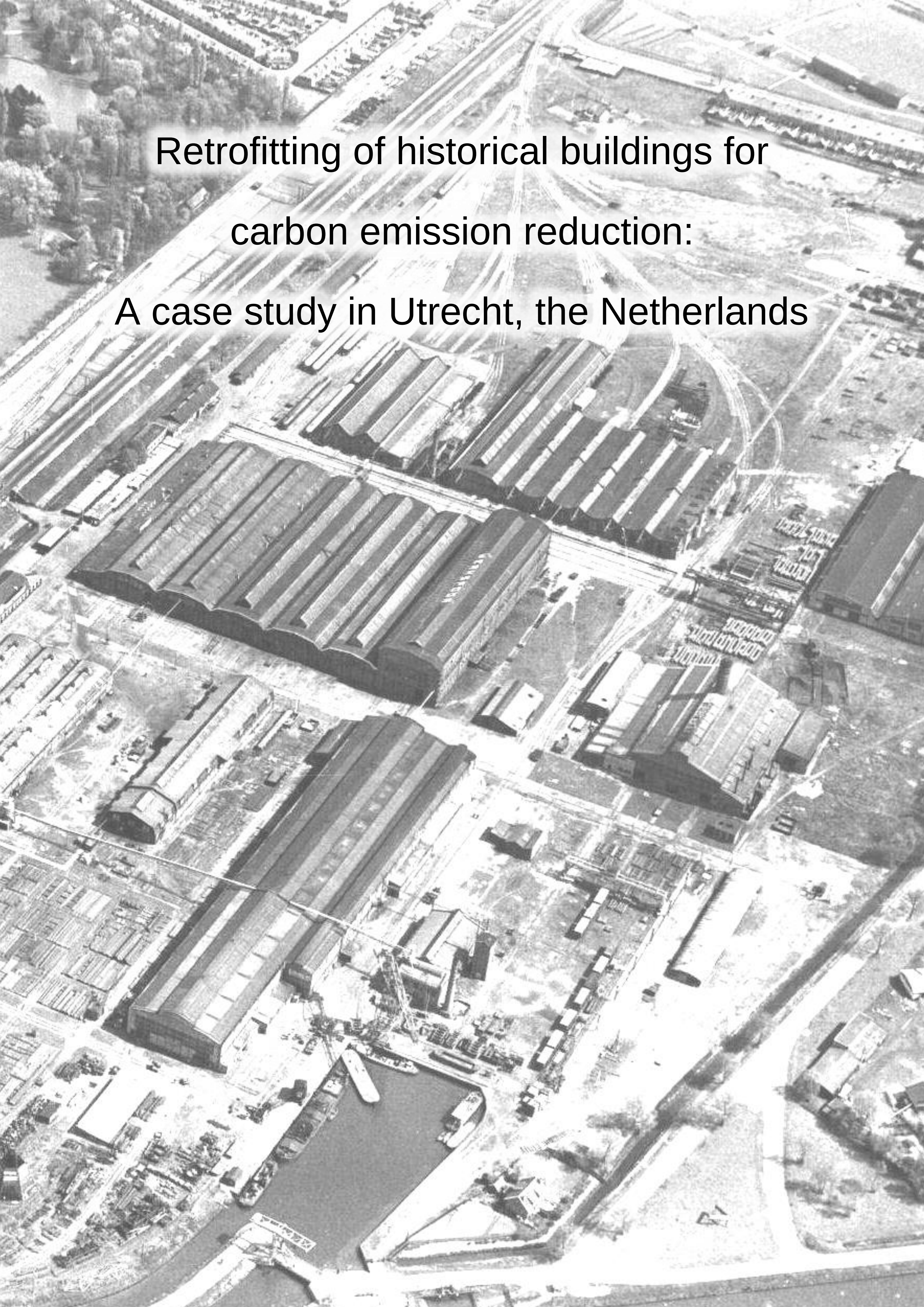
Retrofitting of historical buildings for carbon emission reduction: A case study in Utrecht, the Netherlands



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Executive summary

Buildings are responsible for a total of 40% energy consumption and cause 32% of total carbon emissions in the European Union. The emissions caused by the building sector are partly responsible for the increasing global temperature over the last decades. A reduction of emissions related to buildings has the potential to mitigate climate change. Historical buildings play an important role and should be included to reach this goal.

The aim of this study is to identify retrofitting measures which are the most optimal within the frame of carbon emissions and economic concerns by taking into account the impact on the heritage value of a historical building. For this purpose, an energy building simulation was conducted as a case study for a historical building in Utrecht the Netherlands. First a literature review was executed to determine which retrofits are the most appropriate to conserve the inherent value of a building in the Netherlands. The outcome shows that a variety of options are able to preserve the building's character. The best options for the case study were interior insulation for walls, roofs and floors, replacement of the lighting system, the application of a groundwater or ground heat pump, photovoltaics, and construction overhauls.

The next step was to test the previously identified options. Data concerning building envelope, technical installations and building schedules was collected to determine the energy demand for heating, cooling, and electricity. The total annual energy demand of the old train workshop is 2454 GJ. After the initial simulation as the base case, several measures and packaged measures were tested to conclude which carbon conservation techniques are the most effective. Each simulation is followed by a cost analysis to show the simple payback period, the costs per unit of conserved carbon and a sensitivity analysis with regards to important parameters. The results showed a great potential for several retrofitting measures. The individual measures with the best outcomes were roof insulation, LED lighting, groundwater heat pump, and photovoltaics. The percentages of potential carbon conservation were 11.61%, 15.84%, 28.46%, and 48.53% respectively. An assemblage of the aforementioned individual measures to a retrofitting package can lower the energy demand by 85.50% and the emitted carbon emissions by 68.65%. The total investment costs of the package are € 360831 with a simple payback period of 7.37 years. The related cost per conserved carbon calculation reveals a cost-effective result.

List of abbreviations

HVAC	*Heating, ventilating and air-conditioning*
LCCC	*Levelized costs of conserved carbon*
MACC	*Marginal abatement cost curve*
LCA	*Life-cycle analysis*
SPB	*Simple payback period*
COP	*Coefficient of performance*
NZEB	*Net-zero energy building*
ZEB	*Zero energy building*
GHG	*Greenhouse gas*
PV	*Photovoltaic*
RES	*Renewable energy source*
PEF	*Primary energy factor*
LED	*Light emitting diode*
CLO	*Clothing insulation factor*
EU	*European Union*
EC	*European Commission*
CHA	*Cultural Heritage Agency*
IWEC	*International weather for energy calculations*
ASHRAE	*American Society of Heating, Refrigeration and Air-conditioning Engineers*
IPCC	*Intergovernmental Panel on Climate Change*
ISSO	*Kennisinstituut voor installatietechnik*
NS	*Nederlandse spoorwegen*
SQ	*Sub-questions*

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1. INTRODUCTION

It is virtually certain that worldwide anthