goal	Sustainability	Increased density	Maximum additional area
YES	• good condition of structure • historic or architectural value	• sustainability • structural reserve • availability for interventions (stability) • ability to separate existing and new structures	• sustainability • very dense area • existing building needs to stay in use • light weight • cost-efficiency
NO	• design for short life cycle • low quality construction • end of service life • deterioration • lack of original drawings and calculations	• lack of data for interventions installation • desired density is a lot higher than existing • low bearing capacity of foundation	• long distance supply • large spans • case of separating existing and new structures

First, for reuse projects, the main goal usually is sustainability. The main conditions, when reuse of an old building is valuable, are either good state of structure or historic, architectural value. However, buildings which were designed for a short life cycle, contain low quality construction, are reaching the end of their service life, show signs of deterioration or the documentation about their structure is missing, are not considered good options for reuse.

As for upward extension, the main goal usually is to increase density in an already quite developed urban area. The motivation for such a project could be sustainability goals or, if the existing structure is in good condition, apparent structural reserve and availability to add interventions, especially in order to increase stability of the building. On the other hand, if the existing structure cannot bear any additional loads, there should be possibility to separate old and new systems, for example, pierce the columns of a new structure through the existing.

However, extending upwards might not be structurally or financially feasible if the documentation about an existing structure is not complete which creates difficulties for design of interventions; the desired final density is a lot higher than the existing or foundation load bearing capacity is already all in use.

When designing a vertical extension, one of the purposes is to create a maximum additional area. For this reason, a lightweight structural material as timber is often chosen. First, it stands out from other conventional materials as being truly sustainable due to carbon capture, most environmentally-friendly sourcing and no waste production. For this reason, timber is a material which contributes the most to the design of a sustainable project. Other advantages include high level prefabrication, fast and least disturbing construction process which are beneficial in very dense areas, especially, if the existing building that is being extended needs to stay in use. Lastly, the savings made due to energy and time reduction add to the cost-efficiency of the project.

On the other hand, there are cases when timber might not be the most suitable material for an extension. These include long distance supply as it contradicts with sustainability goals, large span structures due to the large size of elements, the amount of material needed and costs and the case of separating existing and new structures where steel might be a better option due to more stiff and slender elements.

In conclusion, even though building reuse, upward extension and use of timber in construction have many remarkable advantages, these solutions might not always be the best choice. Each reuse project needs to be approached with critical and creative mind of an engineer in order to establish how the most use can be made of what has been already built.

3 Computational tool design

3.1 Introduction

The past decades brought a fast evolution of computers together with a great increase in computational power which caused the continuous development of computational methods, especially in structural engineering. The purpose of computational modelling is to analyse the behaviour of complex structures with the help of computer simulations and it can be used to make predictions in various cases where intuitive analytical solutions are not available. (Plevris and Tsiatas, 2018)

The use of computational tools during the conceptual design phases of projects can have a significant influence over initial design decisions and key parameters. The conceptual design phase is one of the earliest stages of the design process and it acts as a starting point and guidance for the following stages of the project. Using software tools during the initial phase gives a structural designer more control over design and ability to generate alternatives for comparison. (Rolvink et al., 2014)

One of such tools is parametric and associative design. It includes objects, such as structural elements of buildings, which are defined by a user using a set of parameters and associations between the objects. The logic is created which allows the designer to change the parameters in order to generate different outcomes. Holzer et al. (as cited in Rolvink et al., 2014) state that "by linking parametric design to structural analysis and optimisation, architects and structural engineers can explore design in the conceptual design phase through informed geometry alterations. [...] From an architect's perspective, the immediate visualisation of structural feedback, provided by the structural engineers proved valuable to understanding the effects of changes which might otherwise only be driven by aesthetic considerations." Consequently, computational tools help quickly explore different variations and visualize structural feedback which leads to better communication between different disciplines and more informed decision making.

Another field of computer science that was proved useful in different areas is machine learning. It "studies algorithms and techniques for automating solutions to complex problems that are hard to program using conventional programming methods" (Rebala et al., 2019). It is also used to create models for learning from existing cases and predicting an outcome or behaviour. The use of machine learning is spreading in other fields, such as personalised health, autonomous vehicles and systems, predictive maintenance of machinery and infrastructures and others. Moreover, machine learning is finding its way in structural engineering as well, for example, for simulations of structural dynamics and behaviour of concrete materials.

The goal of this thesis is to make use of computational design tools and machine learning, and create a new tool for a specific prediction - addition of extra floors on top of an existing building. The intention is to provide a tool for structural engineers to use in conceptual design stages in order to explore possibilities of existing structures together with developers and architects and to include structural designers in the decision making during the initial phases of reuse projects.

Machine learning (ML) is chosen as the base for the tool, firstly, due to ability to include features that are difficult to analytically evaluate and find relations with the outcome, for example, the relation between the municipality the project belongs to and the possible capacity for additional loading. Secondly, as machine learning is becoming more widely used, it raises an interest, how useful it could be in the specific case of exploration of upward extension. When using modern computational tools as parametric design, it is difficult to replicate the actual state of old structures as these tools are meant to be used for design of new buildings following modern building codes and technologies. On the other hand, a machine learning model learns from actual realized extension projects analyzing existing buildings from different eras, taking into account their differences from modern construction. Moreover, the more projects are analyzed, tested and provided for the model to learn, the more precise predictions will get.

3.2 Description of tool creation

3.2.1 Initial research

To begin with, a few issues arise when it comes to creating a machine learning model to predict a number of possible additional floors on top of an existing building. First, there are not a lot of realized upward extension projects in the Netherlands, moreover, most of them use steel as the main structural material as opposed to timber which is analyzed in this thesis. Also, collecting detailed information about the projects from the companies which designed them show to be challenging due to the confidentiality and time constraints. This leads to limited data available for training and testing a machine learning model.

Data is at the core of any artificial intelligence project and a small size of a dataset might be responsible for a poor performance of a machine learning model. However, lack of data is quite a common problem and small or limited datasets are represented in the domains of artificial intelligence in healthcare, smart operations and predictive maintenance and autonomous vehicles (TNO, 2020). Therefore, there are methods on how to solve this issue and a few of them are presented below.

One of the techniques used when the amount of data needed is impossible to find is transfer learning. The model is pretrained on a large dataset which has the same input but different output than the desired dataset. Then this pretrained model is used with a smaller dataset which requires a smaller number of parameters. This smaller network only needs to learn relations from the specific problem having already learnt the patterns in the data from the detailed model. (Jain, 2017) The comparison between the learning process of traditional machine learning and transfer learning are presented in Figure 3.1.

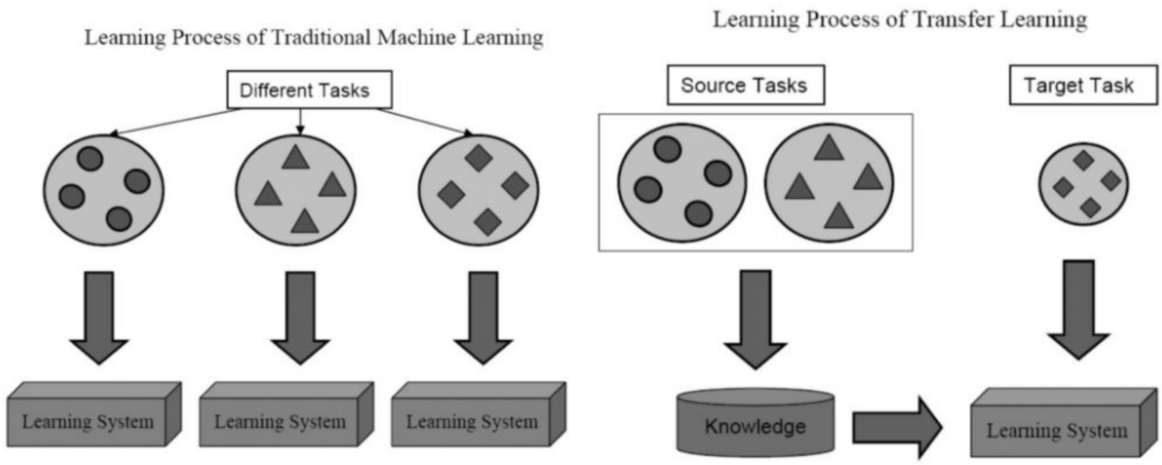


Figure 3.1: *Comparison between the learning process of traditional machine learning and transfer learning (Jain, 2017)*

However, using transfer learning requires significantly more expertise to make it work, which makes it tough. Some of the issues related to transfer learning are (Jain, 2017):

- Finding a large dataset to pretrain on
- Deciding which model to use for pretraining
- Difficult to debug which of the two models is not working
- Not knowing how much additional data is enough to train the model
- Difficulty in deciding where to stop using the pretrained model
- Deciding the number of layers and number of parameters in the model used on top of the pretrained model
- Hosting and serving the combined models
- Updating the pretrained model when more data or better techniques becomes available

Another method widely used when the needed dataset is not large enough is data augmentation. The main idea behind it is changing the input value in such a way that they would provide new data without changing the output. However, this method works best and is mostly used for image classification problems by flipping, rotating, scaling, cropping the images (Figure 3.2). (Folkman, 2019)

The last method analyzed is the use of a synthetic dataset which is a repository of data that is generated by programming. Generally, it takes points that are known, real data, and creates new points in between, synthetic data. Desired properties for this dataset are the wide variety of statistical distribution, the ability to inject random noise and the number of features and length of the dataset should be arbitrary. (Sarkar, 2018)

However, to be able to generate synthetic data, a big enough real dataset is needed to base the new data on. Moreover, there is a risk of introducing biases and the output should be highly

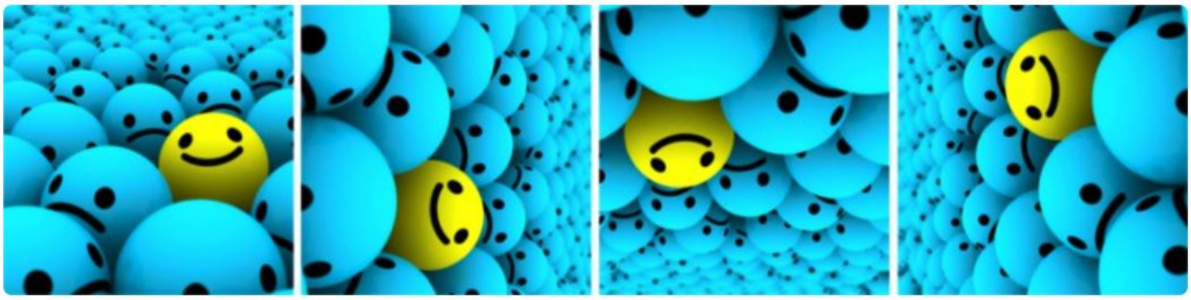


Figure 3.2: *Example of use of data augmentation method by flipping the original image (Folkman, 2019)*

controled as there is a risk of inconsistencies when trying to replicate the complexities in real data. (Dilmegani, 2020)

In conclusion, there are methods available for dealing with the problem of lack of data for the creation of a machine learning model. However, in order to use these methods, experience in programming and data science is necessary to make the models work well, for example when using the transfer learning technique or creating synthetic data; or, as in case with data augmentation, the method requires specific data, so it is not widely applicable. Consequently, none of these methods are used in this thesis, however, they act as inspiration for the final solution.

3.2.2 Methodology

For this thesis, the problem of lack of real data is solved by creating a database of fictional projects. The initial idea was to collect information from realized timber upward extension projects and have their parameters as input and numbers of additional floors as output. However, due to difficulties with data collection, this information is very limited, therefore, a parametric model is built in order to generate an array of fictional extension projects. In this model a structural analysis is carried out on a structure of an existing building and a top up in order to find out how many floors of an extension can be added for different combinations of parameters. The main geometry and options for these parameters are based on actual realized projects that information could have been collected about. The parameters to be changed in the model and possible options include:

- stability structure: rigid frame / supported columns / additional bracings / stability walls
- material properties: original / tested
- safety level: new construction / renovation
- unity check limits: 0.8 / 0.9 / 1.0
- extension and existing area relation: 1.0 / 0.5
- extension shape: rectangular / stair-shaped

By employing the parametric model, one real extension project generates a number of fictional projects, this system is represented in Figure 3.3 below.

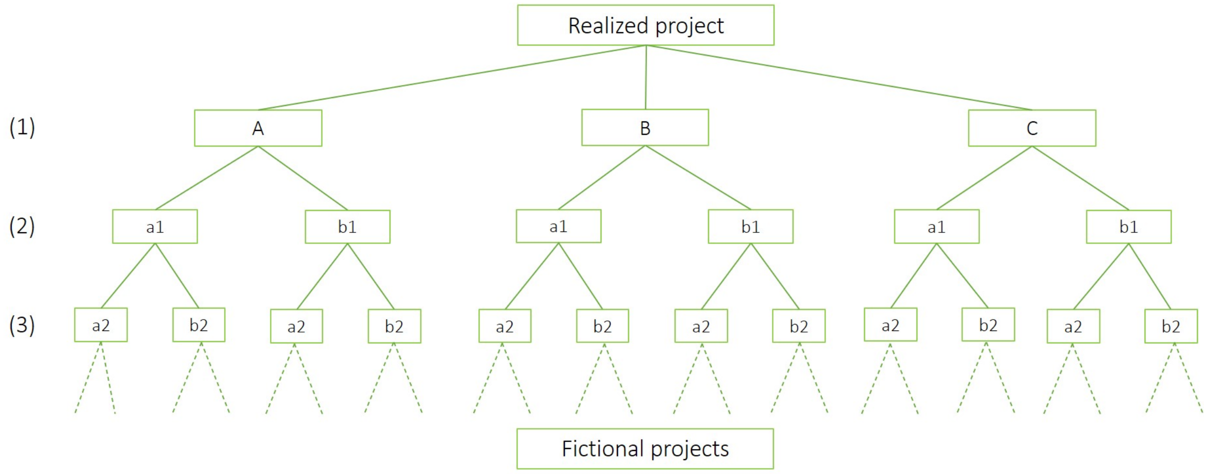


Figure 3.3: *Generation of fictional extension projects; (n) - parameters*

Finally, the issue of lack of data is solved by replacing limited real data by a larger, specially created fictional dataset. Figure 3.4 presents this solution.

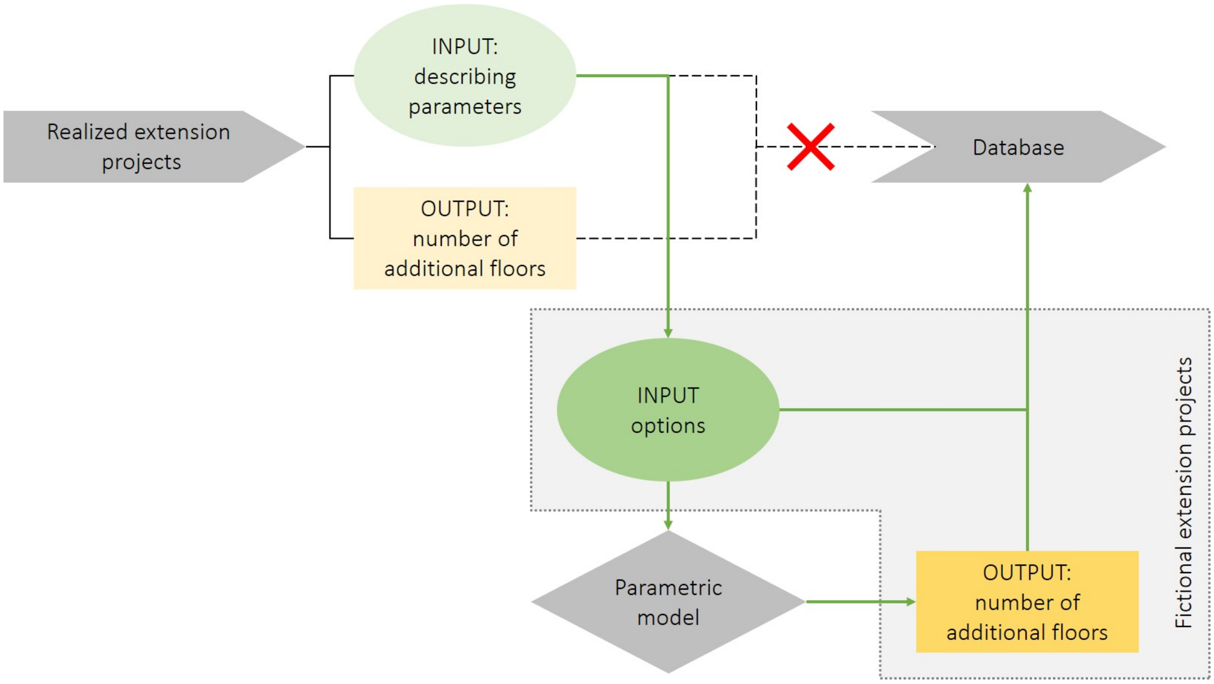


Figure 3.4: *Solution for lack of data problem*

The next step is checking if there is enough data generated for a machine learning model. A recommended way to do this is plotting learning curves as additional data is added and checking the change in model performance (Folkman, 2019).

Two errors are monitored: one for the validation set and one for the training sets. The result of plotting the change of these errors as training sets increase is two learning curves. (Olteanu, 2018) These curves are presented in Figure 3.5.

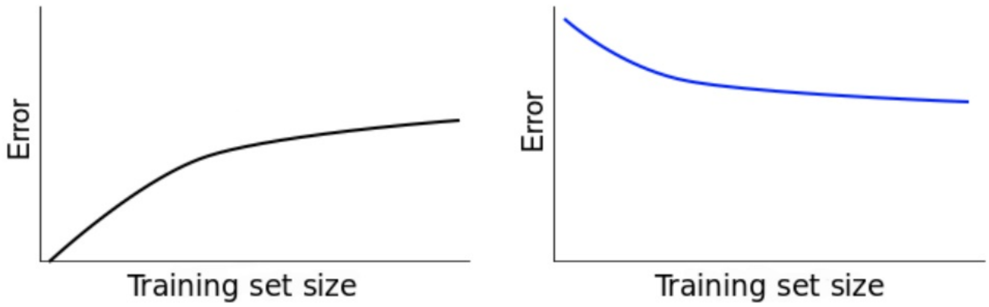


Figure 3.5: *Visualisation of learning curves; left - for training sets, right - for validation set (Olteanu, 2018)*

The error for training sets increases as the training set size increases due to the inability of the model to fit this dataset perfectly anymore. For comparison, if there is only one input in the training set, the error is zero but it starts increasing as more data is added. On the other hand, the error for validation set decreases as the training set size increases. For example, if there is only one point in the training set, the model fits it perfectly but there is a high error for the validation set. Consequently, if the model gets trained on more data, the validation points get closer to the model function. The explanation of the change of error is visualised in Figure 3.6.

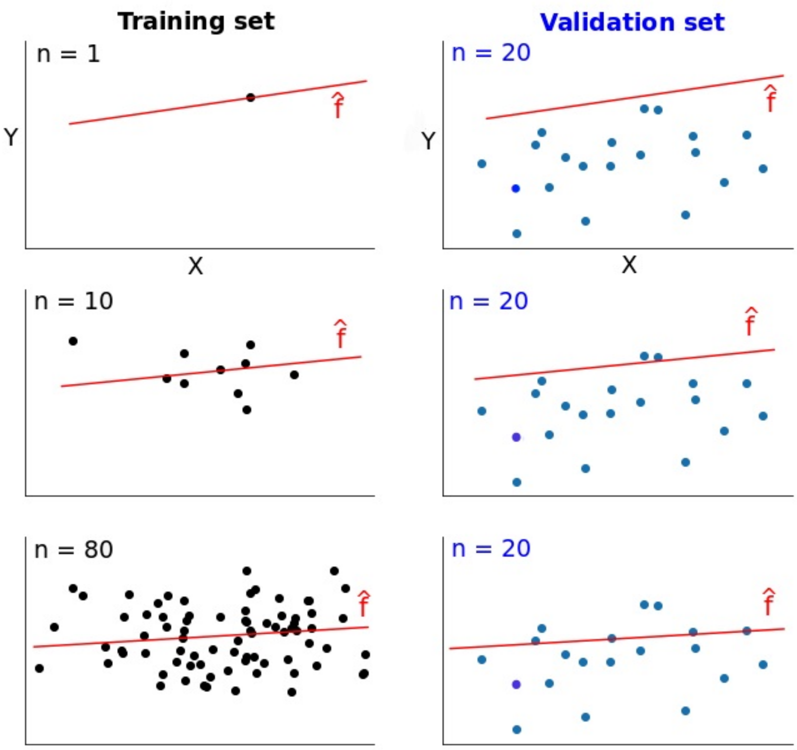


Figure 3.6: *Visualisation change of error in training sets and validation set (Olteanu, 2018)*

The major sources of errors explained above are variance and bias. The amount by which a model function varies as the training sets are changed is called variance and simplifications of this function gives a model bias (Olteanu, 2018). Ideally a model would have low variety and low bias, so the model would not be too simple with poor performance and not too complicated learning the training data too well. However, it is not possible and the optimum becomes the goal (Figure 3.7).

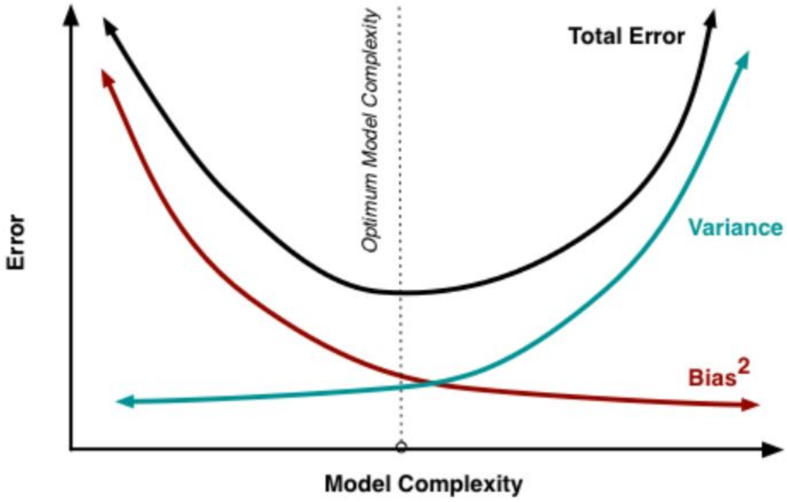


Figure 3.7: *Optimum model complexity based on variance and bias (Olteanu, 2018)*

Analysing the learning curves, information about variance and bias of a model can be retrieved and used to tell if adding more data to the training sets is needed to bring a model closer to the optimal stage.

First, if the two curves, validation curve and training curve, are not converged with a noticeable gap, adding more instances (rows) to the training set will help the model work better. However, if they are converged, not more instances but more features (parameters) should be added as it will make the model more complex.

Next, to indicate the bias problem, the validation error should be observed. The value from the curve needs to be evaluated based on the engineering knowledge of the data that is used. High value of this error shows the bias problem, however, it does not state if it is high or low. To find the answer, the training error has to be examined. If it is low, this means that model fits the training data well which indicates low bias. If the model fails to fit the training data, it has high bias. (Olteanu, 2018)

There are two methods for estimating the variance (Olteanu, 2018):

- examining the gap between the validation learning curve and training learning curve
- examining the training error: its value and its evolution as the training set sizes increase

In general, a narrow gap between validation and training curves indicates low variance while the opposite is also true. Moreover, a high training error also shows low variance as an algorithm creates simple models that do not fit the training data well.

If a model has high bias and low variance, more features to train the model could be included or switching to another algorithm could be considered, which would make it more complex. In the low bias and high variance problem, adding more instances or reducing the number of features should lead to better models.

Unfortunately, there is no perfect scenario and perfect learning curves because of an irreducible error (Olteanu, 2018). It means that creating a model that describes relations between the input and the output perfectly is not possible. The reason being the existence of other features that are not included in the model and measurement errors. Moreover, there is no way to know the value of this irreducible error. Finally, the goal is to lower the error value of the learning curves as much as possible while knowing about the limit given by irreducible error.

Even using the data generation method and analysing the learning curves might still create quite a small dataset for machine learning. In this case, it is recommended for models to have low complexity, or high bias, in order to avoid overfitting them to the data (Gonfalonieri, 2019). Therefore, the main goal of the model of this thesis is to reach the optimum, however, that might not be possible with the available data, in which case the model should be simplified.

In addition to being a low complexity model, it is also learning from fictional data, therefore, the result should be treated as proof of concept for how machine learning can be used to explore adding floors on top of existing buildings.

To conclude, figure 3.8 presents the main steps of the computational tool creation strategy. First, parametric model is created and data about realized extension projects collected. Next, using information from these projects as inputs in the parametric model, a database of fictional projects is generated. Lastly, a machine learning model is built and its performance is checked based on the amount of data provided.

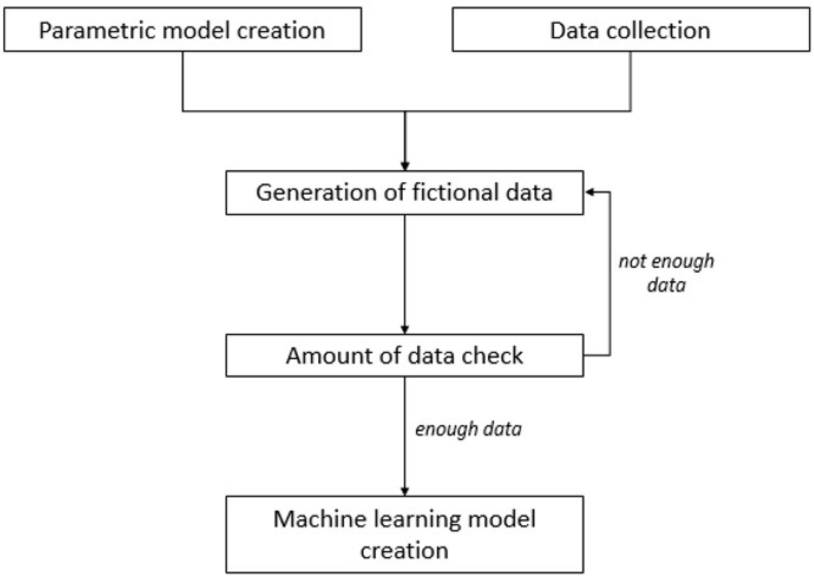


Figure 3.8: *Strategy for creation of a computational tool*

3.3 Data collection

According to the plan, a part of the first step is collection of data from realised extension projects. For this purpose, a search for projects with concrete existing structures and preferably timber extension structures is carried out. Following the analysis of the projects, based on the results, the decision on structural system, geometry, parameters is made in order to describe the object for the parametric model.

3.3.1 Case studies

The search leads to interviews with engineers as well as literature and documentation study, as a result, information about seven extension projects is collected. These projects (and their main sources of information) are:

- Fenix I, Rotterdam (interviews with the structural engineer of ABT, ir. Hilbert-Jan Kuijer),
- Las Palmas, Rotterdam (master's thesis "Assessing Existing Structures 1910-1950" by Sara Florisson (2013)),
- De Karel Doorman, Rotterdam (conference paper "Ultra Light Weight Solutions for Sustainable Urban Densification" by Maurice Hermens, Michiel Visscher, John Kraus (2014)),
- De Gekroonde P, Rotterdam (drawings by Zonneveld ingenieurs),
- Groot Willemsplein, Rotterdam (master's thesis "Optimal Vertical Extension" by Maria Papageorgiou (2016)),
- St. Jobsveem, Rotterdam (master's thesis "Optimal Vertical Extension" by Maria Papageorgiou (2016)),
- Styrpinnen 15, Stockholm (interviews with the structural engineer of Sigma Civil, ir. Petra Videstorm).

The objective of this part of the research is to gain information about the original buildings: year of construction, initial function, and about the original and extension structures: geometry, stability system, parameters of structural elements. The summary of collected data is presented in Table 3.1 and Table 3.2. More detailed descriptions and data about other structural elements of each project can be found in Appendix B.

Table 3.1: *Summary of realised extension projects data - existing buildings*

No.	Project	Location	Const. year	Function	EXISTING										
					Geometry				Stability system	Columns			Beams		
					Grid	No. spans	Floor height	No. floors		Material	Cross section	Strength	Material	Cross section	Strength
					[m]		[m]				[mm]			[mm]	
1	Fenix I	NL	1953	E	10.2-13.5 x 8.6	4 x 14	5.7	2	Rigid frame	In-situ concrete	□ 700x500	C12/15	In-situ concrete	□ 500x1800	C12/15, C15/20, C20/25
2	Las Palmas	NL	1953	E	9.43 x 6.79-7.65	5 x 14	5.5 m	5	Rigid portal	In-situ concrete	Octag. 700, 1000	C8/10, C30/37	*no beams*		
3	De Karel Doorman	NL	1951	D	10 x 8	-	-	4	Rigid frame	In-situ concrete	⊘ 800, 850	C14/17, C28/35, C40/50	In-situ concrete	□ 850x600	C20/25
4	De Gekroonde P	NL	-	B	5.92-7.02 x 3.08-2.72	2 x 5	5.4, 2.98	6	Rigid frame	Concrete	□ 400x500, 300x500	C25/30	Concrete	□ 400x500	C25/30
5	Groot Willem-splein	NL	1946	E	6.8 x 5.15	8 x 6	3.5	5	Rigid frame	Prefab concrete	□ 700x1000, 700x700, 600x600	C16/20	Concrete	□ 350x500	C16/20
6	St. Job-sveem	NL	1913	E	5 x 5	26 x 5	-	6	Walls and floors	Cast iron	-	-	Cast iron	-	-
7	Styrpinnen 15	SE	1901	B	-	-	3.5-3.9	5	-	Composite: steel, concrete	-	-	Steel	-	-

Table 3.2: *Summary of realised extension projects data - extensions*

No.	Project	Ext. year	Ext. method	EXTENSION										
				Geometry				Stability system	Columns			Beams		
				Grid	No. spans	Floor height	No. floors		Material	Cross section	Strength	Material	Cross section	Strength
				[m]		[m]				[mm]			[mm]	
1	Fenix I	2019	Steel table	10.2-13.5 x 8.6	Varies	3.2	6 to 9	Stability walls, bracings	Steel	⊘ 406.4, 508.0, 610.0	S355	Steel	Variety	S355
2	Las Palmas	2003	Reserve	9.43 x 6.79-7.65	2 x 8	-	2	Rigid frame	Steel	-	-	Steel	-	-
3	De Karel Doorman	2012	Reserve, system change	4 x 6	-	-	16	Supported columns, cores	Steel	-	-	Steel	-	-
4	De Gekroonde P	2008	Reserve	5.92-7.02 x 3.08-2.72	2 x 5	3.6	3	Rigid braced frame	Steel	HE160A	-	Steel	HE220A	-
5	Groot Willem-splein	2013	Reserve, system change	6.8 x 5.15	8 x 6	3.5	3	Supported columns, cores	Steel	-	-	Steel	-	-
6	St. Job-sveem	2007	Reserve, change system	5 x 5	20 x 3	-	1	Stability walls	Steel	-	-	Steel	-	-
7	Styrpinnen 15	2020	Reserve	-	-	3.1	3	Walls and floors	Glulam	□ 230x315, 225x255	GL30c	Glulam	□ 140x405	GL30c

3.3.2 Object of the parametric model

Based on the collected information, base for the geometry, set and varying parameters are described to be created with parametric design at a later step. The parameters for the existing building structure are:

- built around 1950s in Rotterdam, the Netherlands,
- industrial function,
- rectangular geometry,
- grid size varies from 5 to 10 m,
- number of spans: 2 to 15,
- floor height: 3.5 to 5.7 m,
- number of floors: 2 to 6,
- rigid frame structure,
- material: in-situ concrete, strength C12/15 to C30/37,
- possibility to add stability walls through all width or part of the width of a building.

The chosen parameters are based on Table 3.1, mostly projects 1-5. The existing buildings of these projects were built in 1946-1953 in Rotterdam, the Netherlands, most of them had initial industrial function. The stability was ensured by rigid frame action, the structure was built in concrete. All of the projects had a rectangular floor plan with grid size varying from 5 to 13.5 m. The buildings were long and narrow with number of spans varying from 2 to 26. Floors had either very high ceiling with floor height around 5.5 m or quite common height of 3.5 m. The number of floors was 2 to 6 in the building.

The strength of the concrete in the analysed buildings varied a lot from low C8/10 to very high C40/50. Since very strong concrete in the old buildings is rare to come by, the highest for the parametric model is chosen to be C28/35. Columns usually had a rectangular cross-section, however, circular and even octagonal shapes were found too. Therefore, for the parametric model a choice of rectangular and circular column cross-sections is set. Columns and eventually rigid frames are connected by main and secondary beams, carrying concrete floors.

Based of the case studies, also an ability to add stability walls is included. Even though analysed projects usually had bracings added in the existing structures for the stability, a choice to use concrete walls is made for the parametric model due to easier installation and better load distribution. An option is to design these walls placed in the shorter facades of the building in addition to inner walls or only positioned on the inside of the structure.

The parameters for the extension structure are:

- residential function,
- extension method: structural reserve,
- rectangular or stair-shaped geometry,

- extension floor area can be the same as existing or smaller,
- grid size is the same as in existing structure,
- floor height: 3.1 to 3.6 m,
- rigid frame structure,
- material: glulam, strength GL30c, GL 32c,
- possibility to add steel bracings to improve stability.

These parameters are chosen based on Table 3.2. The function of transformed buildings is chosen to be residential due to the issue of housing shortage in the Netherlands. The method for extension is based on the structural reserve of existing buildings as the focus of the thesis is using the existing potential of old buildings. Moreover, the solution of placing a steel table on top and having two separate, existing and extension, structures is more complicated, requires a lot more information about the existing building and situation and more attention to detail which makes it more difficult to create a parametric model for a variety of projects.

The options for shape and size of extensions are based on the case studies as well as section 2.2.4. Grid size is the same as in existing structures in order to be able to place extensions directly of top. Also, the maximum span length is chosen to be 10 m due to the material choice of timber in the extension structure. The design for a new timber structure is based on the steel extensions of analysed projects. The stability system is chosen to be a rigid frame structure following the existing solution due to continuity. However, the feasibility of rigid connections between timber elements and effects of it are not examined in this thesis due to the lack of time.

In order to improve the stability of extensions, steel bracings, strength S355, are designed. Bracings instead of concrete walls, as were designed for existing structures, are chosen due to their light weight.

The creation of the parametric model and inclusion of the described parameters are explained in the following section.

3.4 Parametric model

The purpose of a parametric model in this thesis is to generate a sufficient amount of data to be used as a dataset for training and testing a machine learning model. A design representing an existing building will be created as well as an extension structure. Followed by a structural analysis that will be carried out on the structure of the design in order to find the remaining capacity of an existing building and how many additional floors it could carry.

The parametric model is built using a Rhinoceros plug-in Grasshopper, structural analysis is carried out using plug-in Karamba. For the reason of not building an overcomplex parametric model, it is divided into two parts: the first one analysing an existing building and the second one examining the extension.

3.4.1 Model 1

The first part of the parametric model, model 1, is analysing the structure of an existing building. The goal of it is to find the residual strength capacity of structural elements.

The starting point is analysis of existing buildings with rigid frame stability system. This choice is based on a usual structural system of industrial buildings built around 1950s that later were renovated and vertically extended, for example, Karel Doorman (originally built in 1951), Fenix I (repaired and rebuilt after the fire in 1954), Las Palmas (1953), Groot Willemsplein (1946). Moreover, these projects show a possibility during reconstruction to change a structural system from a rigid frame action into a system with supported columns carrying only vertical loads.

Figure 3.9 presents an outline of the parametric model 1.

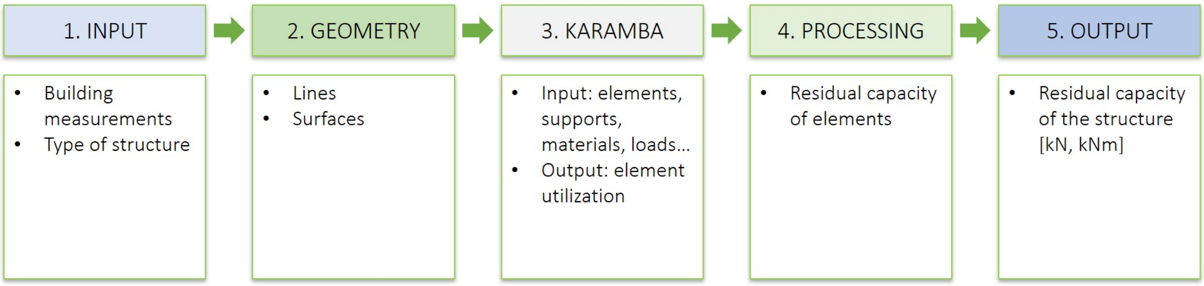


Figure 3.9: *Outline of the parametric model 1*

Input

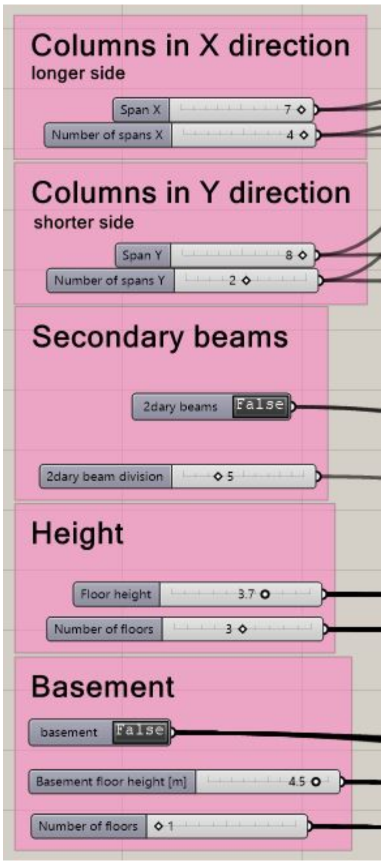
The main inputs to the model 1 are the type of the structure and the building measurements in order to be able to build the geometry. The type of structure is chosen to be a rigid frame system as previously mentioned. This means that along the width of the building columns and main beams are connected rigidly and along the length of the buildings these rigid frames are connected by secondary beams and floors.

Building measurements include column span and number of spans in both directions in plan, distance between the secondary beams, floor height and number of floors, addition of basement as well as number of floors and floor height of it. Boundaries for these parameters are set according to section 3.3.2.

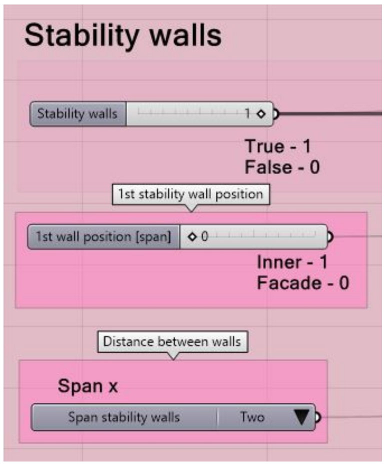
Moreover, an ability to add concrete stability walls is included. The options to choose from are: the placement of the first stability wall (in the facade or on the inside of the structure, at the second column row) and the distance between the walls (2 to 4 column spans). However, the model allows to change the position of stability walls only in the shorter direction of the building considering the higher wind loads and not over-complicating the model. Along the longer direction of the building, a stability wall is placed automatically in the middle of the structure.

Due to the difficulties modelling foundation in Grasshopper, it is assumed that if structural elements as columns and beams can bear additional loading, foundation should be strong enough as well. This decision is made in order to simplify the model and generate many different projects, however, when analysing a specific existing building and designing a top up, great attention should be paid to the foundation as it is one of the sensitive factors.

Figure 3.10 presents the required inputs for a rigid frame structure in model environment.



(a) *Building measurements inputs*



(b) *Stability walls inputs*

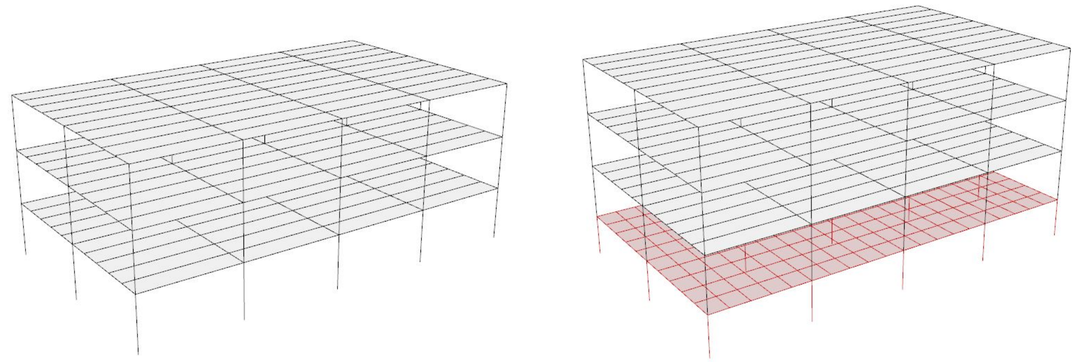
Figure 3.10: *Input for model 1 in Grasshopper environment*

Geometry

Using the input, the geometry is created: lines for beams and columns, surfaces for floors and walls. Created structure options are shown in Figure 3.11 and Figure 3.12.

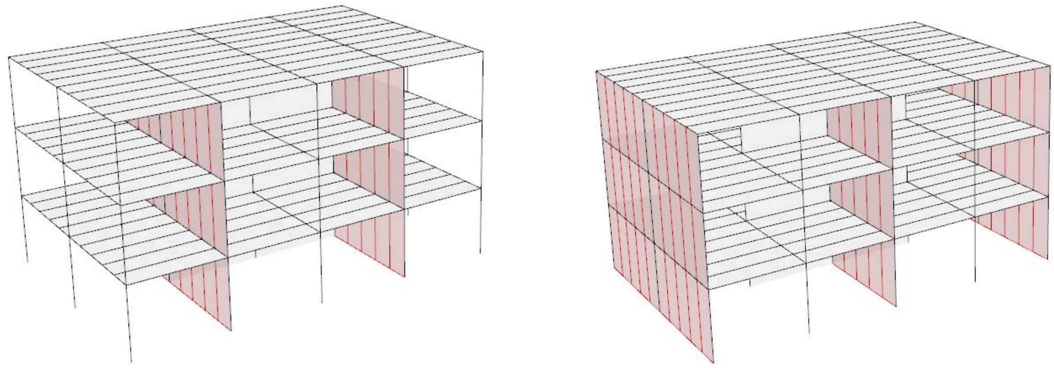
Figure 3.11 presents the base geometry and the addition of one basement layer.

At this stage there is a possibility to add or change position of stability walls which are considered to be interventions to an existing structure which improve the overall stability and help to build more variations of fictional projects. Figure 3.12a and Figure 3.12b show different placement of the first stability wall. Figure 3.12c presents varying distance between the walls and Figure 3.12d the position of the stability wall in the longitudinal direction.

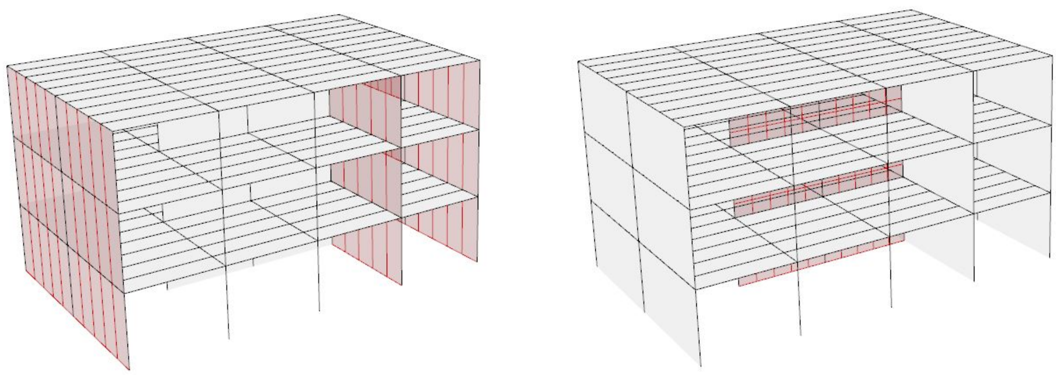


(a) *Base geometry* (b) *Geometry with added basement layer*

Figure 3.11: *Base geometry options for the structure of the existing building*



(a) *First stability wall placed at the second column row (inner walls)* (b) *First stability wall placed at the first column row (facade walls)*



(c) *Increased distance between the first stability walls* (d) *Stability wall in the longitudinal direction*

Figure 3.12: *Stability walls variations for the existing building structure*

Karamba

Using Karamba plug-in components, previously created geometry elements, lines and surfaces, are described as structural elements with assigned properties. Columns and beams get assigned cross-sections, floors and walls - thicknesses. For the columns, two options for the shape of cross-sections are available: rectangular and circular, chosen according to the analysed case studies, and the size of them can be changed manually. For the beams, the sizes of the cross-sections are calculated automatically based on the rules of thumb (Ham and Terwel, 2017) and, for the floors and walls, dimensions are set.

Also, material properties are chosen, in this case the strength of concrete. A list of five grades are given: C12/15, C16/20, C20/25, C25/30, C30/37. For the reason of simplification, the same strength is assigned to all concrete elements.

Moreover, type of connections are chosen. Supports are designed to be fixed while the secondary beam end connections to be hinged.

When it comes to loads, the choice for a safety level to be calculated according to is available. The options are new construction level and renovation level which set the corresponding partial load factors in part 3 of the model.

In order to establish characteristic loads, NEN-EN 1991 Actions on structures (parts 1-1, 1-3 and 1-4) is followed. According to the chosen input option, new construction safety level or reduced renovation level is obtained by assigning respective load coefficients. New construction level is achieved by designing load cases according to NEN-EN 1990 Basis of structural design. In order to represent renovation safety level, load cases are designed according to NEN 8700 Assessment of existing structures in case of reconstruction and disapproval. In order to simplify the load design and assignment in the parametric model, load cases are not described, however, design loads are calculated by multiplication with a partial load factor.

The summary of characteristic loads and their respective partial load factors for both safety levels are presented in Table 3.3.

The permanent loads assigned to the model are self weight and the weight of mechanical installations while the live loads are imposed, snow and wind loads. Self weight is calculated automatically by the Karamba component, only the multiplication by the load factor is entered. The installations and imposed loads are assigned to all floors, the roof layer included, as in the transformed extended design it will serve as a floor. On the other hand, the snow load is omitted in the model 1 and it is included in the extension model as the extension roof is the roof of the final project. The wind loads are calculated according to the NEN-EN 1991-1-4 and assigned to the beams on the front facade. In order to take into account possible increase of the building height and, therefore, wind loads on the existing structure, the reference building height used in the calculations is four times the height of the existing. This number was chosen based on the analysed case studies. Even though the average increase of height observed was around 2.3 times, the highest extensions increased the height of existing buildings 3.5 to 4.5 times (Fenix I and de Karel Doorman).

Performed calculations can be found in Appendix C. Figure 3.13 presents a small loaded structure.

Table 3.3: *Summary of characteristic loads and respective partial load factors*

Characteristic loads			Partial load factors	
Type	Name	Value	New construction level	Renovation level
Permanent	Self weight	*automatic*	1.35	1.3
	Installations	0.3 kN/m^2	1.35	1.3
Live	Imposed	2.5 kN/m^2	1.5	1.3
	Snow	0.35 kN/m^2	1.5	1.3
	Wind	*varies*	1.5	1.4

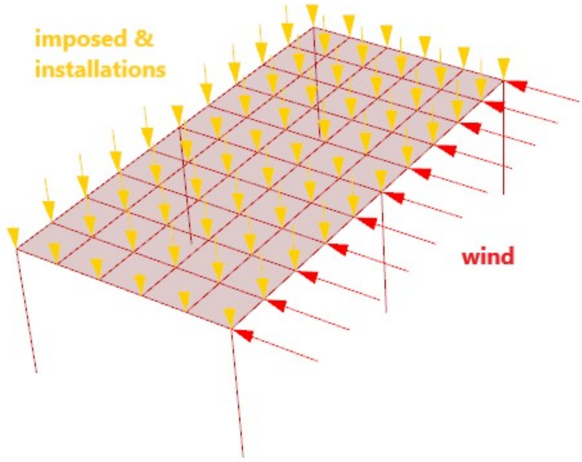
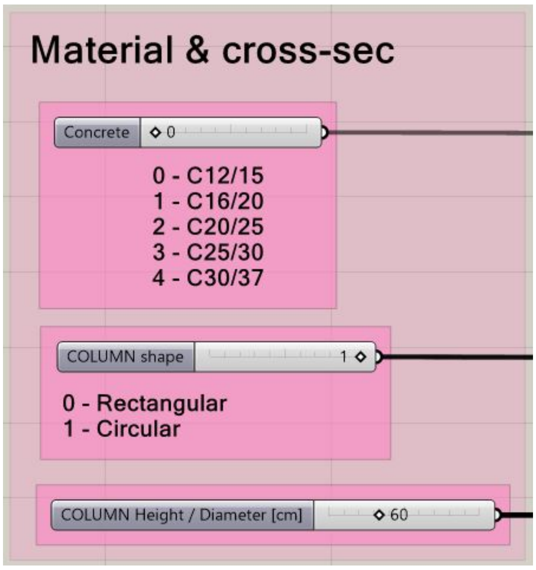


Figure 3.13: *Loads on existing structure*

As in practice there is a possibility to change the stability system from the rigid frames to supported columns, an option to exclude wind loads from the calculation of the frames is included in the inputs. In this case, structural analysis shows how much additional structural reserve could be created if additional structural elements carrying the wind loads, for example stability cores, were designed. The exclusion of these loads allows for such simplified analysis without creating a separate geometry showing the addition of stabilising elements.

Finally, Figure 3.14 shows the Karamba inputs in the model environment.



(a) *Base geometry*

(b) *Geometry with added basement layer*

Figure 3.14: *Karamba inputs in Grasshopper environment*

Therefore, input required for Karamba part includes:

- cross-sections
- material properties
- safety level
- stability system

Next, the model is assembled and analysed. The results of the performance check can be found in Appendix D. The output from the Karamba part is element utilisation coefficients and acting forces of columns and beams. As the focus is on these structural elements, the effects on walls and floors are not analysed in this thesis.

Processing

In this part, the utilisation coefficients of elements are translated into the residual capacity. Beams, inner columns and facade columns are analysed separately. From each group, elements with the highest utilisation of axial, shear and moment strength are found and their acting forces are compared to their design strength.

The results obtained from Karamba are utilisation factors (UC) and forces acting on the elements (E_d). Using formula (1), design strength R_d is calculated.

$$UC = \frac{E_d}{R_d} \tag{1}$$

Consequently, the difference between the acting force and the design strength is the residual capacity:

$$residual\ capacity = R_d - E_d \tag{2}$$

Figure 3.15 presents the results of the processing part.

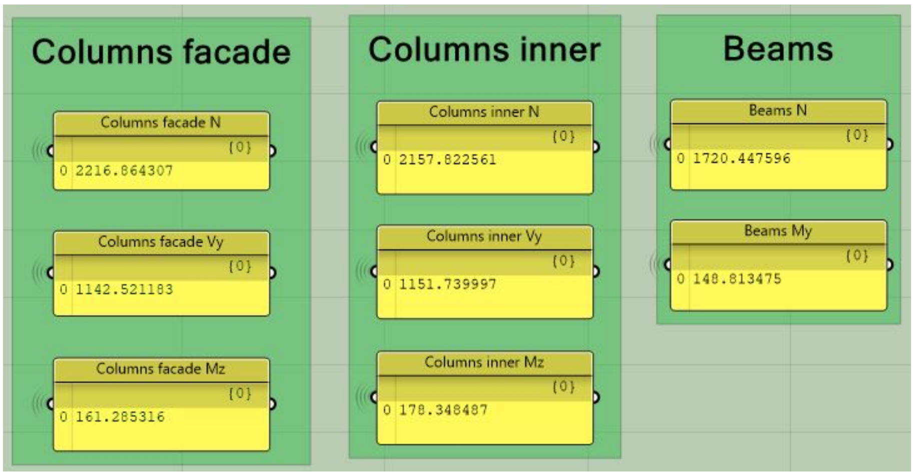


Figure 3.15: *Residual capacity of element groups*

Output

The output of model 1 is the remaining strength of the structure:

- axial, shear and moment strength of inner columns
- axial, shear and moment strength of facade columns
- axial and moment strength of main beams

These values (forces in kN, moments in kNm) are used as input in parametric model 2 to establish how many additional floors could be added on top of an existing structure and existing area expanded.

3.4.2 Model 2

The second part of the parametric model, model 2, is analysing the structure of a vertical extension. The goal of it is to find the effect of the extension onto the existing building and determine how many additional floors this existing structure is able to carry as well as how much the existing building area can be expanded.

Figure 3.16 presents an outline of the parametric model 2.

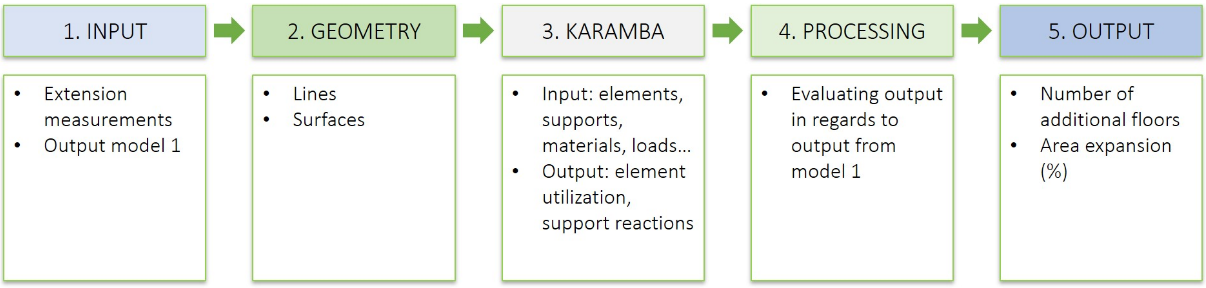


Figure 3.16: *Geometry of the structure of an existing building in model 1*

Input

Main inputs for model 2 are output from model 1, the available capacity of an existing structure, and measurements describing a geometry of an extension. First, the data collected from the model 1 is imported into the model 2 and a slider is created in order to choose an existing structure to be analysed for an extension (Figure 3.17).

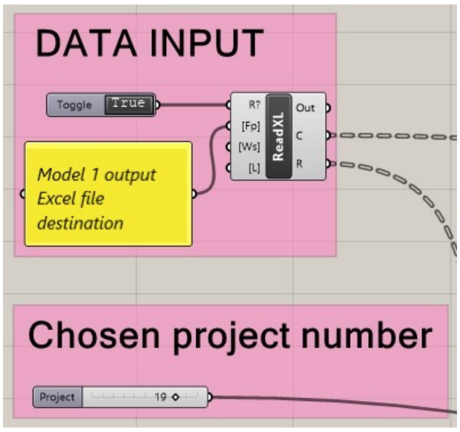
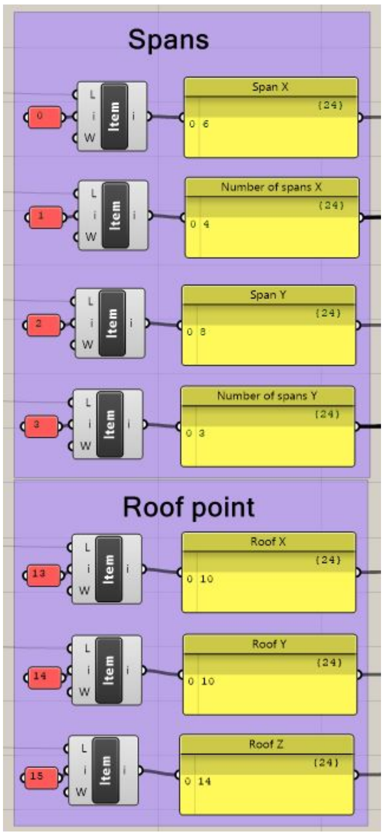


Figure 3.17: *First input for model 2*

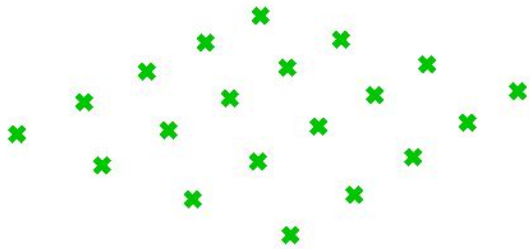
After some data management, the output of model 1 is sorted in order to be used in model 2. This includes span lengths and numbers of spans in both directions and a position of a corner roof point to be able to create a roof layer grid of an existing building that the extension structure could be based on. The input and a roof grid are presented in Figure 3.18.

In addition, information about stability walls and their placement in existing structure as well as structural reserve of all structural element groups and existing floor area are imported.

Other inputs required in model 2 are describing the geometry of an extension. They include floor area relation to the existing building, floor height, number of floors and shape of the structure (Figure 3.19).

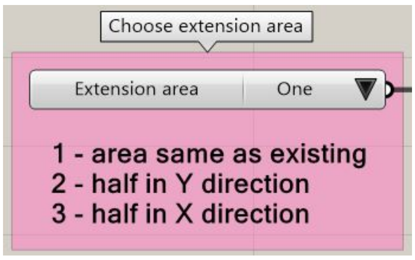


(a) *Geometry output of model 1*

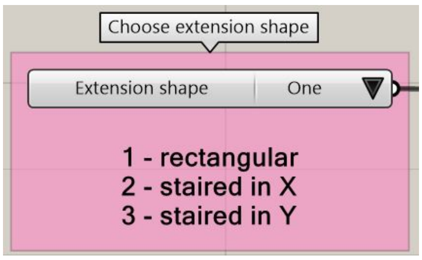


(b) *Roof grid of an existing building*

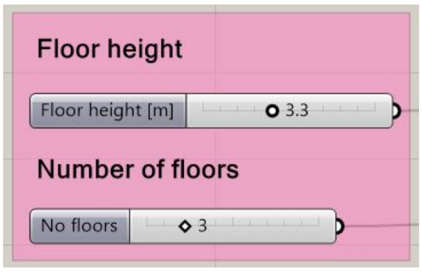
Figure 3.18: *Geometry output of model 1 and a possible connection grid input for model 2*



(a) *Input for size of floor area*



(b) *Input for shape of extension*



(c) *Input for floor height and number of floors*

Figure 3.19: *Model 2 inputs describing geometry of an extension*

Geometry

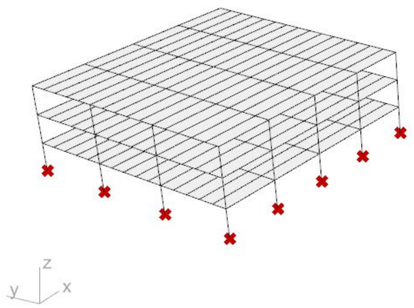
Using these inputs the geometry is created consisting of lines and surfaces representing beams and columns as well as floors. Created structure options are shown in the following figures.

Figure 3.20 presents the choice of different floor area sizes (the red cross-marks represent the roof grid of an existing structure). The options are to build extension with the same floor area as in the existing building (a) or to make it smaller by halving it in Y (b) or X (c) directions. In case the number of spans is an odd number, the “half” is rounded to a larger number as shown in Figure 3.20b.

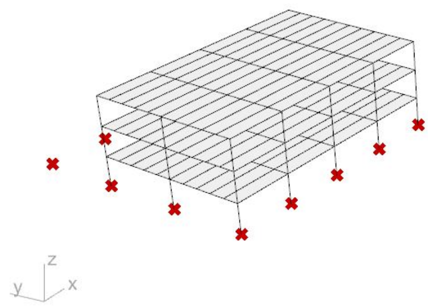
Figure 3.21 presents the choice of different shapes in case the floor area of the extension is the same as in the existing building. The options are a rectangular shape, stair-shape in Y direction and stair-shape in X direction. Also, all three shapes are possible with all floor area size options.

The decision to include the variation of geometry is based on the architectural analysis of the extension case studies. Different shapes do not necessarily create more valuable area, however, they take into account possible differences in height regulations for a building.

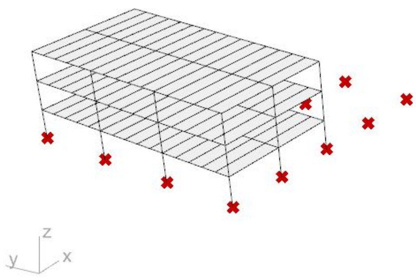
In order to increase stability of the extension structure, X bracings are added according to the position of concrete stability walls in the existing building (Figure 3.22).



(a) *Same size floor area as in existing building*

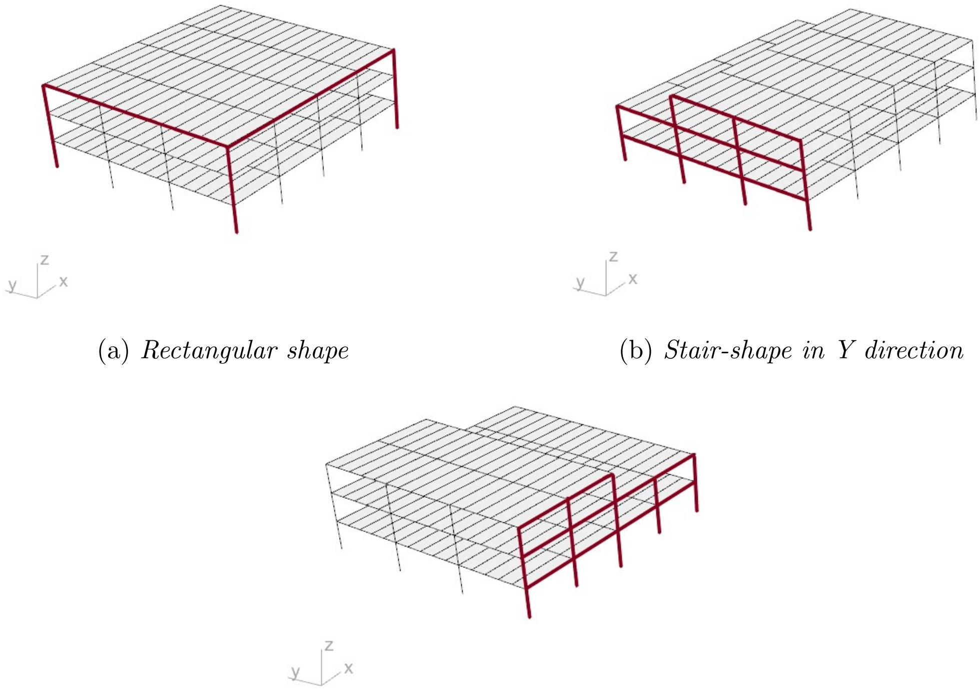


(b) *Floor area is halved in Y direction*



(c) *Floor area is halved in X direction*

Figure 3.20: *Floor area size options for extension*



(a) *Rectangular shape*

(b) *Stair-shape in Y direction*

(c) *Stair-shape in X direction*

Figure 3.21: *Shape options for extension*

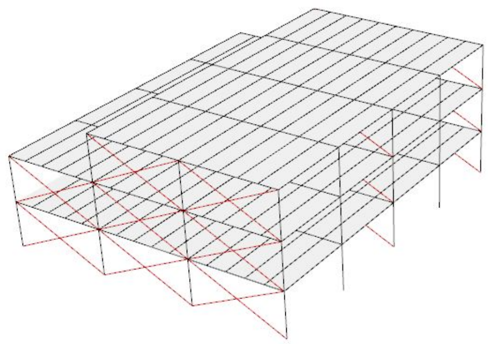


Figure 3.22: *Steel bracings for stability of extension*

Karamba

The next step is setting up the structural analysis, similarly to the model 1, assigning cross-sections, material properties, supports and loads.

First, for cross-sections and materials, a list of possible cross-sections are created for each element group. According to section 3.3.2, two glulam strength classes, GL30c and GL32c, are available and cross-section dimensions are calculated based on rules of thumb (de Groot, 2018). Using a Karamba optimisation component, the most suitable cross-sections are chosen during the structural analysis step. This also allows to choose maximum utilisation coefficient (Figure

3.23) as well as ensures that strength of the elements is not exceeded.

Figure 3.23: *Karamba input for maximum element utilisation coefficient*

As for supports, the extension is rigidly connected to the existing structure, therefore, fixed supports are assigned. Moreover, secondary beams get hinged connections at the ends in order to not transfer bending moments to the main beams.

Lastly, loads are calculated according to the new construction level where characteristic values are the same as in model 1 and the model assembled and analysed (Figure 3.24). Performance check was carried out as well as for the model 1 and results are presented in Appendix D.

The output of the Karamba structural analysis part are the support reactions of the extension structure. As previously mentioned, Karamba cross-section optimisation component takes care of limiting utilisation of elements and chooses the most fitting element sizes in order to get the mass of the structure as low as possible, therefore, element utilisation factors are not checked.

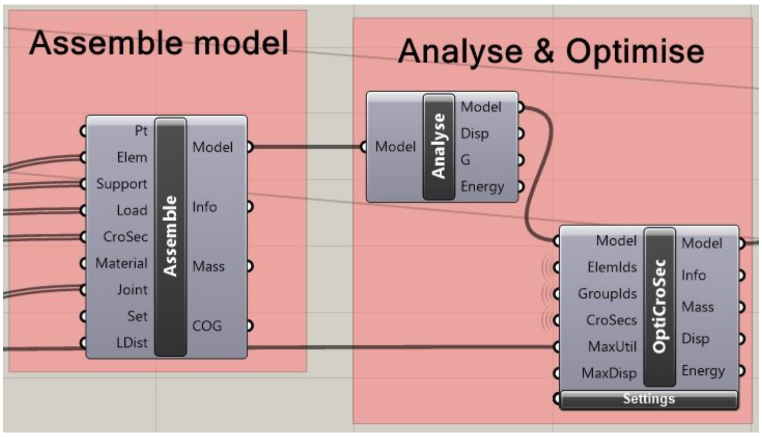


Figure 3.24: *Model assembling and analysis step in Karamba*

Processing

In the processing part of the model 2 the output of the structural analysis is evaluated in regards to the output of the model 1. First, the support reactions are assigned to the respective element groups: facade columns, inner columns and main beams, and the maximum forces are determined. Second, these values are compared to the structural reserve of each element group in order to conclude if they are strong enough to carry the designed extension (Figure 3.25). The highest utilisation factor of all groups shows if the analysed extension is feasible.

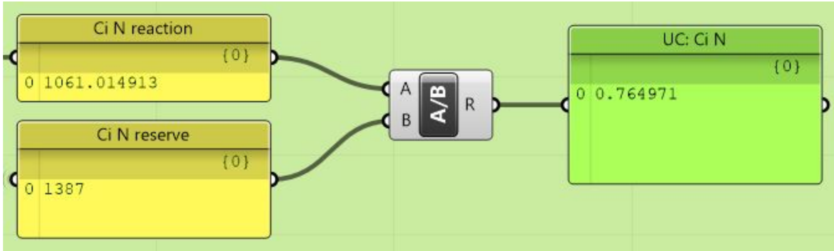


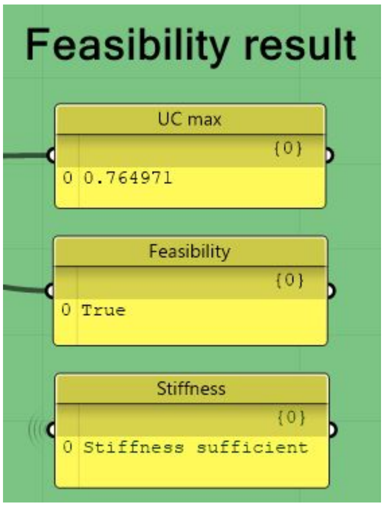
Figure 3.25: *Comparison of the maximum vertical reaction force to the axial structural reserve of the inner columns group*

In addition to the reaction forces and structural reserve check, a simple stiffness check is carried out as well. For this purpose, the largest displacement at the top of the extension is determined and compared to the maximum allowed limit based on rules of thumb (Ham and Terwel, 2017). If the displacement is larger, additional stabilising elements as bracings are required.

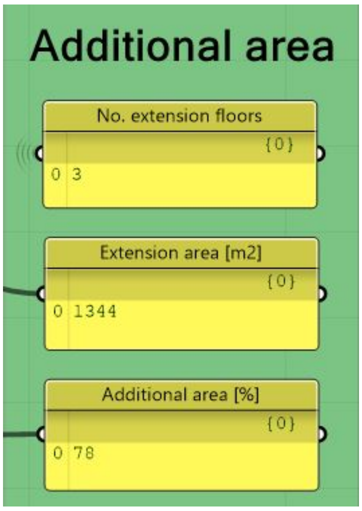
Finally, floor area of the extension is calculated and compared to the floor area of the existing building.

Output

The final output of the model 2 and the whole parametric model are shown in Figure 3.26.



(a) *Feasibility*



(b) *Additional area*

Figure 3.26: *Output of parametric model 2*

The feasibility results include the maximum utilisation coefficient of the existing structure elements. If it is smaller than one, the extension in question is concluded as feasible which is the second obtained result. However, the stiffness check is important as well, especially with lightweight structures. Therefore, the third result shows if required stiffness of the extension is obtained or it needs additional elements. It is important to note that both requirements need to be fulfilled in order for an extension design to be concluded as possible.

Additional area results include a number of extension floors, extension area and, most importantly, built additional area in comparison to the existing floor area expressed in percentage. The last result concludes how much the existing building can be extended.

3.5 Data generation

Following the completion of the parametric model, data is generated in order to be used for the machine learning model. The data generation is carried out utilising the Colibri component from the TT Toolbox plug-in for Grasshopper. The plug-in allows to choose parameters to be iterated and to record preferred outcomes of each selection.

First, the data regarding existing buildings is generated in the model 1. Input, parameters describing possible existing structures, as well as output, structural reserve, are recorded and saved as .csv file. This file is then imported into the model 2 and possible top ups are found for each created existing structure with remaining structural reserve. As parameters describing an extension structure can be altered as well, a few options might be available, therefore, Colibri component is used to generate and record all the possibilities.

Table 3.4 presents all the parameters that could be used for iteration in both parametric models, model 1 and model 2.

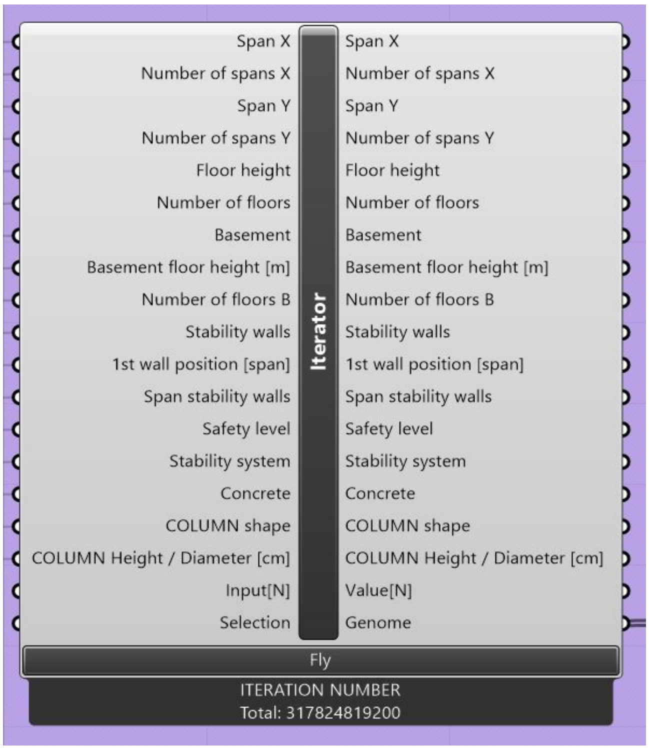
Table 3.4: *Summary of parameters created for iteration*

Model	Parameter	Options
Model 1	Column span in X direction	5-10 m
	Number of spans in X direction	10-15
	Column span in Y direction	5-10 m
	Number of spans in Y direction	4-6
	Floor height	3.5-5.7 m
	Number of floors	2-6
	Basement	True/False
	Basement floor height	2.8-3.5 m
	Basement number of floors	1-2
	Stability walls	True / False
	Stability wall position	Inner / Facade
	Spans between stability walls	2-4
	Safety level	New construction/Renovation
	Stability system	Rigid frames / Supported columns
	Concrete strength	C12/15, C16/20, C20/25, C25/30, C30/37
	Column shape	Circular / Rectangular
	Column cross-section height	50-80 cm
Model 2	Extension area	Same as existing / Half in X direction / Half in Y direction
	Extension shape	Rectangular / Stair-shaped in X / Stair-shaped in Y

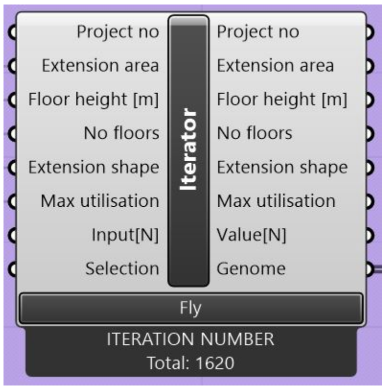
Table 3.4 continuation

Model	Parameter	Options
Model 2	Floor height	3.1-3.6 m
	Number of floors	1-20
	Element utilisation	0.4 / 0.8

Consequently, all the options provide a huge number of iterations (Figure 3.27). In order to be able to process the data, not over-complicate the machine learning model and for it to be able to learn the data well, the final number of projects should be around 10 000. Therefore, only a few parameters are chosen for iteration while others are set to specific values.



(a) *Number of iterations in the model 1*



(b) *Number of iterations in the model 2*

Figure 3.27: *Number of possible iterations*

The chosen set values and parameters for iteration are presented in Table 3.5.

First, regarding grid defining parameters, only the number of spans in X direction is set as a parametric value. The number of spans in Y direction as well as column spans in X and Y directions are set to the average values based on the case studies. This allows to variate the ratio of the building length to width. The options for the existing structure floor height are reduced to 3.5 m and 5.5 m in order to analyse the effect of high ceilings of older buildings and the number of floors can vary between 2 and 6 floors as originally established.

The decision is made not to include a basement in the existing structures which also removes the parameters of basement floor height and number of floors. However, the ability to add stability walls remains in order to analyse the effect of structural interventions. The placement of the first wall is chosen to be in a facade of a building and the distance between walls is set to 3 column spans in X direction. The safety level is fixed to new construction for continuity and safety of the structure.

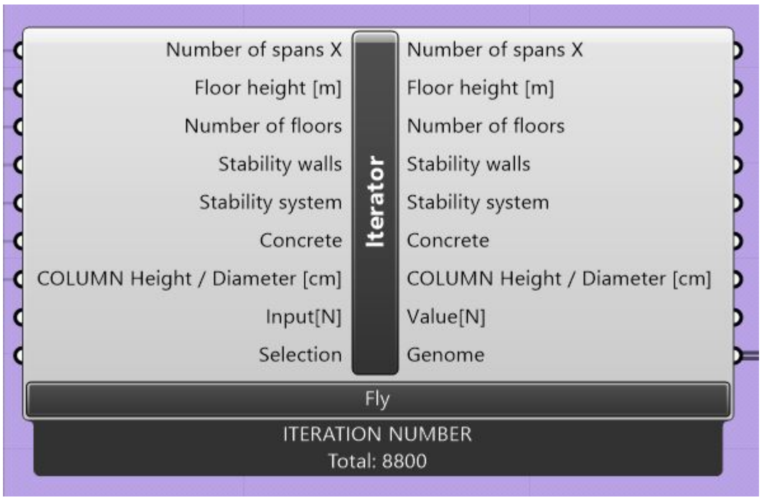
The stability system and concrete strength class values remain parametric to record the changes. Column cross-section is chosen to be rectangular as it is a more common shape but the cross-section size is still parametric due to the variety of sizes independent of the number of floors in the case studies.

Table 3.5: *Summary of the final parameters for iteration (iterative parameters in bold)*

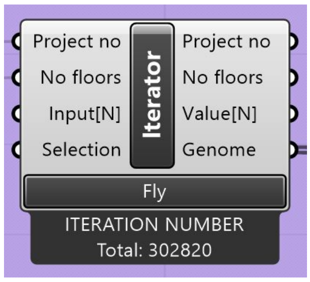
Model	Parameter	Options
Model 1	Column span in X direction	6 m
	Number of spans in X direction	5-15
	Column span in Y direction	7 m
	Number of spans in Y direction	4
	Floor height	3.5 / 5.5 m
	Number of floors	2-6
	Basement	False
	Basement floor height	-
	Basement number of floors	-
	Stability walls	True / False
	Stability wall position	Facade
	Spans between stability walls	3
	Safety level	New construction
	Stability system	Rigid frames / Supported columns
	Concrete strength	C12/15, C16/20, C20/25, C25/30, C30/37
	Column shape	Rectangular
	Column cross-section height	50-80 cm
Model 2	Extension area	Same as existing
	Extension shape	Rectangular
	Floor height	3.1 m
	Number of floors	1-20
	Element utilisation	0.8

In the model 2, the only parametric value is the number of floors, which allows to find the highest possible option for a specific existing structure. As for the other parameters, extension area is set to be the same as in the existing building and extension shape to be rectangular as they provide the largest additional area in comparison to the other options. However, this also means that architectural restrictions are not included in the analysis. The extension floor height is set to 3.1 m based on the case study of Styrpinnen 15, the only analysed timber extension. Finally, the utilisation factor is fixed to 0.8 which is the most commonly chosen optimal value.

The changes in the parameters reduce the final iteration number to be more manageable but still produces a large enough amount of data (Figure 3.28, 8 800 data rows collected).



(a) *Number of iterations in the model 1*



(b) *Number of iterations in the model 2*

Figure 3.28: *Number of final iterations*

Lastly, all the chosen input parameters are connected to the 'Iterator' component and the output values to record are connected to the 'Parameters' component. They represent genome and phenome of the 'Aggregator' which combines all the data and saves it as a .csv file in the chosen location (Figure 3.29).

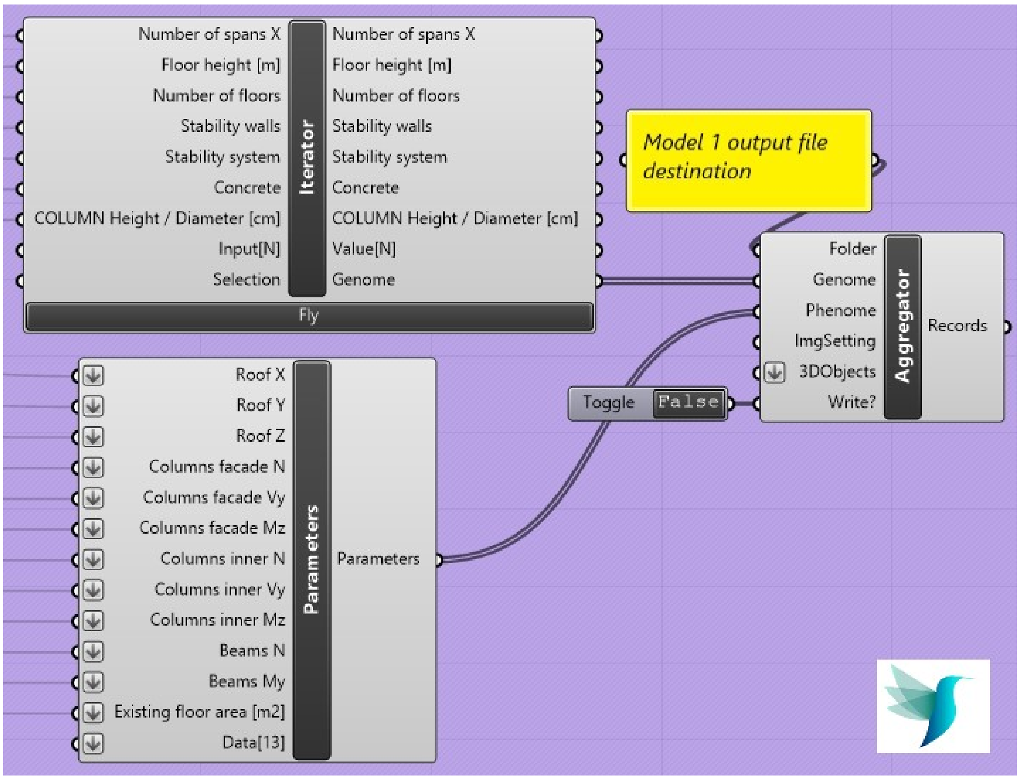


Figure 3.29: *Composition of Colibri components for data generation in model 1*

After the generation of data in model 1 is completed, the file is checked and the projects representing existing structures which are not structurally feasible (structural reserve is negative) are eliminated. This leads to a final number of data rows to 8 652. Subsequently, the data generation is continued in model 2.

Due to the inclusion of the number of additional floors as an independent parameter, a large amount of generated data has to be sorted and removed as only the largest possible number of floors is needed. The method of managing the final generated excel file to remove the unnecessary data is preferred to the inclusion of an optimisation step in the model 2 script. Optimisation components would require to manually optimise each existing structure in order to find the largest number of floors. As long as a method on how to automate this process is not found, data management in the excel file is more efficient. An example is shown in Appendix E. In addition, data correctness check can be carried out at the same time.

Finally, data generation step produces a large data set of fictional timber extension projects that can be used to explore machine learning for predicting vertical extensions.

3.6 Machine learning model

This section is dedicated to exploration of data and its use for ML, building a ML model, finding methods to evaluate and improve it.

3.6.1 Data pre-processing

First, it is important to understand the data that was created and to clean it in order to be able to use in the following steps. Therefore, a brief explanation and analysis are presented in this section.

The dataset is an M×N matrix where M represents the columns (features) and N the rows (instances). In this specific case, M are the project parameters and possible additional area as created in parametric model. Moreover, the columns (M) can be divided into X and Y which represent parameters or input and additional area or output respectively. The rows (N) are the extension projects. Table 3.6 presents a small fragment of the dataset displaying the values M, X, Y and N.

Table 3.6: *Fragment of the dataset with explanation of division*

<table>
<tr><td rowspan="3"></td><td colspan="8">M</td></tr>
<tr><td colspan="7">X</td><td>Y</td></tr>
<tr><td>Ratio X/Y</td><td>Floor height, m</td><td>No. floors</td><td>Stability walls</td><td>Stability system</td><td>Concrete strength</td><td>Column size, cm</td><td>Additional area, %</td></tr>
<tr><td rowspan="4">N</td><td>1.1</td><td>3.5</td><td>6</td><td>0</td><td>1</td><td>0</td><td>50</td><td>0</td></tr>
<tr><td>2.6</td><td>3.5</td><td>2</td><td>1</td><td>2</td><td>3</td><td>50</td><td>300</td></tr>
<tr><td>1.9</td><td>3.5</td><td>3</td><td>0</td><td>2</td><td>2</td><td>70</td><td>600</td></tr>
<tr><td colspan="7">...</td><td>...</td></tr>
</table>

Due to the dataset containing X and Y values, input and output, it will be used for supervised learning (SL). SL means that the machine is given a set of data points together with the right answers corresponding to those data points. In this case, the parameters of an existing structure are described by input and the largest additional area possible for that structure is given. The algorithm has to learn contribution of each parameter for the outcome and next time be able to predict it based on new parameters given. (Rebala et al., 2019)

Moreover, as Y contains quantitative values, regression task will be performed. Regression "refers to the ability to predict values of a continuous variable" (Rebala et al., 2019) in contrast to classification which assigns values to distinct categories.

However, before going into the machine learning, an exploratory data analysis is performed in order to understand the data better. First, a few patterns were noticed already during the data management step:

- Ratio of building length to width does not have a large influence over the end result. Although, a difference can be seen when this ratio is around 1.0 which may allow an addition of one extra storey.
- If existing building is not taller than 11 m, additional 1 or 2 floors can be placed with no improvements of stability.
- Stability of structure as well as strength of elements are the main parameters influencing the outcome.

In addition, since parameters 'Stability walls' and 'Stability system' are related, they are merged into one parameter called 'Stability type' with four options: (1) no stability walls and rigid frame structure, (2) stability walls and rigid frame structure, (3) stability walls and supported column structure, (4) no stability walls and supported column structure. This reduces the number of parameters describing existing structures (Table 3.7).

Table 3.7: *Fragment of the dataset with explanation of division*

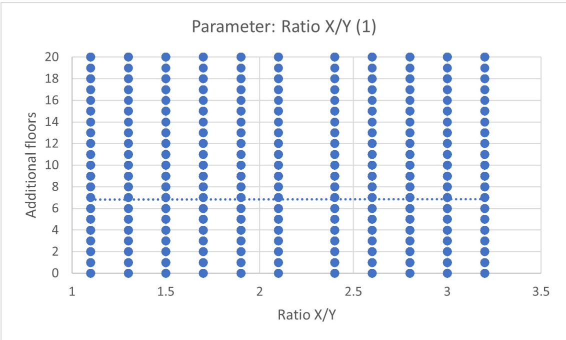
	M						
	X						Y
	Ratio X/Y	Floor height, m	No. floors	Stability type	Concrete strength	Column size, cm	Additional area, %
N	1.1	3.5	6	1	0	50	0
	2.6	3.5	2	3	3	50	300
	1.9	3.5	3	4	2	70	600
	...						...

Moreover, a limit for additional extension floors is set to 20 instead of 33 which was calculated by parametric model. First, the highest numbers for additional floors were shown to be in existing buildings with stability type 4. However, this system was not modelled in detail which might lead to over-optimistic results. Second, according to the case studies, the highest number of additional storeys is 16. Therefore, a reduced number of 20 is chosen.

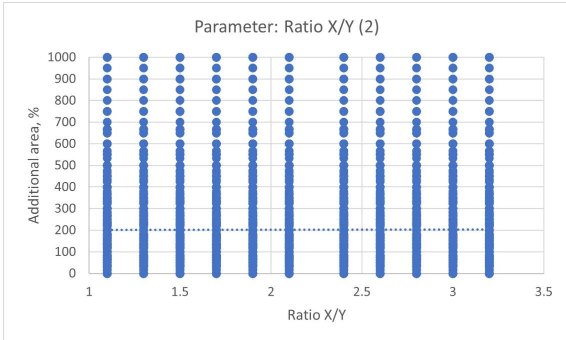
Figure 3.30 and Figure 3.31 present the graphs showing the effect of each parameter on the output. For comparison, influence on possible additional floors as well as additional area are presented.

First, according to Figure 3.30a and Figure 3.30b, the ratio of building length to width does not have and influence on the result which is additional number of floors and additional area. It was only noticed during data management that ratio around 1.0 might allow placement of an additional one storey due to lower wind loads, however, the difference is not distinct.

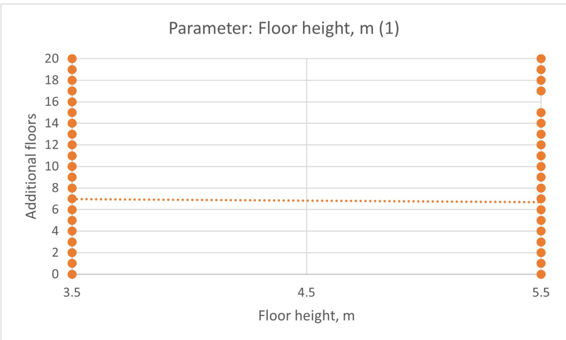
Floor height of an existing building is not an influential parameter as well. Lower height allows for a slightly larger extension, nonetheless, the impact is not significant (Figure 3.30c).



(a) *Ratio X/Y influence on the number of additional floors*



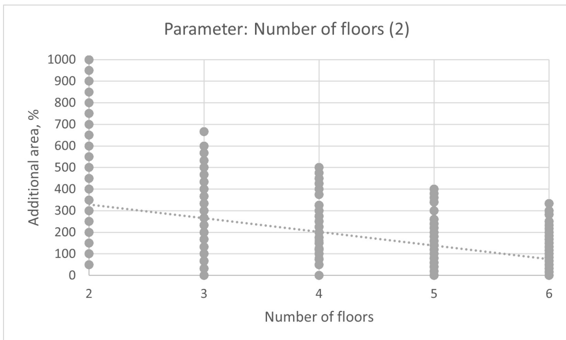
(b) *Ratio X/Y influence on additional area*



(c) *Floor height influence on the number of additional floors*

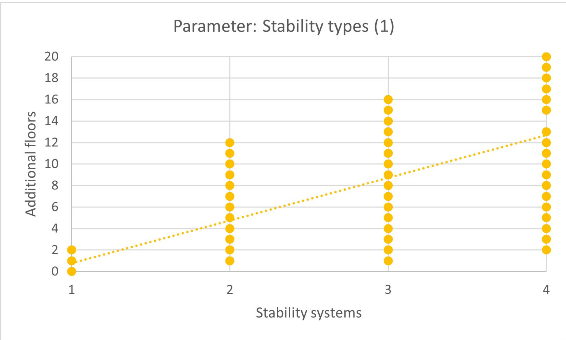
(d) *Floor height influence on additional area*

(e) *Number of floors influence on the number of additional floors*

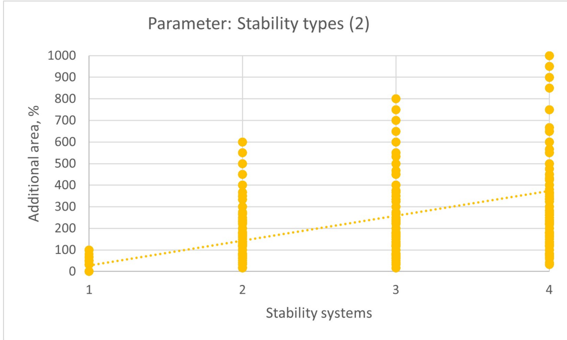


(f) *Number of floors influence on additional area*

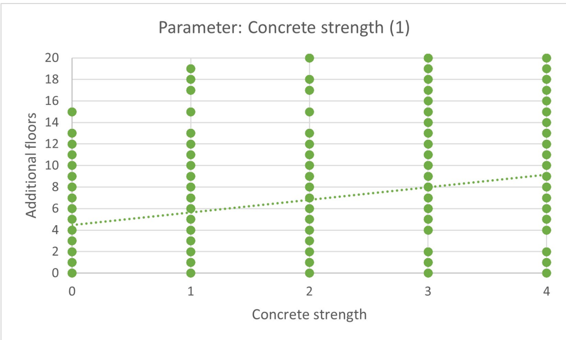
Figure 3.30: *Parameter influence of the output*



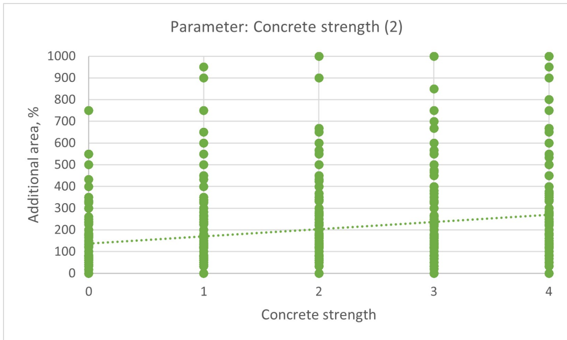
(a) *Stability type influence on the number of additional floors. (1 - no stability walls and rigid frame structure; 2 - stability walls and rigid frame; 3 - stability walls and supported column structure; 4 - no stability walls and supported column structure)*



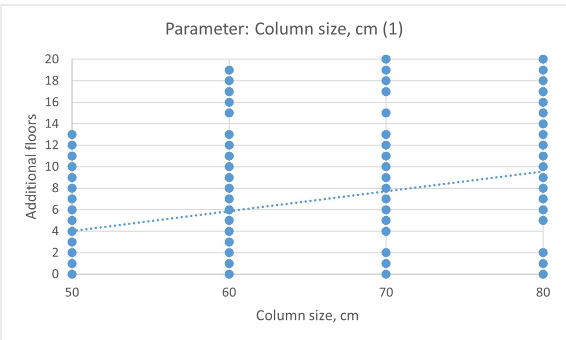
(b) *Stability type influence on additional area. (1 - no stability walls and rigid frame structure; 2 - stability walls and rigid frame; 3 - stability walls and supported column structure; 4 - no stability walls and supported column structure)*



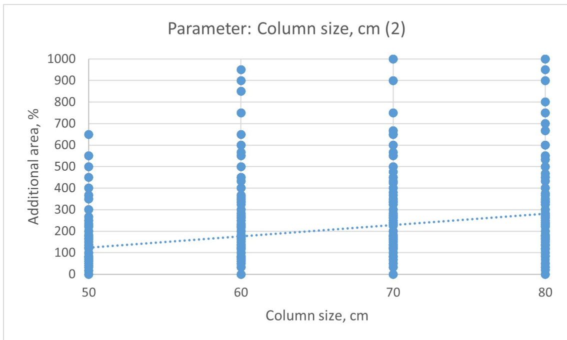
(c) *Concrete strength influence on the number of additional floors. (0 - C12/15, 1 - C16/20, 2 - C20/25, 3 - C15/30, 4 - C30/37)*



(d) *Concrete strength influence on additional area. (0 - C12/15, 1 - C16/20, 2 - C20/25, 3 - C15/30, 4 - C30/37)*



(e) *Column size influence on the number of additional floors*



(f) *Column size influence on additional area*

Figure 3.31: *Parameter influence of the output (continued)*

The number of floors of existing buildings show to have some influence on how much the building can be extended as the lower structures, 2-3 storeys high, can bear more additional floors (Figure 3.30e). The reason for it might be the lower wind loads on existing building itself. This also leads to the lower buildings being extended a lot more percentage-wise (Figure 3.30f).

Stability type is the most dominant parameter, according to the angle of the trend-line in the graphs (Figure 3.31b). Low existing buildings can be extended 1 or 2 floors high with no interventions, however, a lot higher extensions are possible if stability walls are included or stability system is changed from a rigid frame to supported column structure where lateral loads are transferred through additional stabilising elements as stability cores. Stability system 3 is not efficient due to the addition of stability walls as they are not necessary for stability but contribute to the weight of the structure.

Parameters concrete strength and column cross-section size show quite high influence as well (Figure 3.31c, Figure 3.31d, Figure 3.31e and Figure 3.31f). As expected, higher strength elements with larger cross-sections lead to higher lightweight extensions.

Finally, the data is cleaned: number of parameters reduced and the limit for a feasible extension is set; also, the most influential parameters are found, which are stability type, concrete strength and column cross-section size. The final dataset can be used to train and test a machine learning model.

3.6.2 Cross-validation

First, the procedure for building the model is chosen. N-fold cross-validation (CV) is a common method used to evaluate how well a ML model works with unseen data. It is preferred to a simple train-test split, where data is divided into 80% and 20% groups for training and testing, as it usually results in less biased or less optimistic estimate. (Brownlee, 2018)

Using an N-fold CV, the dataset is partitioned into N parts called folds. One fold is left out as testing data while the model is trained on the remaining N-1 folds. This is repeated N times allowing each fold to perform as testing data. (Nantasenamat, 2020)

Most commonly 5 or 10 folds are used, an example of the 5-fold CV is presented in Figure 3.32.

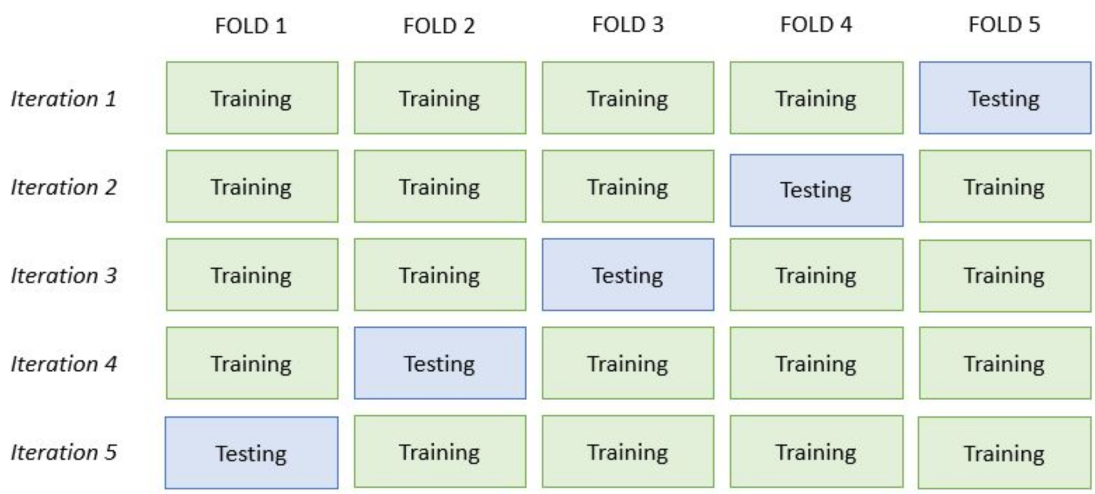


Figure 3.32: *Example of 5-fold cross-validation*

Eventually, 5 models (in 5-fold CV) are trained and tested, results collected and the evaluation of the model performance is computed based on average values from all models.

3.6.3 Multiple linear regression

Learning algorithm chosen for the model is multiple linear regression (MLR). According to Chou et al. (2014), linear regression (LR) is commonly used for modelling the mechanical properties of construction materials and due to its simplicity MLR is applied in this thesis as well. The main source for this section is Rebala et al. (2019).

MLR determines the relationship between multiple independent variables X and one output (dependent variable) Y (Chou et al., 2014). MLR is based on assumptions that the relation between X and Y is linear and independent variables are not correlated to each other. The general formula for prediction is:

$$y = \theta_0 + \theta_1 * x_1 + \theta_2 * x_2 + \theta_3 * x_3 + ... \tag{3}$$

where

y - value to be predicted,

x_i - parameter value influencing y,

θ_i - coefficient determining the contribution of x_i.

The value of θ_0 can be written as $\theta_0 * x_0$ when a variable of x_0, which is equal to 1, is brought in. Consequently, the equation (3) can be written in a more compact form which is called a hypothesis function:

$$y = \sum_{i=0}^{n} (\theta_i * x_i) \tag{4}$$

where

n - number of parameters (features) used to predict y.

All input values, or values for x_i, are known from the dataset. In order to find parameter contribution coefficients, θ_i, two methods can be used: normal method or gradient descent method. Normal method is recommended for datasets with matrix size 1000×1000 or less. Moreover, it includes matrix inversion which might cause inaccuracies using Grasshopper, therefore, gradient descent method (GDM) is chosen.

GDM analyses the total model error function which can be expressed by:

$$J(\theta) = \frac{1}{2m} \sum_{i=1}^{m} (h(x^i) - y^i)^2 \tag{5}$$

where

$h(x^i)$ - predicted value y for the ith row,

$h(x^i) - y^i$ - the error between predicted value and actual value,

m - number of data points in the dataset (rows),

$J(\theta)$ - total error term of the model.

Equation (5) for the total error is quadratic and a general shape of it is presented in Figure 3.33.

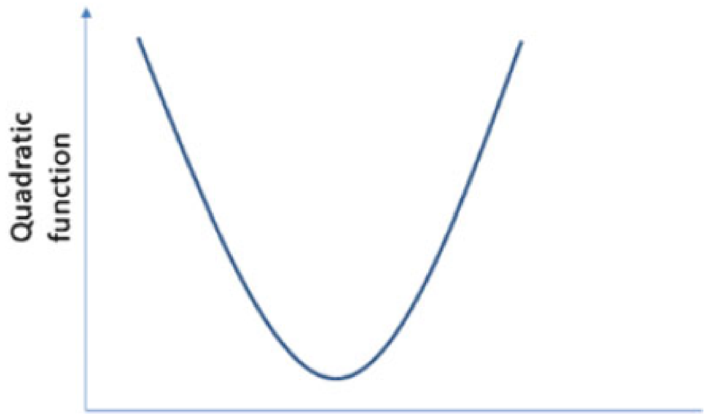


Figure 3.33: *General shape of a quadratic equation (Rebala et al., 2019)*

This function shape (Figure 3.33) has three specific properties:

- There is only one minimum.
- The absolute value of the slope increases as you go further from the minimum.
- The sign of the slope indicates if you are to the left or to the right on the minimum.

Therefore, the GDM uses the slope and the value at any point for guidance in order to get close to the minimum. The slope of $J(\theta)$ in respect to each of θ_j (for $j = 0, 1, 2, ..., n$) is represented by equation (6):

$$\frac{\delta J}{\delta \theta_j} = \frac{1}{m} \sum_{i=1}^{m} (h(x^i) - y^i) * x_j^i \tag{6}$$

where

subscript $_j$ refers to the values of the jth parameter (column),

superscript ^{i} refers to the values of the ith row,

x_j^i refers to the value of jth parameter in the ith row.

Therefore, it is possible to determine the slope in respect to each parameter at any point. Knowing this, a correction can be calculated:

$$\theta_j = \theta_j - \alpha * \frac{\delta J}{\delta \theta_j} \tag{7}$$

where

θ_j - initial and corrected coefficient values,

α - a constant, correction factor, also called learning rate.

When continued iterations bring solution closer to the desired value, the solution is said to be converging. For this purpose, the value of $J(\theta)$ should be monitored, as a decreasing value shows that the solution is getting closer to the minimum. When the change in $J(\theta)$ is very small, the iterations may be stopped as a satisfactory solution is reached.

As a result, steps required for use of the GDM are:

1. Pick initial value for each of θ_j.
2. Consider an α, learning rate. There is no algorithmic method for choosing the best value, various combinations need to be considered and solution monitored. Recommended range is from 0.001 to 1.
3. Compute slope according to equation (6).
4. Correct θ_j values using equation (7).
5. Keep monitoring $J(\theta)$ for convergence.

3.6.4 Model building

In this thesis, the ML model is built using a Rhinoceros plug-in Grasshopper, using ML components from LunchBoxML plug-in. According to its creators, Proving Ground, LunchBoxML was mostly created for someone who is just starting with ML, in addition, it provides easy implementation for more experienced users (Miller, 2019).

The first step in the model creation is importing and preparing the final dataset in Grasshopper. The imported data from the .csv file here is stored as a data tree where each branch contains information about an extension project. The column names and project numbers are removed in order to have a clean dataset consisting only of input and output which subsequently will be used for ML. This results in a data tree with 8 652 branches each containing 7 values, 6 of which are parameters describing the existing building and the last one is an output, additional extension area (Figure 3.34).

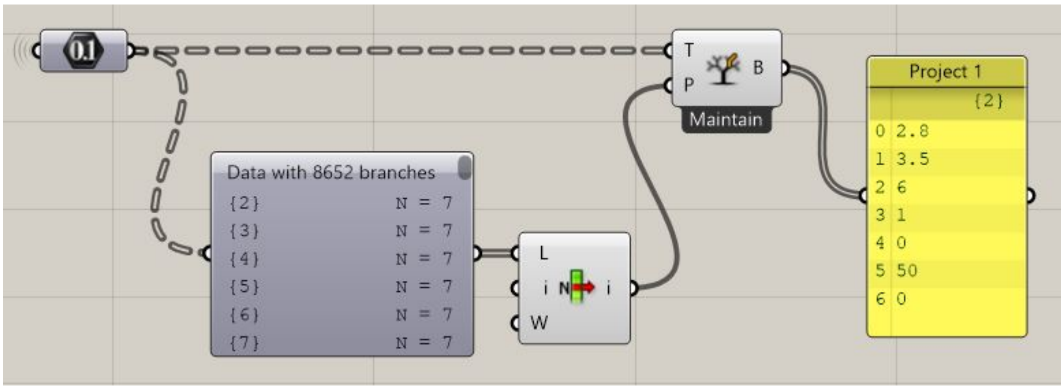


Figure 3.34: *Structure of the dataset in Grasshopper. The box 'Project 1' shows type of information stored in each branch of the data tree.*

Next, these branches are shuffled in order to create a similar and random mix of data in each division and the data is split into 5 equal parts, folds, for 5-fold CV. In order to achieve it in Grasshopper, the data tree in divided into 5 branches each of them containing 1730 additional branches which hold the project information. This step is shown in Figure 3.35.

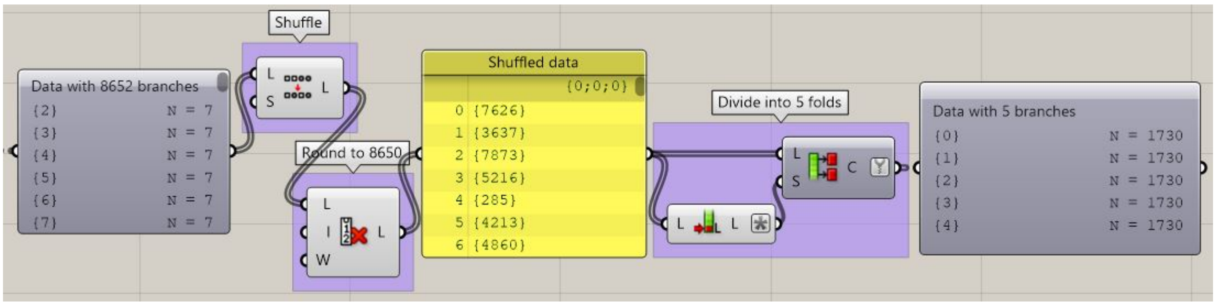


Figure 3.35: *Step of data shuffling and creating 5 folds in Grasshopper*

After the folds are formed, the setup for iterations (Figure 3.32) is modelled. This includes the choice of which fold is used for testing, therefore, separating testing and training data, as well as specifying input and output. As a result, four data boxes are created: training data input, training output, testing input and testing output (Figure 3.36). One of the folds out of five, therefore, 20% of data, is used for testing, while 80% for training.

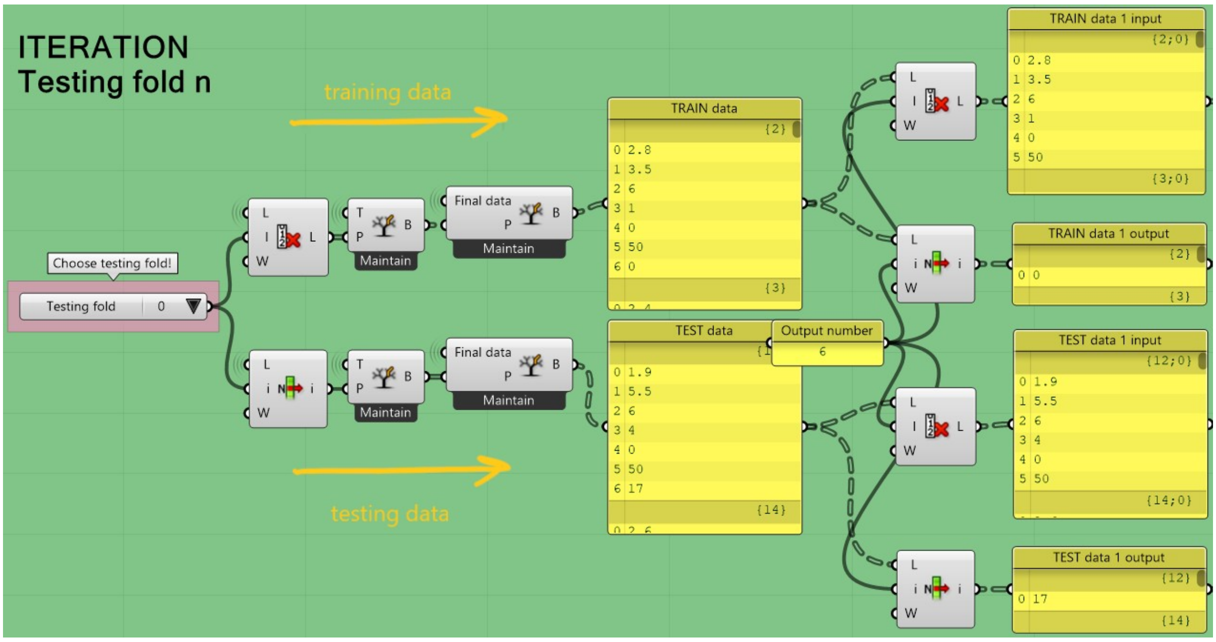


Figure 3.36: *Step of training and testing data as well as specifying input and output*

Consequently, these data boxes are plugged into the learning algorithm, MLR, and predictions are made. In addition, total model error is calculated according to equation (5) for the use of GDM. The error $J(\theta)$ is mainly used to find corrections for contribution coefficients θ_j and not to evaluate the performance of the model (Rebala et al., 2019).

For the GMD, the steps explained in section 3.6.3 are followed: initial choice of 1 for each θ_j value is made, slopes are computed, learning rate value set to 0.001 and θ_j corrections are calculated. This process is repeated 10 times with increasing α value from 0.001 to 1, however, no significant change in the total error $J(\theta)$ value is observed (Figure 3.37).

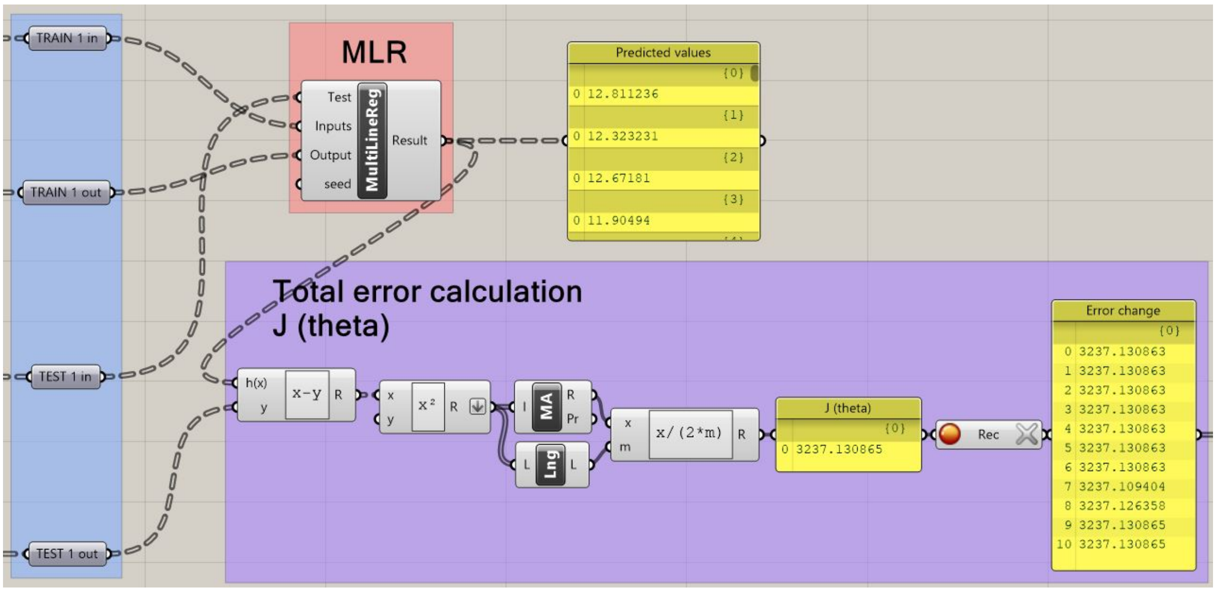


Figure 3.37: *Step of using MLR to make predictions and total error calculation*

3.6.5 Model evaluation

Due to the use of visual programming with Grasshopper where the learning algorithm, MLR, is already coded and hidden in a component and not publicly available, it is difficult to tell how it really works. It might be that GDM is already included in the code of algorithm, therefore, it does not allow alterations of contribution coefficients done manually. Unfortunately, this is a common drawback of such prepared, easy to use programs as customisation is either not possible or challenging to achieve. Consequently, for this thesis, it is assumed that MLR component of LunchBoxML does alterations automatically and the predictions are as good as they can be obtained using Grasshopper.

In order to evaluate these predictions and how well the model performs, first, mean error (ME) and root mean square error (RMSE) values are calculated. ME monitors the sign of the error and can be calculated:

$$ME = \frac{1}{m}\sum_{i=1}^{m}(y^p - y^i) \tag{8}$$

where

m - number of data points,

y^p - predicted value,

y^i - actual value.

Negative ME value indicates that a model is under-predicting while positive value implies over-predicting (Tayo, 2020). As 5-fold CV is used for the model, there is an ME value for each iteration, the results are shown in Table 3.8. As the average ME value is positive, the model is over-predicting.

Table 3.8: *ME values of the model (MLR)*

Iteration	ME_i	$\overline{ME}$
1	2.6587	
2	-4.0300	
3	0.5794	0.0011
4	1.3704	
5	-0.5731	

Another calculated error is RMSE:

$$RMSE = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(y^p - y^i)^2} \tag{9}$$

The results of all iterations are presented in Table 3.9.

Table 3.9: *RMSE values of the model (MLR)*

Iteration	$RMSE_i$	$\overline{RMSE}$
1	80.463	
2	79.911	
3	79.357	80.260
4	80.917	
5	80.654	

RMSE value shows the average prediction error and it is interpretable in prediction value y units which makes them easy to compare. As the average value of the prediction y^p is 169.013 (average of all iterations), the average error of 80.260 makes a 47% error which is very high.

Moreover, the largest absolute errors for each iteration are observed and shown in Table 3.10 and they make up around 45% of actual output values.

Table 3.10: *Largest prediction errors (MLR)*

Iteration	Max absolute error	Prediction error, %
1	452.89	45.3
2	452.73	45.3
3	453.50	45.3
4	453.75	45.4
5	374.51	41.6

In order to examine the relation between the actual and predicted values, it is visualised in a graph and presented in Figure 3.38. The graph points resemble a curved shape which implies a nonlinear relation. Moreover, in comparison to the ideal guideline, it shows that for the lower actual values the model tends to over-predict while for the higher values under-predict. Another difference between these values is their range as the actual ones are all positive, varying from 0 to 1000, while predicted range is from around -200 to 550.

As some of the points in the graph are considerably far from the guideline, it is decided to check how many of the predictions are out of the acceptable range. For this purpose, predictions as well as their describing parameters and actual output values are exported as an excel file. An allowed error is chosen to be ±1 floor. As the model is intended for the initial design stage, a higher error is allowed; for a final design, a prediction of an additional one more floor than feasible would not be accepted.

By calculating the difference between the actual and the allowed errors, the predictions which are out of acceptable range are determined. This process is carried out for all five iterations, as a result, the average amount of not acceptable predictions are 54%. This, in addition to the result of RMSE calculation and the largest errors evaluation, shows that the ML model is not accurate enough.

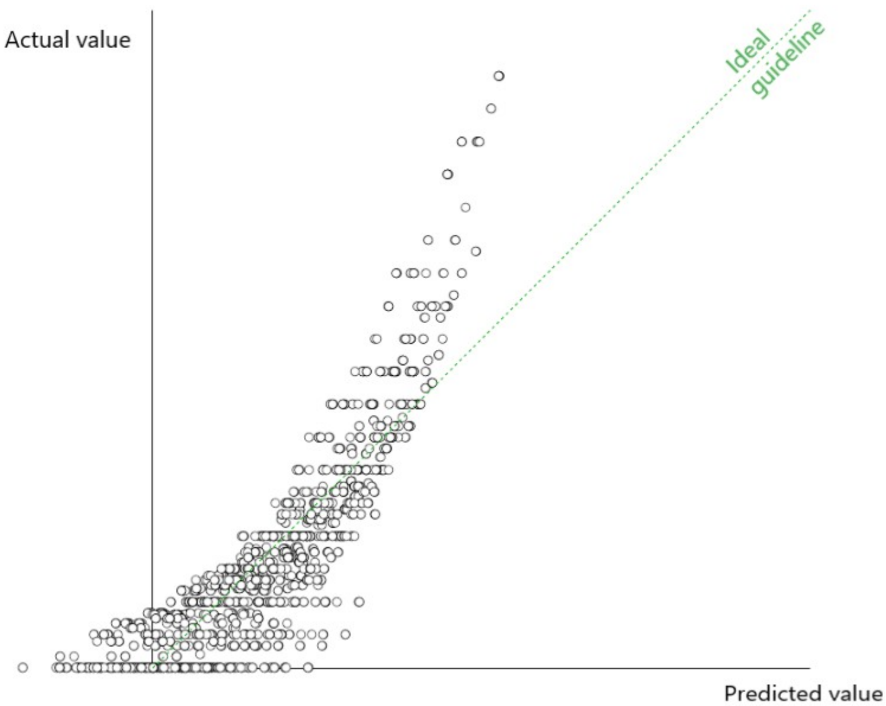


Figure 3.38: *Relation between actual and predicted values using MLR (Iteration 5)*

To analyze which parameter, feature, mostly causes the large error of the model, 100 biggest prediction errors where found for each iteration. However, data observation leads to a conclusion that not only one parameter is responsible for the error but a combination of them as among the projects with the highest prediction errors all parameter values vary. Nonetheless, some values occur more frequently than others and Table 3.11 presents the most frequently occurring values for each parameter for all iterations.

Table 3.11: *Most frequently occurring values for each parameter for projects with highest prediction errors*

Parameter	Value	Frequency
Ratio X/Y	*varies*	-
Floor height, m	*varies*	-
Number of floors	2	64%
Stability type	1	57%
Concrete strength	5	46%
Column size, cm	80	63%

According to the table, it seems that the largest errors occur for existing buildings that could be extended the most: 2-floor-high, built from the strongest concrete and having the largest column size, as well as the buildings that could be extended the least as the stability type 1 represents a rigid frame structure with no interventions. As the value 2 for the parameter 'Number of floors' occurs slightly more often than others it was chosen for a further analysis.

First, Figure 3.39 presents a graph showing a relation between the number of floors of existing buildings and size of the error. According to this diagram, the largest errors occur in predictions for the lowest, 2-floor-high existing buildings while the smallest errors are for the buildings which have 5 stories. However, the highest error for the structures with 2 floors are significantly larger.

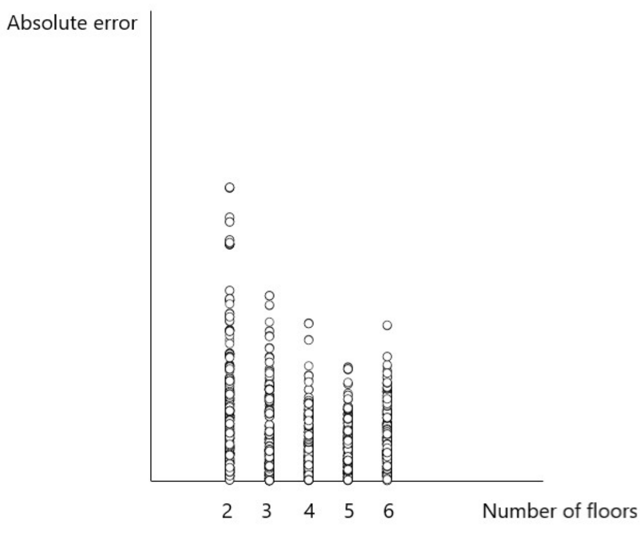


Figure 3.39: *Relation between the number of floors of an existing building and absolute value of the error (Iteration 5)*

Consequently, a relation between the existing area of the building and the size of an error is analysed as well and presented in Figure 3.40. It shows a larger and heavily varying error for smaller existing areas. Positive error values show that in those cases the model is over-predicting while negative values indicate under-predicting. Even though predictions for most buildings with different size existing areas are not accurate, the error value decreases as the area size increases.

Figure 3.40: *Relation between the existing area of a building and size of the error (Iteration 5)*

For this reason, all projects that contain 2-storey existing buildings are removed from the dataset and the model is trained again in order to observe how the prediction error changes. In this case, average RMSE value is 56.83 which makes 43% error for the average prediction value of 132.38. The largest absolute errors are checked as well, the average value for all iterations is 222.26 which makes up around 35% of the actual output value. In comparison to the errors of the original dataset, 47% for RMSE and 45% for the largest absolute error, both of the values decreased due to the change of the dataset.

Similar analysis could be done with other parameters by removing the data points with values that cause the largest errors. However, it is not a solution for a ML model. The results of the model evaluation show that:

- the model predictions are not accurate enough,
- several parameters cause the large prediction error,
- the relation between input and output values might be nonlinear.

3.6.6 Model alteration

Some values of a parameter causing more error than others suggests that contribution of that parameter is nonlinear. For example, it can be that contribution is a square of a value or a combination of two parameters is more meaningful (Rebala et al., 2019). So, the hypothesis function gets modified:

$$y = \theta_0 * x_0 + \theta_1 * x_1 + \theta_2 * x_2^2 + \theta_3 * x_3 * x_4 + ... \tag{10}$$

However, in statistics it is still a part of LR as modifications are made to individual parameters and the equation still follows the form where an independent parameter is multiplied by a contribution coefficient (θ_i) (Frost, 2017). And equation (10) can be rewritten in the form of equation (3) with additional features representing values of x_2^2 and $x_3 * x_4$ (Rebala et al., 2019). Therefore, LR can fit curvature to the data.

Nonlinear regression (NLR) is regression that does not follow a required form of LR described above. Examples of NLR equations (Frost, 2017):

- Power:
$$y = \theta_1 * x_1^{\theta_2} \tag{11}$$

- Weibull growth:
$$y = \theta_1 + (\theta_2 - \theta_1) * exp(-\theta_3 * x^{\theta_4}) \tag{12}$$

- Fourier:
$$y = \theta_1 * cos(x_1 + \theta_4) + \theta_2 * cos(2 * x_2 + \theta_4) + \theta_3 \tag{13}$$

A common guideline is to start with simple LR using equation (3) and add nonlinear contribution of parameters, for example equation (10), in order to make it fit the dataset better. If it is not possible to get a good fit with LR, NLR might be used, however, it makes a model more complex and difficult to interpret.

As for this thesis, Grasshopper is used for ML model building and, as mentioned at the beginning of section 3.6.5, it is hard to tell how MLR component works and customise it. Therefore, as an alternative NLR component is used in order to explore the difference of accuracy of predictions. First, training and testing data is plugged into the NLR component and predictions are made (Figure 3.41).

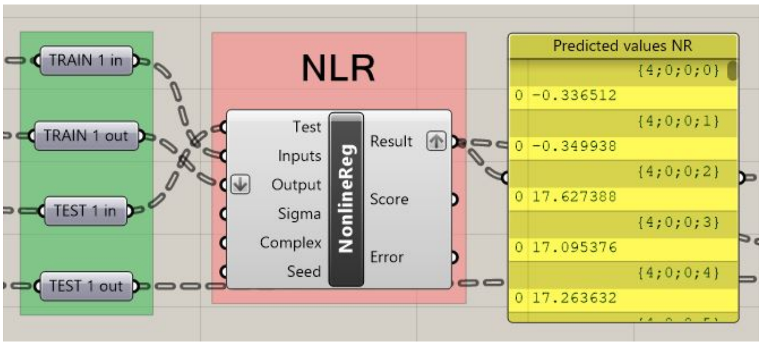


Figure 3.41: *Step of using NLR to make predictions*

Next, ME and RMSE are calculated and results are presented in Table 3.12 and Table 3.13.

Table 3.12: *ME values of the model (NLR)*

Iteration	ME_i	$\overline{ME}$
1	-0.6429	
2	-1.5222	
3	-0.5695	-1.0752
4	-1.6007	
5	-1.0408	

Table 3.13: *RMSE values of the model (NLR)*

Iteration	$RMSE_i$	$\overline{RMSE}$
1	17.294	
2	15.612	
3	15.523	16.276
4	15.859	
5	17.094	

According to Table 3.12, the average ME value for all iterations is negative, therefore, the model is under-predicting. According to Table 3.13, the average RMSE value is 16.276 and it makes a 10% error for the average prediction value of 167.94 which is a lot more acceptable. Moreover, the prediction range is from -4 to 850, a lot closer to the actual value range [0; 1000].

As for the largest absolute errors for each iteration, the values are shown in Table 3.14. The average maximum error is around 17%.

Table 3.14: *Largest prediction errors (NLR)*

Iteration	Max absolute error	Prediction error, %
1	139.39	23.2
2	130.01	13.00
3	120.83	12.08
4	99.59	12.45
5	149.67	24.94

In order to observe the relation between actual and predicted values, a visualising graph is created, it is shown in Figure 3.42. In contrast to Figure 3.38, the points mostly follow the guideline which means that predicted values are quite similar to the actual output. Wider scatter is seen as the values get larger, the reason for it is expected to be a smaller existing area of existing buildings as it was analysed for the MLR model.

For comparison, the check of how many predictions are out of the acceptable range is carried out as well where allowed error is ±1 floor. This check shows that only 1% of predictions are not acceptable which makes the model to be very accurate.

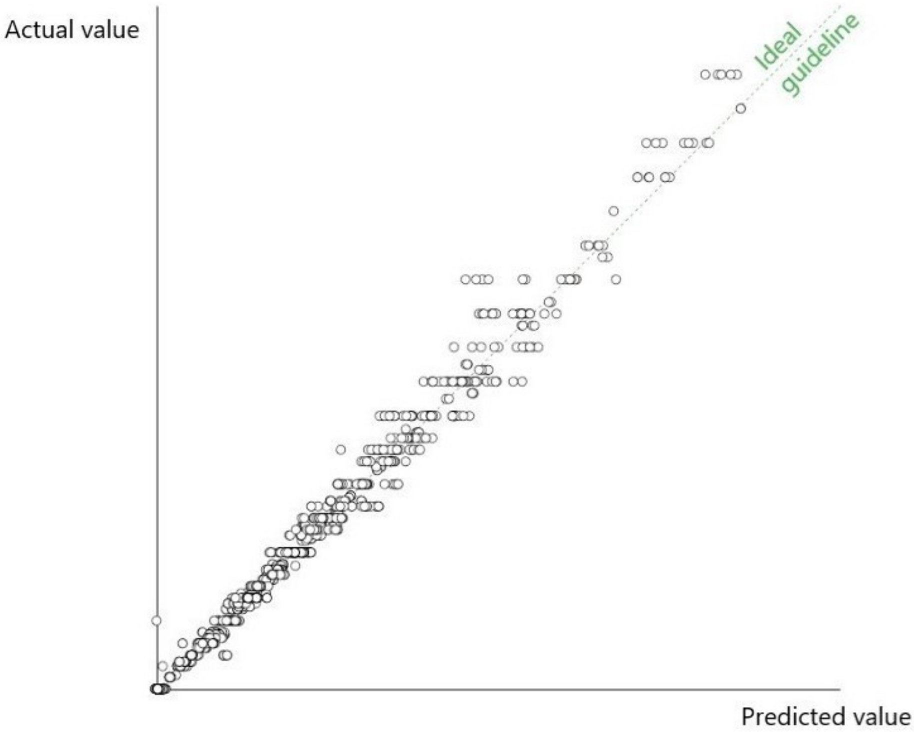


Figure 3.42: *Relation between actual and predicted values using NLR (Iteration 5)*

In order to compare the results of evaluation of MLR and NLR models, they are presented in Table 3.15.

Table 3.15: *Comparison of evaluation results*

	Prediction range	$\overline{ME}$	$\overline{RMSE}$	Max error	Predictions out of acceptable range
MLR	[-200; 550]	0.0011	80.260	45%	54%
NLR	[-4; 850]	-1.0752	16.276	17%	1%

First, the prediction range of NLR model is a lot closer to the range of actual output value range which is [0; 1000]. Next, according to $\overline{ME}$, MLR model is over-predicting while NLR model is under-predicting. In case of working with structural design, under-predicting is more acceptable due to safety reasons. $\overline{RMSE}$, which represents the average prediction error, is almost 5 times smaller for the NLR model, moreover, with the change from MLR to NLR, the largest absolute error values decreased from 45% to 17%. Lastly, there is a large difference between the amount of predictions that are out of acceptable range where an error of ± 1 floor is allowed. For the MLR model, this amount is 54% while for the NLR model only 1%.

Overall the model which uses NLR as a learning algorithm shows a lot better results, however, for this thesis, it is not researched enough. Moreover, Grasshopper allows some customisation for the NLR component which are 'Sigma' and 'Complex' inputs. These inputs describe the degree and complexity of the solver which define the fit of the trendline. For the analysis described above, default setup is used, therefore, there is space for improvement. The final conclusion is that a more accurate model can be built if some nonlinear contribution of input parameters of the dataset is introduced.

3.6.7 Reliability check

For the last check of the created ML models, it is investigated how well they perform with data collected from actual realised extension projects. The models operate on the fictional dataset generated using the parametric models and even though the initial input parameters are based on the real data, it is difficult to judge how feasible is the output.

For this purpose, five extension projects from the previously described case studies are chosen as they were the base for creation of the fictional database. These projects are: Fenix I, Las Palmas, De Karel Doorman, De Gekroonde P, Groot Willemsplein. Detailed information about them can be found in section 3.3.1 and Appendix B.

The project input parameters as well as the actual extension and predictions of models MLR and NLR are presented in Table 3.16.

Table 3.16: *Comparison of evaluation results*

Project	Input						Output			
	Ratio X/Y	Floor height, m	Number of floors	Stability type	Concrete strength	Column size, cm	Actual extension, %	Extension all area, %	Prediction MLR, %	Prediction NLR, %
Fenix I	2.5	5.7	2	2	0	70	191	450	184	227
Las Palmas	2.5	5.5	5	1	4	70	10	40	75	0
De Karel Doorman	4.8	3.5	4	4	4	80	151	400	434	386
De Gekroonde P	1.1	3	6	2	3	50	50	50	0	76
Groot Willem-splein	1.8	3.5	5	4	1	70	60	60	227	155

In the table, the input fields present parameters that describe the existing buildings while the output fields show how much these buildings were actually extended as well as the predictions of MLR and NLR models. The field 'Extension all area, %' refers to a fictional value which shows how much the existing buildings could have been extended if the extension floor area was the same as existing floor area with the same number of additional floors.

For the Fenix I project, the values for actual extension as well as MLR and NLR predictions are very similar which is surprising as the ML models do not take into account the stair-shape of the extension together with the table structure which was employed to place the extension op top. It could be that these solutions allowed to achieve 9 additional storeys on top of part of the existing building which would not be possible if the extension floor area was the same as the existing.

Las Palmas case predictions for MLR and NLR models vary: while MLR indicates possible extension of 75%, NLR model presents that an extension is not feasible at all. Even though both values are not accurate, the NLR prediction is closer to the realised project as the actual extension is relatively small in comparison to the existing building.

The predictions of both ML models for De Karel Doorman project are quite accurate considering that actual extension was placed over a half of the existing building which was an architectural choice. The ML results show that all 16 additional storeys could have been placed over all existing floor area.

For De Gekroonde P project, MLR and NLR model predictions differ: MLR concludes that adding an extension is not possible while NLR result suggests a similar to the actual outcome. The realised extension area reduction might have been caused by a stricter safety level or a non-structural influence.

The predictions for the Groot Willemsplein project suggest that the structural capacity was not used to the fullest. Moreover, a similar result could have been achieved without as many structural interventions: the change of the stability system is indicated by the parameter 'Stability type' value.

Overall, the results of ML models, especially NLR model, are satisfying for the initial model assembling stage. The inaccuracies might be caused by the influence of other parameters which are not included in the learning of ML models, for example, non-structural components as architectural restrictions, varying safety levels, possible costs.

3.7 Conclusions

In recent times the use of computational tools in structural engineering has been increasing rapidly and it proves to be especially helpful during the initial stage of building projects. It provides quick structural feedback which involves engineers in the initial decision making and connects architectural design and structural performance. Section 3, the practical part of this thesis, aims to explore the use of parametric modelling and ML for analysing possibilities of upward extensions as well as to find answers to the last two sub-questions of the project.

The goal is to explore how ML could be used in order to make predictions on how much existing buildings could be extended. For this purpose, the steps shown in Figure 3.8 are followed. First, the data from seven case studies is collected which includes main project information, as municipality and year of construction, as well as parameters describing original and extension designs (summary is presented in Table 3.1 and Table 3.2). According to this data, the focus of the research is narrowed down and an object of the parametric model is defined. The considered existing buildings have industrial initial function and are built in concrete. As for the extension, the main chosen method is the use of the remaining structural reserve of the elements with inclusion of stability walls as well as possible change of stability system. Lastly, the structural material for the extensions is selected to be timber. Detailed description is given in section 3.3.2.

The study of the realised extension structures lays out the parameters and the possibilities for the parametric model.

As for the creation of this model, it is divided into two parts and is built using Grasshopper. Model 1 analyses an existing building with the goal to determine residual structural capacity of the elements while model 2 analyses an extension structure in order to find how much that existing building can be expanded. Therefore, the parametric model is used to create and analyse vertical extension projects.

The next step is data generation where all the parameters available in model 1 and model 2 are evaluated and the most influential ones are chosen for iterations. Due to time constraints, step 4, according to Figure 3.8, is not carried out. Instead, it is estimated that 5 000-10 000 projects, data points, should be sufficient for a simple ML model and, finally, 8 652 fictional upward extension projects are generated.

The ML model section is composed of five steps: data pre-processing, model building, model evaluation, model alteration and reliability check. For the data pre-processing, the data and its structure is analysed which leads to the conclusion that it will be used for supervised learning and a regression task will be performed. Moreover, a limit for 20 additional storeys is introduced, two parameters 'Stability walls' and 'Stability system' are merged into one called 'Stability type'. Lastly, most influential parameters are found: stability type, concrete strength and column cross-section size.

The ML model is built in Grasshopper as well. For its structure, 5-fold CV is chosen for validating the results, evaluating the performance of the model and creating less bias. For a learning algorithm, MLR is applied due to its simplicity and wide use. After the predictions are made, they are evaluated by determining ME, RMSE, the largest absolute errors and the amount of predictions that are out of acceptable range. As the results are not satisfactory enough, analysis for a parameter which causes the largest errors is performed. However, it determines that a combination of parameters is the reason for the prediction inaccuracy and their contribution is most likely nonlinear. In order to inspect how the prediction errors would change by introducing nonlinear relations, NLR is applied as a test and the results show significant improvement. For a reliability check, both ML models are employed to make predictions for five realised extension projects that were initially analysed and used as references for fictional project database. MLR model predictions have quite large errors, however, they are more accurate in the middle range of output values, for example, projects Fenix I and De Karel Doorman, as expected according to Figure 3.38. When using NLR model, the errors decrease, however, the predictions are not reflecting the real projects well either due to the possible influence of other parameters that are not included in the learning database, for example, architectural decisions, varying structural safety, available budget for the extension project.

In conclusion, the dataset created using the parametric model has some complexity which cannot be defined by linear relations. MLR algorithm is too simple for acceptable extension predictions and more precise results could be achieved by introducing nonlinear contribution of parameters that are causing the error. Moreover, for the improved reliability of the predictions, non-structural parameters should be incorporated as well.

4 Conclusions

4.1 Results

The first part of the thesis is aimed for researching and learning about building reuse, upward extension and use of timber in construction in general. Each component is analysed, their advantages, main arising issues and structural considerations are found. The most important aspects of each component are presented in Table 2.5 and section 4.2. The goal of the theoretical part is to set a guideline which would help make decisions when it comes to exploring the future possibilities of existing buildings. Moreover, it provides the background information for the practical part of the thesis.

The goal of the second part is to produce a proof of concept for a computational ML tool which would help explore the upward building extension possibilities during initial stages of reuse projects. For a substantial ML model, the amount of available data about realised projects appears to be not enough which raises an issue as the data is the core of artificial intelligence projects. The final solution includes employing parametric modelling in order to create a sufficient database of fictional projects which are based on parameters of the case studies in order to demonstrate the feasibility of using ML for making upward extension predictions.

The development process of the parametric model shows that many parameters can be included in the analysis of structures describing geometry, materials and elements, loads, safety, etc. Parameters chosen for the data iteration are ratio of length to width of an existing building, its floor height and number of floors, stability walls, stability system as well as concrete strength and column cross-section size. However, during the data pre-processing part, it is concluded that not all parameters have a considerable influence on the outcome. The length to width ratio together with floor height do not contribute to the size of extension but, in this case, help produce more projects. Consequently, data generation leads to a dataset of 8 652 fictional projects.

Furthermore, parametric model itself is quite useful when analysing existing structures and possible extensions. Despite the downside of requiring a significant amount of time as well as initial information to set up the model, it provides quick structural feedback for alterations. Moreover, if an optimisation component was introduced in the extension part of the model, it could be used to create an initial design of an extension structure for a selected existing building. Therefore, the research, apart from demonstrating the viability of ML, shows the potential of the use of parametric modelling in the initial reuse project development stage as well.

Next, introduction of ML for use in built environment to make extension predictions follows. Its implementation using engineer-friendly software as well as application of a simple learning algorithm, MLR, are explored. The model makes predictions based on which the performance is evaluated. The results with around 47% inaccuracy show the need to incorporate nonlinear contribution of some input parameters which cause the largest error in order to get more precise predictions. For that reason, the trial of using NLR as a learning algorithm is carried out which provides a great improvement since the average prediction error decreases to around 10%.

As the models are only operating on fictional data, the reliability check of making predictions for realised extension projects is performed as well. Both models, MLR and NLR, make large errors of around 200% and 50% respectively, however, the analysis of values indicates that the performance of NLR model is sufficient and could be improved by including additional parameters as architectural decisions or different safety levels.

Finally, parametric modelling, structural analysis and ML were accomplished using only Rhino plug-in Grasshopper which proved to have limitations. Nevertheless, it shows possibilities of exploring different fields while working with only one computer program. Grasshopper has a variety of plug-ins which can introduce the user to new subjects, for example, ML. When basic experience is acquired, more specific programs can be used to gain deeper knowledge.

4.2 Conclusions

This thesis aims to bring attention to more sustainable construction options, particularly, building reuse, upward extension and use of timber. Moreover, the use of computational tools is explored in order to find how they could be implemented in reuse project analysis. The goal is to find methods and tools that would help in the decision making of upward extensions on top of existing buildings. Therefore, the main research question is:

How to explore the feasibility of a timber upward extension on top of existing buildings?

In order to answer it, the following sub-questions are answered. First, the guideline is set for when building reuse, upward extension and timber structure are advantageous.

(Q1) How to determine if the building is good enough for **reuse**?

In order to establish if an existing building in question is suitable for reuse, a careful assessment needs to be performed. General considerations include location of the project, requested change of function, historic or architectural value and expected costs. As for structural considerations, the main aspects are condition of the structure as well as available information about the original design and alterations made during its use. The biggest restrictions for reuse are design for short life cycle, low quality construction, end of service life, deterioration and lack of original drawings and calculations. To conclude, an existing building is suitable for reuse if it has historic value or its structure is in good condition. (Research to answer this sub-question in described in section 2.1.)

(Q2) When **upward extension** is a reasonable solution?

Upward extension is a great option for increasing density in already developed areas. Three methods are possible for how an extension can be placed on top of an existing building: making use of structural reserve, changing stability system or separating old and new structures. In order to determine which, if any, of the methods are possible, during the structural assessment of an existing building, the condition of structural elements is analysed. Foundation, vertical load bearing members, roof floor and possible connection points describe the remaining capacity and possible use of the existing structure. Moreover, due to the increased height of the existing building, horizontal loads increase as well, therefore, great attention must be paid to stability of the extended structure. Ability to strengthen existing and add new elements needs to be evaluated as well.

As a result, upward extension is a feasible option if structural analysis of an existing building shows possibility to apply one of the methods to place an additional structure on top without the loss of stability. Due to the increase of loads, interventions might be required which can be implemented if documentation about the existing structure is available. (Research to answer this sub-question in described in section 2.2.)

(Q3) When **timber** is the best choice for extension structure?

Timber as a structural material is mostly appealing for upward extension projects due to its light weight, particularly, strength to weight and stiffness to weight ratios. Although, additional stabilising elements might be required due to the low inertia. Moreover, wood properties accommodate a quick and quiet construction process which is very advantageous in busy city areas where extension projects are realised. Finally, timber is the most sustainable construction material as it provides CO2 storage and no waste production process. Using timber adds to the development of a sustainable reuse and extension projects. (Research to answer this sub-question in described in section 2.3.)

Next the use of computational tools, parametric modelling and ML, are investigated.

(Q4) How **machine learning** can be used to explore feasibility of extension?

ML is a method of data analysis which uses algorithms to learn from the data and it could potentially be used to make predictions on how much existing buildings could be extended. By using a specifically for this purpose designed ML model and knowing some parameters of the existing building as well as the desired extension, a structural engineer could quickly tell the size of the possible extension. The use of such model could help reduce options and calculation time during the initial decision making of a reuse project as well as connect architectural and structural design.

The ML models, using MLR and NLR algorithms, built for this research cannot be employed for making predictions in structural design practice as they operate on fictional project database and are not reliable enough for this purpose. However, they can be used as a learning example and a starting point for the future research and building of a functional ML model.

As there are many methods and algorithms available for the use of ML, the dataset and its structure need to be analysed in order to make a decision on how it can be used for ML. For the exploration of extension feasibility, the data is used for supervised learning and regression task is performed due to quantitative values and a clear output for each data point.

Another aspect to consider is validation of results and evaluation of model performance. The methods and checks depend on the collected data as well, although, for the purpose of validating predictions of possible extensions when using a large dataset, 5-fold CV is suitable due to its wide use and less biased results. Error calculations, for example, ME, RMSE, the largest errors as well as the amount of predictions that are out of the acceptable range, assist to evaluate the accuracy of the predictions.

For the ML models of this research, first, MLR is employed as a learning algorithm, however, due to the large prediction error, around 47% for an average prediction, the nonlinear contribution of parameters: number of floors, stability type, concrete strength and column cross-section size, should be included. A trial with NLR, which shows a big improvement in predictions as the average prediction error reduces to around 10%, proves that including nonlinear relations increases the accuracy of the model.

Finally, there is potential of using ML for exploring feasibility of upward extensions. However, investments should be made in order to build a useful database of realised projects and to customise a reliable ML model.

(Q5) How to create a useful **database** of projects?

First, in order to be able to employ the final ML model for making predictions to base an initial extension design on, real data for training needs to be used. This thesis show that collecting data is not that simple as it requires a considerable amount of time, moreover, some information might be confidential, not available to public or not recorded yet. Therefore, to have a useful database, investments might have to be made.

Another consideration is parameter choice for data input. Selection of project features should be based on how much they influence the desired outcome, if they are related to each other, do they differentiate the projects. Good collection of parameters used for a ML model should not introduce unnecessary complexity to the model which would elongate the processing time and confuse the results. The research concludes that the most influential structural parameters are the stability type, the concrete strength and the cross-section size of the elements. Moreover, the reliability check indicates that parameters from other fields represented by other project parties, as an architect and a developer, have a significant influence on the outcome and should be included in the ML learning database as well.

As all the sub-questions are clarified, an answer to the **main research question** can be formulated:

When exploring the feasibility of a timber upward extension on top of an existing building, first, it should be checked if there are no major impediments that claim the building to be unsuitable for reuse, unreasonable to extend vertically or the use of timber to be unfit. Moreover, in order to make an informed decision and bring quick structural feedback to the initial design phase, computational tools can be used.

One of the options is parametric modelling. Even though it requires a considerable amount of initial information about the existing building and a possible extension structure, a parametric model can help analyse the behaviour of the old structure, the hidden structural reserve and the extension possibilities. Due to the needed investments to built the model for a specific existing building, it is suitable for more detailed exploration, for example, introducing possible interventions to the existing building or finding the shape and composition of the extension structure.

Another option is machine learning which is quite a new field for structural engineers. Novelty might cause issues, however, it has potential for being used in the future to predict the optional extension design for any existing building. The reason for this is that ML model provides a quick feedback only by submitting the required parameters, moreover, its predictions are based on the database of realised similar projects which is a great advantage when working with archaic or obsolete structures that can be difficult to model using recent structural analysis software. At this moment, the biggest issue of using ML for the extension exploration is the lack of data that the model could learn from. For the ability to use ML models in the future, the data needs to be started to collect.

4.3 Recommendations

This section provides recommendations for future research on exploring the use of parametric modelling and machine learning for initial building extension design.

Database

The database generated for the use with ML contains six input parameters, two of which, ratio between the length and the width of an existing building and its floor height, showed to not have a significant influence on the final output. The impact of other possible influences could be evaluated in order to create a more interesting database.

Also, each of the parameters chosen for the exploration have an obvious effect on the extension height as they describe structural input. The reliability check using realised projects data indicated that missing architectural input and differing safety levels have a negative influence on the accuracy of the ML model. Therefore, different scenarios could be created, for example, represented by location of a project, structural engineer, year of construction, where each option contributes to a level of safety. Thus, a different database is generated where ML is more useful as predictions are more difficult to envision.

Finally, the biggest improvement to the database would be compiling it of realised upward extension projects, real data. Possible routes to follow are either finding parameters that influence the output but are publicly available or developing a method for verifying fictional data. Moreover, a research on how the data could be shared among structural engineering offices in a confidential way could be carried out.

Machine learning

ML model evaluation showed that simple MLR is not capable to describe the complexity of the available data. However, the use of NLR might be an over-complicated solution as results and how they are achieved are difficult to understand without experience in ML. Therefore, MLR including nonlinear contribution of parameters could be explored. First, a deeper research into the Grasshopper plug-in LunchBoxML could be carried out in order to learn how MLR and NLR components are coded, how they operate, if there is a possibility to customise them. The second step could be bringing the ML model further and building it using Python or MATLAB software.

Another interesting point to investigate is to compare (1) using a well performing ML model to predict the size of an extension, (2) using a general parametric model for analysis, (3) building a parametric model for a specific existing building and (4) carrying out a full existing structure assessment during an initial project stage in order to find which method is more useful or time saving and what circumstances cause it.

Parametric modelling

In this thesis, the parametric model fulfilled the function of generating fictional upward extension projects, creating data, for the use with ML. However, parametric modelling shows potential to be useful during initial extension design phase as well. Research could be done focusing on the use of parametric modelling for analysing the possibilities of reuse and extension on top of existing buildings. It could include design of different geometries and functions of buildings, varying stability systems, methods for placing an extension and an optimisation option.

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A Interviews

A.1 Interview: Hilbert-Jan Kuijer

Interviewee: ir. Hilbert-Jan Kuijer, structural engineer at ABT

Date: 31 August 2020

General questions: building reuse

1. When to consider building reuse? What factors influence this choice?

I would say always consider building reuse. From a sustainability point of view, it is probably far better to reuse an existing building then build a new one. Main factor to influence this choice is to what extent the program of requirements matches with the possibilities of the existing building (structure).

2. What resources are necessary/recommended to have when working with existing buildings?

Existing drawings and calculations are very important to have. The more structural information is available, the more possibilities you have to make fully use of the existing building and also the more possibilities you have to make interventions in the structure. If the only information you can obtain is from inspections and non-destructive research methods, it is very hard, if not impossible, to prove the structure is able to withstand new and additional loads.

3. What are possible improvements for an existing structure?

There are a lot of improvements possible, difficult to give a general list of improvements because it really depends on the type of structure (concrete, steel, masonry, wood) and what is needed. But you can think of:

- placing extra piles
- using additional steel to support (concrete)
- placing additional or new elements for stability
- adhesive Reinforcement (steel or carbon)
- strengthening steel beams by turning them not composite beams together with a concrete floor on top
- strengthening concrete floors by adding an extra structural concrete layer on top

General questions: upward extension

4. Why choose a top up? Is it a better solution than renovation or change of function?

I don't think you can say a top up is better than another solution. Probably the main reason to choose a top up is creating extra square meters of office/apartments/etcetera, so mainly commercial reasons. Then the question can be whether to choose to top up an existing building or demolish the existing building and build a new higher building. Probably in a lot of situations the latter will be a lot easier and therefore more cost effective. Main reason to choose a top up will then probably be for sustainability reasons or for reasons of the historical importance of the existing building.

5. What are the biggest challenges/issues when designing a top up?

The biggest challenges are the bearing capacity of the existing foundation and the possibility to provie stability to the new higher building.

6. What parameters influence the height and structure of a top up?

See the answer on question 7, as well as local building regulations.

Project questions: de Fenixloodsen

7. Why the decision to reuse and top-up was made?

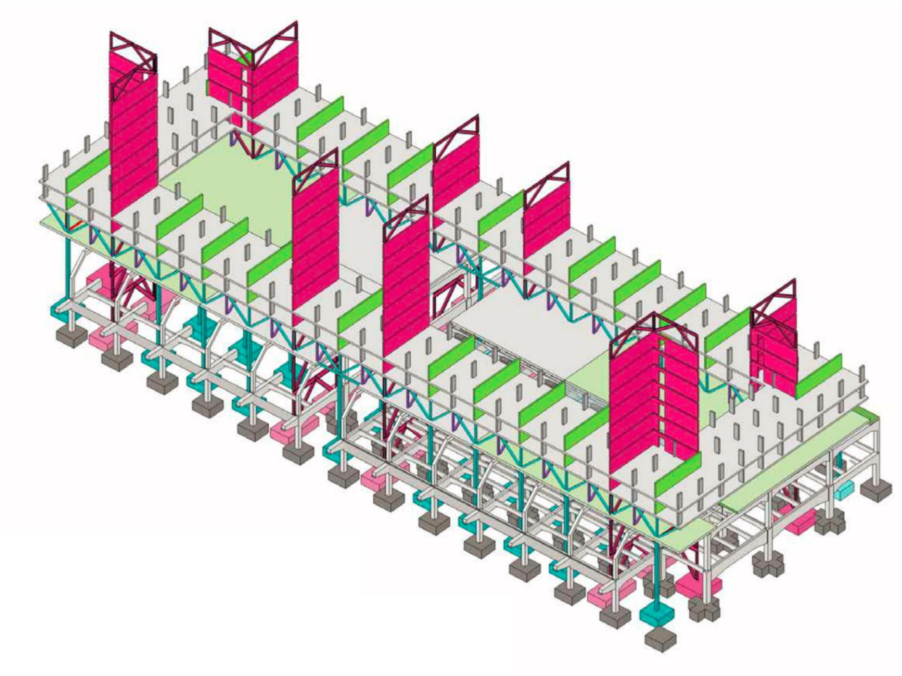
The Fenixloodsen is an important historical building in Rotterdam. Although it is not a "rijksmonument" or "Gemeentelijk monument", it is still important to Rotterdam and a well known building. Especially because there are not that many buildings in Rotterdam who survived the Second World War. The decision to top up was made because that was the only way to realize this amount of apartments and at the same time keep the existing building.

8. What was the main challenge in this project? How it was solved?

There were several challenges in the project, the first was placing a "heavy" building on top of an existing warehouse that does not have enough capacity to bear the load (see further answer by question 10). The second challenge was stability of the new structure, solved by carefully placing steel bracings through the existing structure. Another big challenge was how to fit in all the cultural functions in the existing building. To accomplish that several floors were demolished, beams were cut and even columns were removed, resulting in an almost total recalculation of the existing building.

9. How the decision to place a steel table structure through the existing building was reached?

The existing building could not take the new load. Placing new columns (the legs of the table) at a grid just in between the existing columns was a logical solution. For the transition structure between the columns on a 8,6 m grid and the apartment walls on a 4,3 m grid several possible alternative structures were investigated together with the architect. The steel table formed by two longitudinal 2D trusses with a perpendicular truss every 8,6 m alternating with a concrete wall acting as a deep beam every 8,6 m turned out as a cost effective structure, satisfying the requirement of openness in the incision layer (the name the architect gave the layer in between the existing old warehouse and the new apartment building on top). In the incision layer big loft apartments could be created. On top of the layer apartments with small 800 mm deep piers could be created. Because of the small piers the floor plans are very flexible. The buyers were free to buy 1, 2 or 3 bays in this way making apartments very different in size, but with the same structure.



10. Why concrete was chosen for the top up structure?

Concrete is indeed not the most obvious choice for a top up, because it is heavy. The concrete was chosen for economic reasons because the client Heijmans (Heijmans was both the contractor and the property developer of the project) wanted to build the apartments by using the tunnel form construction method, used a lot by Heijmans for series-produced houses.

11. How it was decided on the height of the top up?

I do not know for sure but I think there were limits, set by the local authority, on the height of the buildingat the side of the harbour and at the Veerlaan.

12. What interventions to the existing structure was done?

A lot of interventions were done, refer to the answer on question 8.

A.2 Interview: Karel Terwel

Interviewee: Dr. ir. Karel Terwel, project manager at IMd, assistant professor at Delft University of Technology

Date: 4 September 2020

General questions: building reuse

1. When to consider building reuse? What factors influence this choice?

Very broad question. You consider reuse when the existing building has economical, or historical value. You will consider it, when it is more expensive to demolish and rebuilt; and often you have to reuse when it is a monument. Currently, more and more people consider reuse, because they deem sustainability important.

2. What is of importance in existing building chosen for reuse?

Usually, it is the other way around. A client/developer has a plot with an existing building and has to decide what to do with it. Buildings were reuse might be logical are monuments, buildings with a very limited age, buildings with positive characteristics like sufficiently high floor loads, high ceilings, room for installations, etc.

3. What resources are necessary/recommended to have when working with existing buildings?

Knowledge about existing buildings (you will be happy with proper archives), creativity, perseverance.

4. What influence a structural material of an existing building has on the decision to reuse?

Sometimes, if it has overcapacity. Other times if there is no corrosion/deterioration.

General questions: upward extension

5. Why choose a top up? Is it a better solution than renovation or change of function?

Because space in especially city centers is scarce, top ups can be financially interesting. In for instance London also a lot of new basements are currently made below old buildings.

6. What are the main factors when deciding on an upward extension?

If It is financially viable, if municipality accepts it, if structure has sufficient capacity.

A.3 Interview: John Gibbons

Interviewee: John Gibbons from SRES-Sweden AB, real estate company

Date: 27 August 2020

General questions: building reuse

1. When to consider building reuse? What factors influence this choice?

Once it is determined structurally safe and agrees with modern day environmental impacts.

2. What is of importance in existing building chosen for reuse?

None, apart from aesthetics (for example, old cathedral, governmental buildings, etc). Cheaper to knock down and build new rather than maintaining existing (general rule of thumb).

3. What resources are necessary/recommended to have when working with existing buildings?

Detailed layout plans, engineering drawings and craftsmen that that have experience with such work.

4. What are possible improvements for an existing structure?

Assessing the structural integrity of the building, strengthening the building, insulating it adequately, rewiring with energy efficient ideas (eg. solar). New façade especially in urban areas to absorb solar energy and stop reflection, thus, reducing the overall"heat" generated within a city.

General questions: upward extension

5. Why choose a top up? Is it a better solution than renovation or change of function?

It only occurs where footprint of buildings is excessively large. It also stops urban sprawl! Outside of cities there's no real reason for this.

6. What structural material is best for an extension structure? Why?

Precast reinforced concrete. Great for shear loading, great tensile strength, great buckling strength. There are also lots of other methods out there.

7. What are the biggest challenges when designing a top up?

Ensure that it meets all the normal set of criteria such as: strength, durability, energy efficiency, sustainability, make sure it does not cast shadows!

8. What parameters influence the height and structure of a top up (including non-structural)?

Environmental - wind loading, temperature etc. This then determines the material type which then determines the shape and contour of the building (look at the Burj Khalifa – the whole design configuration of this building is designed purely around wind turbulence and vibration).

B Realised projects data

B.1 Fenix I

The following information regarding the Fenix I project was obtained from the interview by the author with a structural engineer of ABT, ir. Hilbert-Jan Kuijer. The description about the history, existing and extension structures of Fenix I project is presented in section 2.2.4. In addition, the ground floor plan of the existing building and the 7^{th} floor plan of the extension are shown in Figure B.1 and Figure B.2 respectively. Note that the scale of both drawings are different.

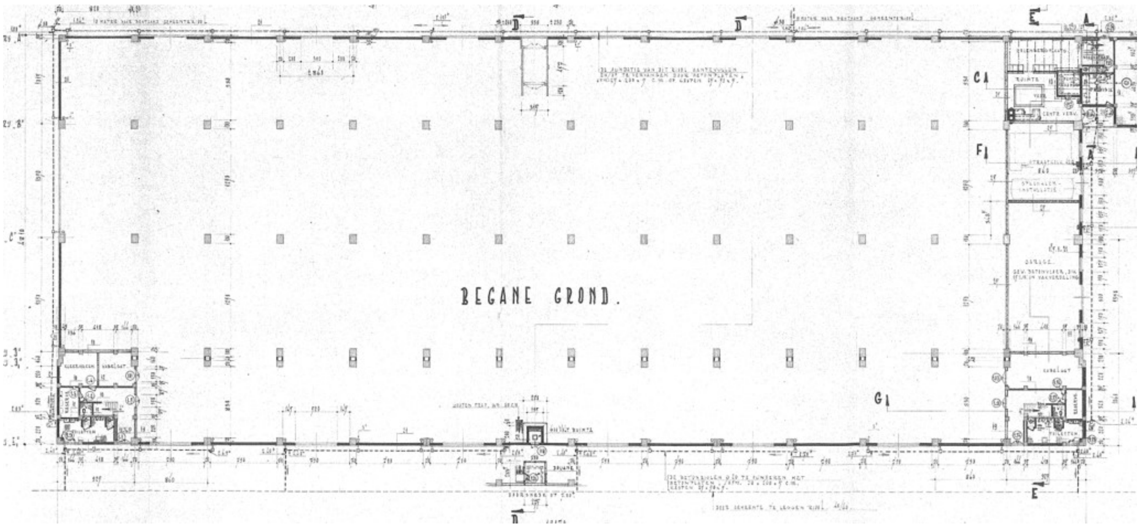


Figure B.1: *Ground floor plan of the existing building of Fenix I*

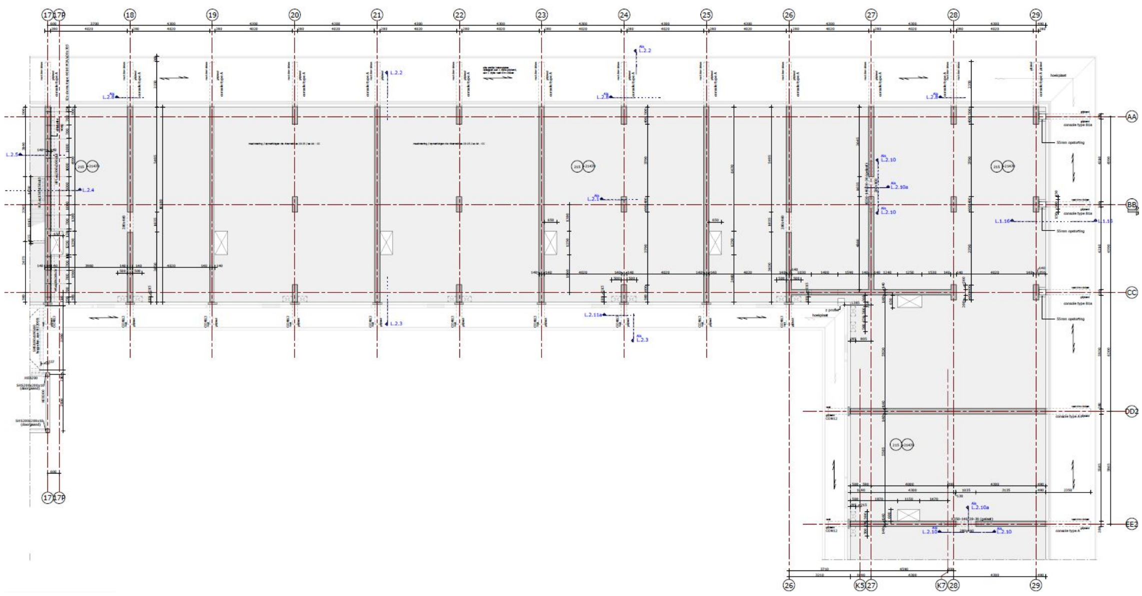


Figure B.2: *Part of the 7^{th} floor plan of the extension of Fenix I*

The existing building has a simple rectangular geometry with column span 8.6 m in longitudinal direction while the extension forms an O-shape with the atrium in the middle (Figure B.3). Span between the column rows and stability walls in extension structure is 4.3 m, which is half of the span in existing building.

Figure B.3: *Section of the extended Fenix I (ABT, 2019)*

The parameters of the original building as well as existing and extension structures are presented in Table B.1.

Table B.1: *Parameters of Fenix I project.*

FENIX I			
Location			Rotterdam, Netherlands
Construction year			1916-1922 and reconstruction after fire in 1954
Function			Industrial
Extension year			2019
Existing structure	Geometry	Grid	10.2-13.5 x 8.6 m
		No. spans	4 x 14
		Floor height	5.7 m
		No. floors	Ground floor and first floor
	Stability system		Rigid frame
	Columns	Material	Cast in-situ concrete
		Cross-section	Ground floor 700 x 700 mm and 1000 x 700 mm First floor 500 x 600 mm and 700 x 500 mm
		Strength	C12/15

FENIX I (continuation)			
Existing structure	Beams	Material	Cast in-situ concrete
		Cross-section	Primary beams: 500x1800 mm and 400x1000 mm Secondary beams: ca. 400x900
		Strength	C12/15, C15/20, C20/25
	Floors	Type	-
		Material	Cast in-situ concrete
		Thickness	130 mm, C20/25
	Foundation	Type	Cast in-situ concrete pile caps with wooden piles (mostly 33 piles at each pile cap)
		Strength	100 kN per pile
Extension structure	Geometry	Grid	Concrete walls at 4.3 m
		No. spans	Varies
		Floor height	3.2 m
		No. floors	6 to 9 floors
	Stability system		Existing structure changed to braced frame; extension structure: two first levels have bracings, others concrete stability walls
	Columns	Material	Steel
		Cross-section	Round 406.4, thickness 25-50; Round 508.0, thickness 30-40; Round 610.0, thickness 40
		Strength	S355
	Beams	Material	Steel
		Cross-section	Variety
		Strength	S355
	Walls	Material	Cast in-situ concrete
		Thickness	280 mm
		Strength	C20/25
	Floors	Type	-
		Material	Cast in-situ concrete
		Thickness	215 mm

B.2 Las Palmas

The following information about the Las Palmas project was provided by Sara Florisson in her master's thesis "Assessing Existing Structures 1910-1950" (2013). The description about the history, existing and extension structures of Las Palmas project is presented in section 2.2.4. The original building has a simple rectangular geometry and is built in cast in-situ concrete. The egg-shaped extension is placed only on three rows of existing columns as shown in section drawing (Figure B.4).

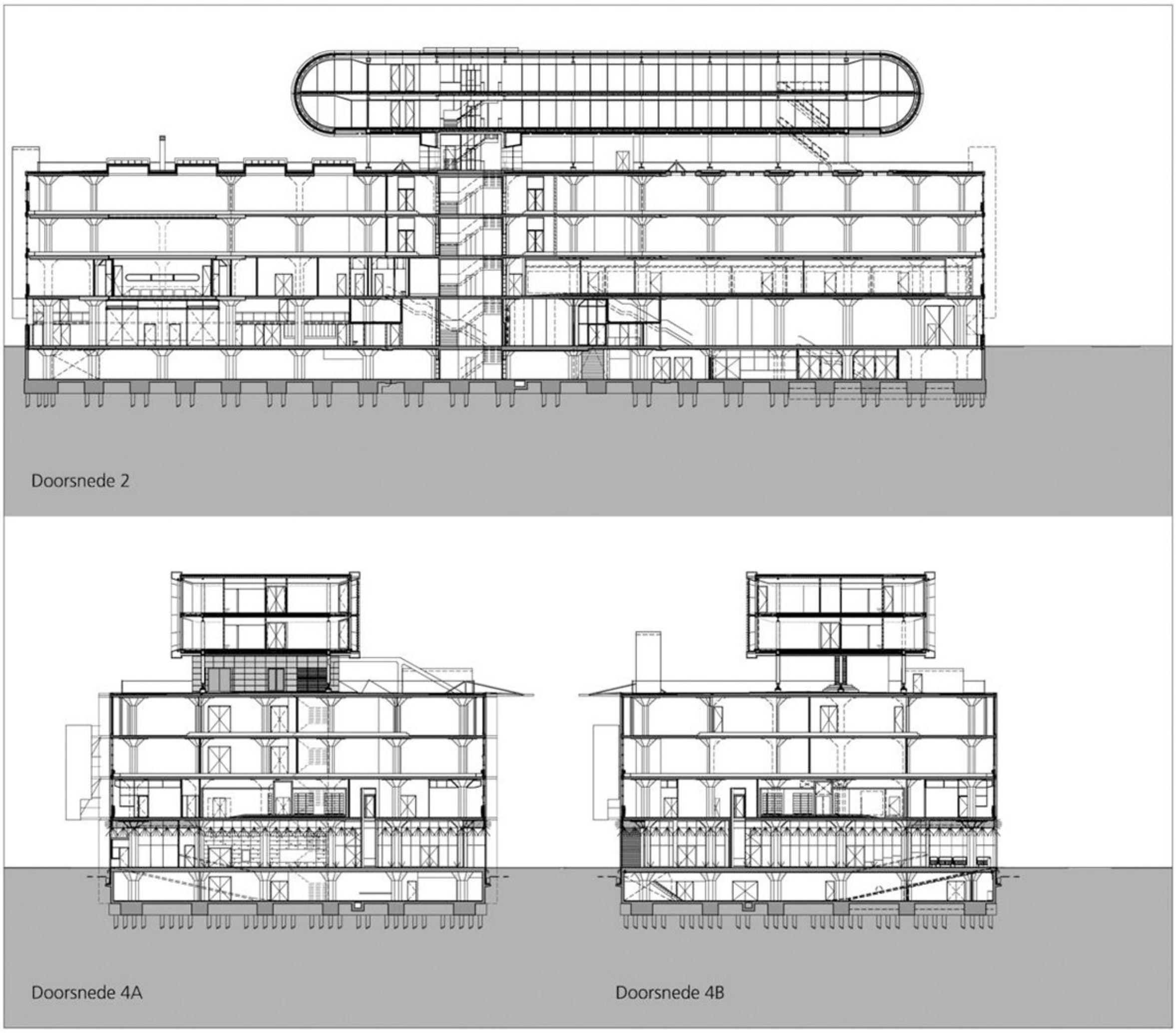


Figure B.4: *Section of Las Palmas (Benthem Crouwel Architects, 2009)*

The parameters of the original building as well as existing and extension structures are presented in Table B.2.

Table B.2: *Parameters of Las Palmas project.*

LAS PALMAS			
Location			Rotterdam, Netherlands
Construction year			1953
Function			Industrial
Extension year			2003
Existing structure	Geometry	Grid	9.43 x 6.79-7.65 m
		No. spans	5 x 14
		Floor height	5.5 m
		No. floors	Basement and 4 layers
	Stability system		Rigid portal
	Columns	Material	Cast in-situ concrete
		Cross-section	Octagonal (mushroom) Upper 700 mm, basement 1000 mm
		Strength	Original: C8/10 Tested: C30/37
	Beams		No beams
	Floors	Type	Two-spanned
		Material	Cast in-situ concrete
		Thickness	-
	Foundation		*No information*
Extension structure	Geometry	Grid	9.43 x 6.79-7.65 m
		No. spans	2 x 8
		Floor height	-
		No. floors	2 floors
	Stability system		Rigid frame
	Columns	Material	Steel
		Cross-section	-
		Strength	-
	Beams	Material	Steel
		Cross-section	-
		Strength	-
	Floors		*No information*

B.3 De Karel Doorman

The main source of information about the De Karel Doorman project was a conference paper "Ultra Light Weight Solutions for Sustainable Urban Densification" by Maurice Hermens, Michiel Visscher, John Kraus (2014).

The description about the history, existing and extension structures of De Karel Doorman project is presented in section 2.2.4. The existing building has a simple rectangular geometry and it is built in cast in-situ concrete as well as the buildings of Fenix I and Las Palmas. The original Ter Meulen structure went through two transformations (Figure B.5) and finally additional 16 stories were added.

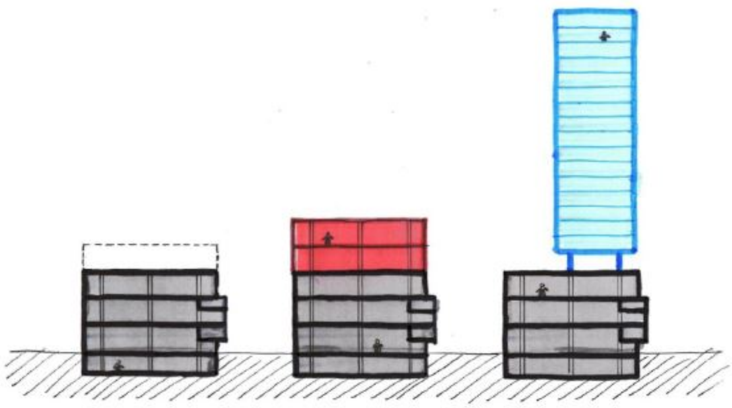


Figure B.5: *Development of building Ter Meulen (Hermens et al., 2014)*

The parameters of the original building as well as existing and extension structures are presented in Table B.3.

Table B.3: *Parameters of De Karel Doorman project.*

<table>
<tr><th colspan="4">DE KAREL DOORMAN</th></tr>
<tr><td colspan="3">Location</td><td>Rotterdam, Netherlands</td></tr>
<tr><td colspan="3">Construction year</td><td>1948-1951</td></tr>
<tr><td colspan="3">Function</td><td>Shopping centre</td></tr>
<tr><td colspan="3">Extension year</td><td>2012</td></tr>
<tr><td rowspan="5">Existing</td><td rowspan="4">Geometry</td><td>Grid</td><td>10 x 8 m</td></tr>
<tr><td>No. spans</td><td>-</td></tr>
<tr><td>Floor height</td><td>-</td></tr>
<tr><td>No. floors</td><td>Basement and 3 layers</td></tr>
<tr><td colspan="2">Stability system</td><td>Rigid frame</td></tr>
</table>

DE KAREL DOORMAN (continuation)			
Existing structure	Columns	Material	Cast in-situ concrete
		Cross-section	Basement: round 850 mm; Floors: round 800 mm
		Strength	Original: C14/17 Tested: C28/35, C40/50
	Beams	Material	Cast in-situ concrete
		Cross-section	Main: 850 x 600 mm
		Strength	C20/25
	Floors		*No information*
	Foundation	Type	Prefabricated reinforced concrete piles
		Strength	Original: 900 kN Tested: 1600-2000 kN
Extension structure	Geometry	Grid	4 x 6 m
		No. spans	-
		Floor height	-
		No. floors	16 floors
	Stability system		Supported columns with 2 cores for existing and new structure
	Columns	Material	Steel
		Cross-section	-
		Strength	-
	Beams	Material	Steel
		Cross-section	-
		Strength	-
	Walls	Material	Cast in-situ concrete (core 7 x 9 m)
		Thickness	400 mm
		Strength	-
	Floors	Type	-
		Material	Timber
		Thickness	-

B.4 De Gekroonde P

The main source of information about the De Gekroonde P project was structural drawings provided by Zonneveld ingenieurs.

De Gekroonde P was an outdated, non-lettable office building until 2008 when developer Nieuw Holland organised a renovation and extension (Figure B.6). The existing building had a basement and five layers built in concrete. According to the drawings (plan of the first floor is presented in Figure B.7), stability of the structure is ensured by rigid connections between columns and beams. The original geometry is rectangular with three column rows along the width of the building and six rows along the length.

Figure B.6: *De Gekroonde P, Rotterdam (Ventu, 2020)*

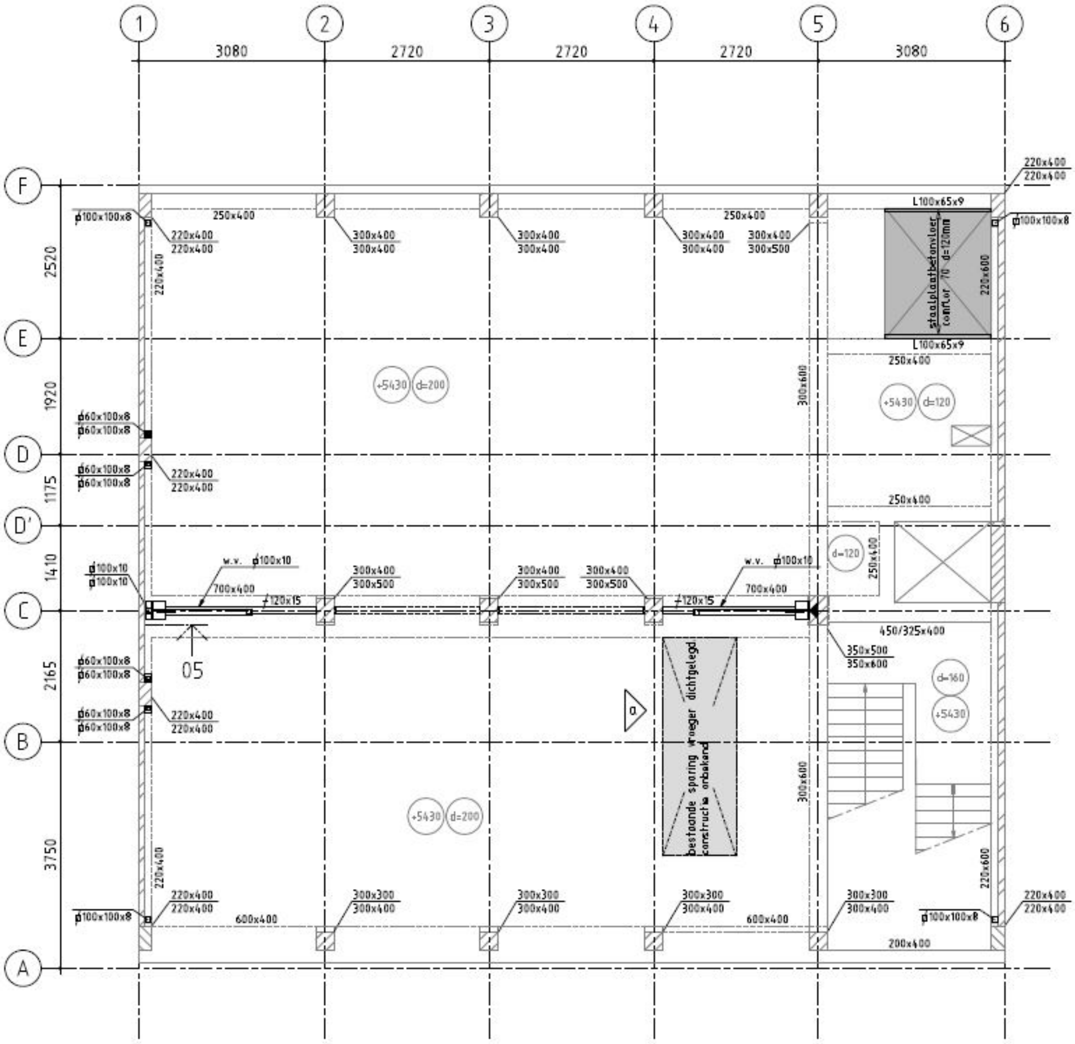


Figure B.7: *First floor plan of the existing structure of de Gekroonde P*

The extension structure with three additional layers follows the shape of the original building. According to the drawings (a typical extension floor plan is presented in Figure B.8), the new steel structure is placed directly of top of the existing structural elements. In order to improve stability of the building, steel bracings are added over the height of the existing building (Figure B.9).

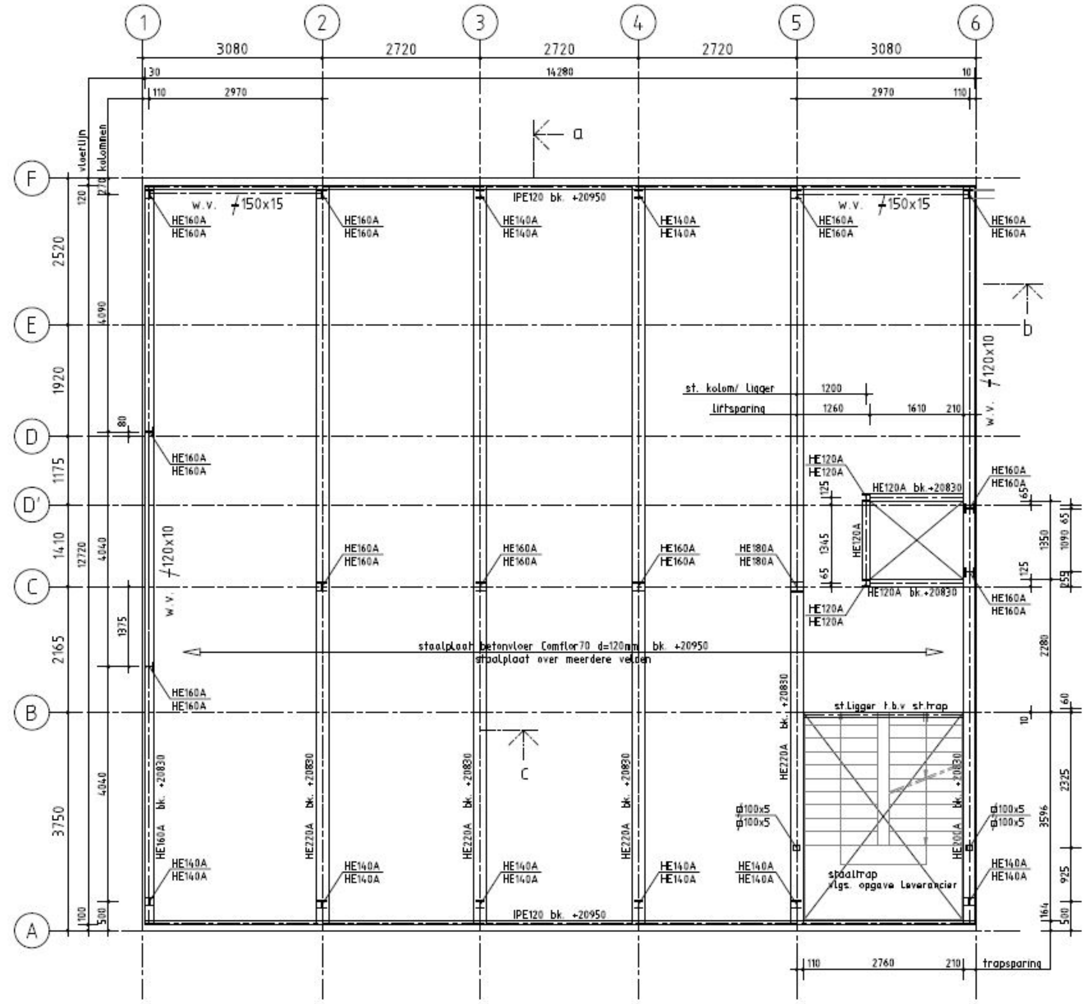


Figure B.8: *Typical floor plan of the extension of de Gekroonde P*

Figure B.9: *Bracings in the existing building of de Gekroonde P (Ventu, 2020)*

The parameters of the original building as well as existing and extension structures are presented in Table B.4.

Table B.4: *Parameters of De Gekroonde P project.*

<table>
<tr><th colspan="4">DE GEKROONDE P</th></tr>
<tr><td colspan="3">Location</td><td>Rotterdam, Netherlands</td></tr>
<tr><td colspan="3">Construction year</td><td>Unknown</td></tr>
<tr><td colspan="3">Function</td><td>Office</td></tr>
<tr><td colspan="3">Extension year</td><td>2008</td></tr>
<tr><td rowspan="18">Existing structure</td><td rowspan="4">Geometry</td><td>Grid</td><td>5.92-7.02 x 3.08-2.72 m</td></tr>
<tr><td>No. spans</td><td>2 x 5</td></tr>
<tr><td>Floor height</td><td>Basement 2.64 m; First floor 5.4 m; Other floors 2.98 m</td></tr>
<tr><td>No. floors</td><td>Basement and 5 layers</td></tr>
<tr><td colspan="2">Stability system</td><td>Rigid frame</td></tr>
<tr><td rowspan="3">Columns</td><td>Material</td><td>Concrete</td></tr>
<tr><td>Cross-section</td><td>Basement: 400 x 500 mm;
Floors: 300 x 500 mm</td></tr>
<tr><td>Strength</td><td>C25/30</td></tr>
<tr><td rowspan="3">Beams</td><td>Material</td><td>Concrete</td></tr>
<tr><td>Cross-section</td><td>Main: 400 x 500 mm</td></tr>
<tr><td>Strength</td><td>C25/30</td></tr>
<tr><td rowspan="3">Floors</td><td>Type</td><td>One way spanned</td></tr>
<tr><td>Material</td><td>Concrete</td></tr>
<tr><td>Thickness</td><td>100 mm</td></tr>
<tr><td colspan="2">Foundation</td><td>No information</td></tr>
<tr><td rowspan="14">Extension structure</td><td rowspan="4">Geometry</td><td>Grid</td><td>5.92-7.02 x 3.08-2.72 m</td></tr>
<tr><td>No. spans</td><td>2 x 5</td></tr>
<tr><td>Floor height</td><td>3.6 m</td></tr>
<tr><td>No. floors</td><td>3 floors</td></tr>
<tr><td colspan="2">Stability system</td><td>Rigid frame (braced frame in existing structure)</td></tr>
<tr><td rowspan="3">Columns</td><td>Material</td><td>Steel</td></tr>
<tr><td>Cross-section</td><td>HE160A</td></tr>
<tr><td>Strength</td><td>-</td></tr>
<tr><td rowspan="3">Beams</td><td>Material</td><td>Steel</td></tr>
<tr><td>Cross-section</td><td>HE220A</td></tr>
<tr><td>Strength</td><td>-</td></tr>
<tr><td rowspan="3">Floors</td><td>Type</td><td>One way spanned</td></tr>
<tr><td>Material</td><td>Composite: IPE120 and concrete</td></tr>
<tr><td>Thickness</td><td>120 mm</td></tr>
</table>

B.5 Groot Willemsplein

The following information about the Groot Willemsplein project was provided by Maria Papageorgiou in her master's thesis "Optimal Vertical Extension" (2016).

The original building was constructed in 1946. It was serving as a distillery until 1970s when the building went through a transformation to become an office. However, eventually Groot Willemsplein became vacant and in order to revive it, the second transformation was carried out (Figure B.10).

Figure B.10: *Groot Willemsplein, Rotterdam (Staalmeesters Group BV, 2017)*

The original building has a rectangular geometry and it was constructed in concrete where stability of the structure is provided by the rigid connections and the moment resisting frames (the second floor plan is presented in Figure B.11). During the analysis of the existing structure, an unexpected structural reserve was found mostly due to the initial function of the building as it was designed for a load of 15 kN/m^2. This allowed the addition of three lightweight steel structure layers to be placed directly on top of the existing structure.

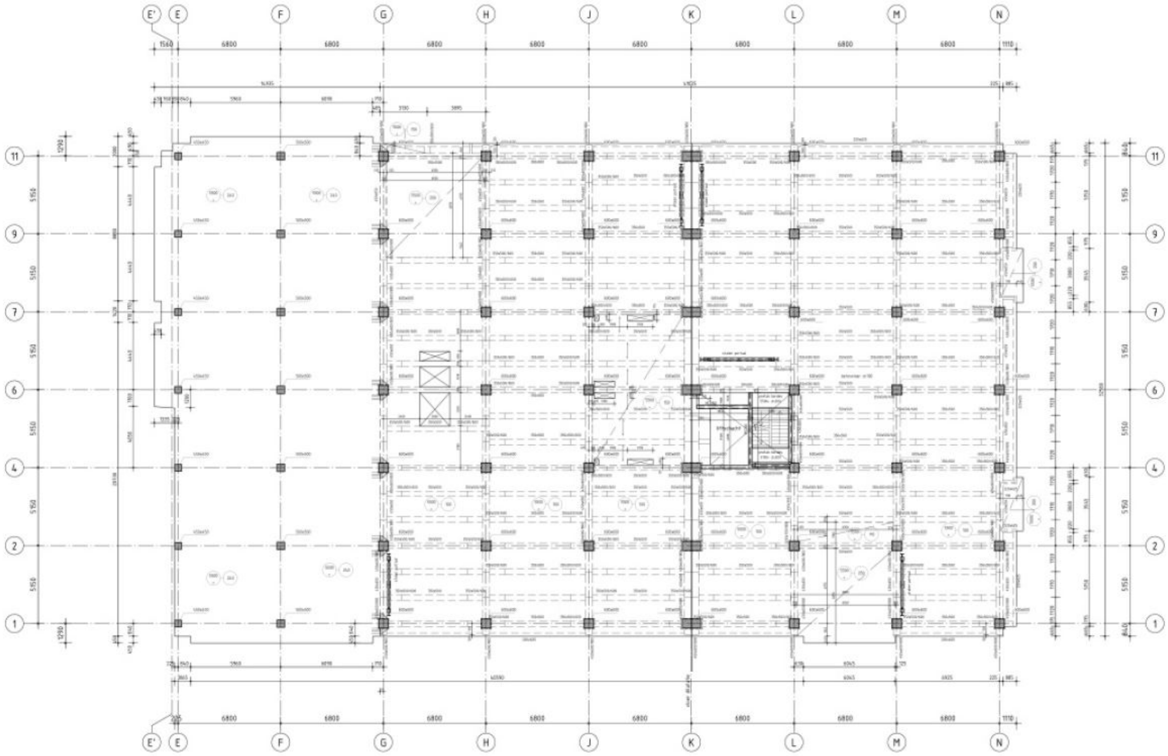


Figure B.11: *The second floor plan of the existing structure of the Groot Willemsplein (Papageorgiou, 2016)*

Due to the use of the building, as it was planned to be rented by two different companies, a separate entrance to the extension part was required. As a solution, two concrete cores were added to the structure. In addition, the decision to connect new and existing floors to the cores was made which transformed the stability system from a rigid frame to the supported columns with cores as in De Karel Doorman project.

The parameters of the original building as well as existing and extension structures are presented in Table B.5.

Table B.5: *Parameters of Groot Willemsplein project.*

GROOT WILLEMSPLEIN	
Location	Rotterdam, Netherlands
Construction year	1946 and revonation in 1970s
Function	Industrial
Extension year	2013

GROOT WILLEMSPLEIN (continuation)			
Existing structure	Geometry	Grid	6.8 x 5.15 m
		No. spans	8 x 6
		Floor height	3.5 m
		No. floors	5 floors
	Stability system		Rigid frame
	Columns	Material	Prefabricated concrete
		Cross-section	Ground floor: 700 x 1000 mm; First floor: 700 x 700 mm Upper floors: 600 x 600 mm
		Strength	C16/20
	Beams	Material	Concrete
		Cross-section	Main: 350 x 500/600 mm Secondary: 350 x 500 mm
		Strength	C16/20
	Floors		*No information*
	Foundation	Type	Prefabricated reinforced concrete piles
		Strength	620-1200 kN
Extension structure	Geometry	Grid	6.8 x 5.15 m
		No. spans	8 x 6
		Floor height	3.5 m
		No. floors	3 floors
	Stability system		Supported columns with 2 cores for existing and new structure
	Columns	Material	Steel
		Cross-section	-
		Strength	-
	Beams	Material	Steel
		Cross-section	-
		Strength	-
	Floors	Type	-
		Material	Hollow core slabs
		Thickness	-

B.6 St. Jobsveem

The following information about the St. Jobsveem project was provided by Maria Papageorgiou in her master's thesis "Optimal Vertical Extension" (2016).

St. Jobsveem was constructed in 1913 and it was initially used as a warehouse. When decision for renovation was made due to the historic value, it was found that the building still had some technical possibilities to be transformed into a residential building (Figure B.12). However, not much information about the original design was available, therefore an extensive research and testing was needed.

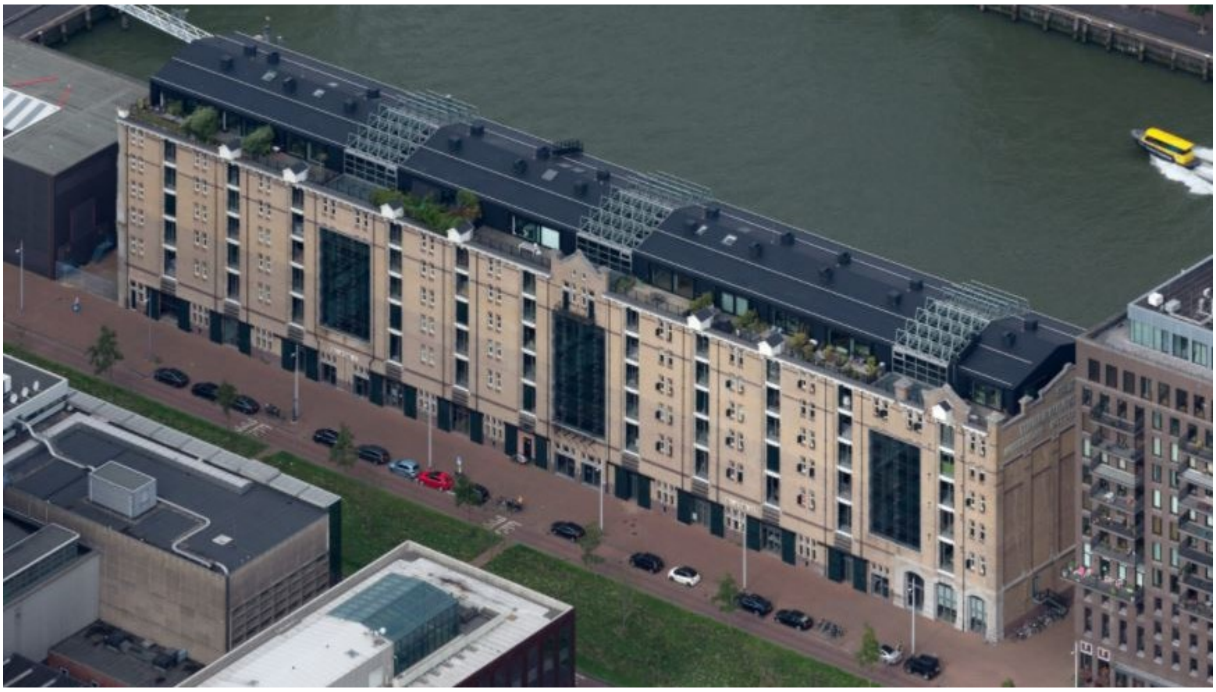


Figure B.12: *St. Jobsveem, Rotterdam (Mei architects and planners, 2007)*

The original warehouse was approximately 130 m long, 25 m wide with columns placed in 5 x 5 m grid and a load bearing facade around it. Cast iron columns supported steel floor beams which carried the timber floors. Floors together with the masonry facades provided the stability for the building.

The analysis of the existing structure showed that there was a structural reserve for two additional layers, however, due to the monumental status of the building, the height of the existing facade could not be exceeded. Eventually, the solution of rebuilding the top floor and adding an additional smaller structure for penthouses was agreed on. This extension had a lightweight structure of steel frames and timber roof. The representation of the new structure is shown in Figure B.13.

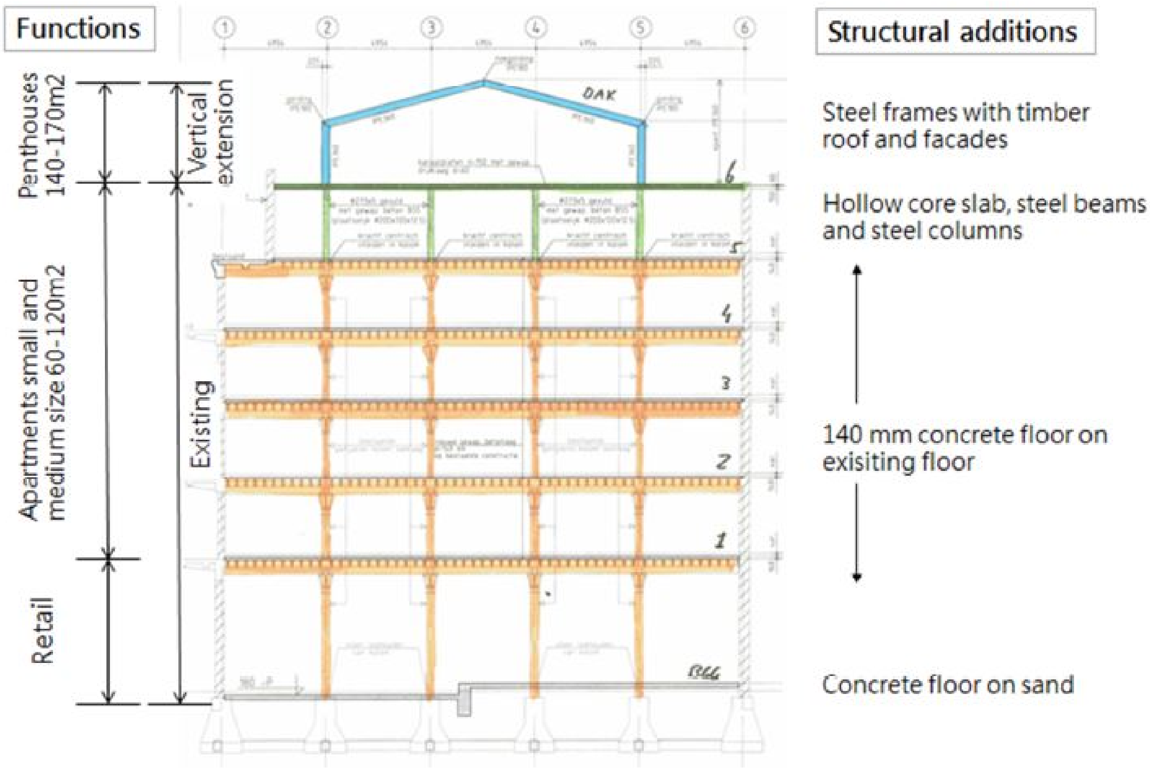


Figure B.13: *Representation of the new structural system of St. Jobsveem (Papageorgiou, 2016)*

Nonetheless, the biggest intervention in the existing structure was the creation of three atriums which were required according to the daylight regulations. In order to provide the daylight, the floor had to be demolished which divided the structure into four separate parts. As the floors previously were providing the stability, a problem arose. To solve it, the decision was made to place steel bracings on both sides of the atriums to stabilise the structure (Figure B.14). As diagonal bracings would we running in front of the windows, the choice was made to create big frames with horizontal elements on each floor, using huge HE profiles.

Figure B.14: *Placement of stability frames in St. Jobsveem project (Papageorgiou, 2016)*

The parameters of the original building as well as existing and extension structures are presented in Table B.6.

Table B.6: *Parameters of St. Jobsveem project.*

ST. JOBSVEEM			
Location			Rotterdam, Netherlands
Construction year			1913
Function			Industrial
Extension year			2007
Existing structure	Geometry	Grid	5 x 5 m
		No. spans	26 x 5
		Floor height	*Unknown*
		No. floors	6 floors
	Stability system		Walls and floors
	Columns	Material	Cast iron
		Cross-section	-
		Strength	-
	Beams	Material	Steel
		Cross-section	-
		Strength	-
	Floors	Type	One way spanned
		Material	Timber joists and floorboards
		Thickness	36 mm
	Foundation	Type	Timber piles with concrete pile caps
		Strength	-
Extension structure	Geometry	Grid	5 x 5 m
		No. spans	20 x 3
		Floor height	*Unknown*
		No. floors	1 floor
	Stability system		Stability walls
	Columns	Material	Steel
		Cross-section	-
		Strength	-
	Beams	Material	Steel
		Cross-section	-
		Strength	-
	Floors	Type	-
		Material	Hollow core slabs
		Thickness	-

B.7 Styrpinnen 15

The following information regarding the Styrpinnen 15 project was obtained from the interview by the author with a structural engineer of Sigma Civil, ir. Petra Videstorm.

The original structure was built for Hernösands Enskilda Bank in 1901 in the heart of Stockholm, Sweden. Since then, it went through two transformations when an additional floor and a penthouse were placed on top as well as installations replaced. Due to the great location of the building and a historic importance, in 2019 the decision to reuse and extend was made.

The biggest issue for the upward extension was the settlements and the strength of the foundation. Eventually, the solution of reinforcing the foundation as well as the choice of wood for the extension structure lead to the addition of three more layers (Figure B.15). In this case, the use of timber was a necessary solution due to its lightweight and high level of prefabrication.

Figure B.15: *Styrpinnen 15, Stockholm (Sigma Civil, 2020)*

The extension structure was placed on top of the existing structure. The stability was provided by shear walls and floors and bracings in the facade. In order to achieve a lightweight structure, glulam is used for beams and columns and CLT for floors and walls. The timber structure of the extension is presented in Figure B.16.

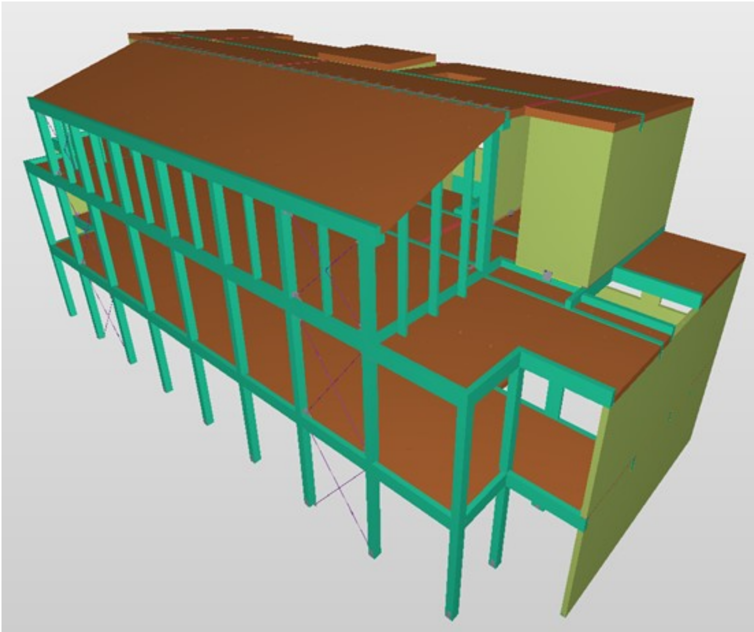


Figure B.16: *The timber structure of the extension of Styrpinnen 15 (Sigma Civil, 2020)*

The parameters of the original building as well as existing and extension structures are presented in Table B.7.

Table B.7: *Parameters of Styrpinnen 15 project.*

<table>
<tr><td colspan="4">STYRPINNEN 15</td></tr>
<tr><td colspan="3">Location</td><td>Stockholm, Sweden</td></tr>
<tr><td colspan="3">Construction year</td><td>1901</td></tr>
<tr><td colspan="3">Function</td><td>Office</td></tr>
<tr><td colspan="3">Extension year</td><td>2020</td></tr>
<tr><td rowspan="14">Existing structure</td><td rowspan="4">Geometry</td><td>Grid</td><td>Width and length of the grid: 10.5 x 25.5 m</td></tr>
<tr><td>No. spans</td><td>Unknown</td></tr>
<tr><td>Floor height</td><td>3.5-3.9 m</td></tr>
<tr><td>No. floors</td><td>5 floors</td></tr>
<tr><td colspan="2">Stability system</td><td>Unknown</td></tr>
<tr><td rowspan="3">Columns</td><td>Material</td><td>Composite: steel and concrete</td></tr>
<tr><td>Cross-section</td><td>-</td></tr>
<tr><td>Strength</td><td>-</td></tr>
<tr><td rowspan="3">Beams</td><td>Material</td><td>Steel</td></tr>
<tr><td>Cross-section</td><td>-</td></tr>
<tr><td>Strength</td><td>-</td></tr>
<tr><td rowspan="3">Floors</td><td>Type</td><td>-</td></tr>
<tr><td>Material</td><td>Concrete</td></tr>
<tr><td>Thickness</td><td>170-245 mm</td></tr>
<tr><td></td><td colspan="2">Foundation</td><td>Unknown</td></tr>
</table>

STYRPINNEN 15 (continuation)			
Extension structure	Geometry	Grid	Width and length of the grid: 10.5 x 25.5 m
		No. spans	*Unknown*
		Floor height	3.1 m
		No. floors	3 floors
	Stability system		Walls and floors
	Columns	Material	Glulam
		Cross-section	230 x 315 mm, 225 x 255 mm
		Strength	GL30c
	Beams	Material	Glulam
		Cross-section	140 x 405 mm
		Strength	GL30c
	Walls	Material	CLT
		Thickness	140 mm
		Strength	-
	Floors	Type	-
		Material	CLT
		Thickness	200 mm

C Load calculations

Characteristic loads for structural analyses using parametric models are determined according to NEN-EN 1991 Actions on structures.

Permanent loads

Permanent loads in this thesis consist of the self weight of structural elements and loads of mechanical installations. The self weight value is obtained automatically by Grasshopper plug-in Karamba based on size and material assigned to each component. As for the installations, the value of 0.3 kN/m^2 is set based on previous experiences. The self weight of facade structures are not included as they are not researched in the case studies.

Live loads

Live loads include imposed, snow and wind loads.

Imposed loads

Imposed loads here are a combination of imposed loads based on a category of use and the self weight of movable partitions. The characteristic values are determined according to NEN-EN 1991-1-1. The value 2.0 kN/m^2 of imposed loads is set based on Table 6.2 in the code, category A which is intended for areas for domestic and residential activities. As for partitions, they are assumed to have self weight 1.0 kN/m wall length which leads to the characteristic load value of 0.5 kN/m^2 (section 6.3.1.2 in the Eurocode). In total, the value for imposed loads is 2.5 kN/m^2.

Snow loads

Snow loads are calculated according to NEN-EN 1991-1-3, mainly equation (14):

$$s = \mu_i C_e C_t s_k \tag{14}$$

where

μ_i is the snow load shape coefficient, for monopitch roofs with assumed 0° slope the value is 0.8;

C_e is the exposure coefficient, for normal topography the value is 1.0;

C_t is the thermal coefficient, the value is 1.0;

s_k is the characteristic value of snow load on the ground.

Snow load on the ground is calculated by equation (15), based on Annex C, Table C.1 of the Eurocode.

$$s_k = 0.164Z - 0.082 + \frac{A}{966} \tag{15}$$

where

Z is the zone number given on the map (Figure C.7 in NEN-EN 1991-1-3), Rotterdam area is in zone 3;

A is the site altitude above Sea Level [m], for this thesis, the average elevation of the Netherlands is chosen, 30 m.

The calculations lead to the characteristic value of snow load to be 0.35 kN/m^2.

Wind loads

For the wind loads, procedure layed out in NEN-EN 1991-1-4 is followed, mainly Table 5.1 in the code. As the value depends on geometry of a building, wind load calculation is included in the parametric model making use of the GhPython Script component.

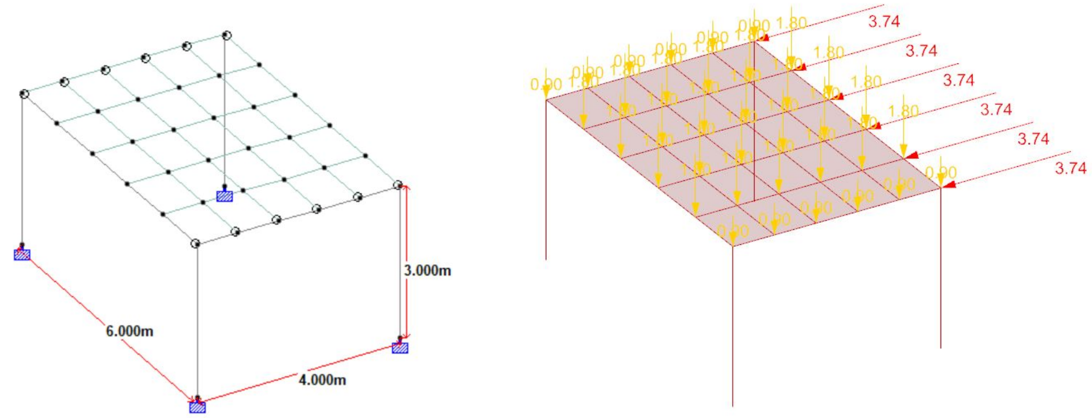
Table C.1 presents the summary of characteristic loads.

Table C.1: *Summary of characteristic loads*

Characteristic loads		
Type	Name	Value
Permanent	Self weight	*automatic*
	Installations	0.3 kN/m^2
Live	Imposed	2.5 kN/m^2
	Snow	0.35 kN/m^2
	Wind	*varies*

D Parametric model performance check

Performance checks are carried out to both parametric models, model 1 and model 2. For this purpose a simple one-storey structure is set up which is 6 m long and 4 m wide. The only loads included in the analysis are imposed load and wind load. The dimensions and loading are presented in Figure D.1. The results, reaction forces as well as the displacement at the top of the structure, are compared to the analysis of the same structure using STAAD.Pro.



(a) *Dimensions of the one-storey structure in STAAD.Pro*

(b) *Loading on the structure in Grasshopper*

Figure D.1: *Dimensions and loading of the one-storey structure*

Model 1

Properties of the elements:

- Concrete C16/20, E = 29000 MPa
- Columns circular (L = 3 m), ⌀80 cm
- Beams of portals (fixed to columns, L = 4 m): h = 48 cm, b = 29 cm
- Secondary beams (hinges at the ends, L = 6 m): h = 60 cm, b = 36 cm
- Floor thickness: 13 cm

Loads:

- Imposed q = 3.75 kN/m2
- Wind (point loads) Q = 3.74 kN

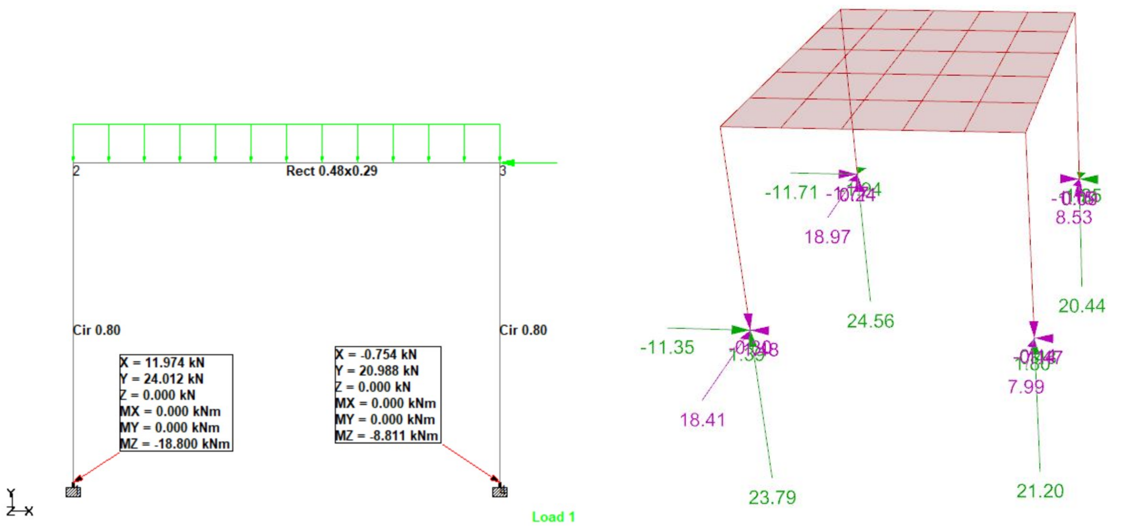
Supports: fixed.

The results of the comparison between STAAD.Pro and Grasshopper analyses are presented in Table D.1 (node numbers are indicated in Figure D.2a).

Table D.1: *Summary of model 1 performance check*

Displacement / reaction	STAAD.Pro		Grasshopper		Error
u_1	0.073	mm	0.065	mm	11%
R_{0V}	0.75	kN	0.64	kN	15%
R_{0N}	20.99	kN	20.82	kN	1%
R_{0M}	8.81	kNm	7.96	kNm	10%
R_{2V}	11.98	kN	11.86	kN	1%
R_{2N}	24.01	kN	24.18	kN	1%
R_{2M}	18.80	kNm	18.96	kNm	1%

Figure D.2 presents the results from STAAD.Pro and Grasshopper. According to Table D.1, some errors, displacement, shear reaction and moment reaction at node 0, are over the acceptable limit, however, as no mistakes in the model 1 were found in the set time limit, it is assumed that the model performs well.



(a) *Results of STAAD.Pro with node numbers* (b) *Loading on the structure in Grasshopper*

Figure D.2: *Dimensions and loading of the one-storey structure*

Model 2

Properties of the elements:

- GLULAM GL30c, E = 10800 MPa
- Columns rectangular (L = 3 m): h = 30 cm, b = 25 cm
- Beams of portals (fixed to columns, L = 4 m): h = 27 cm, b = 9 cm
- Secondary beams (hinges at the ends, L = 6 m): h = 33 cm, b = 11 cm
- Floor thickness: 6 cm

Loads:

- Snow q = 0.53 kN/m2
- Wind (point loads) Q = 1.5 kN

Supports: fixed.

The results of the comparison between STAAD.Pro and Grasshopper analyses are presented in Table D.2. According to the errors, as no error exceed the 5% limit, model 2 performs well.

Table D.2: *Summary of model 2 performance check*

Displacement / reaction	STAAD.Pro		Grasshopper		Error
u_1	2.24	mm	2.26	mm	1%
R_{0V}	1.36	kN	1.42	kN	4%
R_{0N}	2.30	kN	2.29	kN	0%
R_{0M}	4.26	kNm	4.3	kNm	1%
R_{2V}	3.14	kN	3.09	kN	2%
R_{2N}	4.02	kN	4.01	kN	0%
R_{2M}	5.79	kNm	5.75	kNm	1%

E Data management

Data management is the process carried out on the data generated using parametric model 2 in order to determine how many additional storeys can be placed on top of each existing building created by model 1 and to find how much their existing areas can be expanded.

Table E.1 presents a fragment of model 2 generated data. Rows in bold indicate the largest possible extension for each project.

Table E.1: *Fragment of data generated using model 2*

Project number	No. floors	UC max	Feasibility	Stability	Additional area	Overall feasibility
4220	1	0.03	TRUE	Stiffness sufficient	20	TRUE
4220	7	0.50	TRUE	Stiffness sufficient	140	TRUE
4220	10	0.73	TRUE	Stiffness sufficient	200	TRUE
4220	**13**	**0.96**	**TRUE**	**Stiffness sufficient**	**260**	**TRUE**
4231	**1**	**0.07**	**TRUE**	**Stiffness sufficient**	**20**	**TRUE**
4231	7	1.14	FALSE	Stiffness sufficient	140	FALSE
4231	10	1.89	FALSE	Stiffness sufficient	200	FALSE
4231	13	2.80	FALSE	Stiffness sufficient	260	FALSE
4464	1	0.06	TRUE	Stiffness sufficient	25	TRUE
4464	**7**	**0.94**	**TRUE**	**Stiffness sufficient**	**175**	**TRUE**
4464	10	1.35	FALSE	Stiffness sufficient	250	FALSE
4464	13	1.75	FALSE	Stiffness sufficient	325	FALSE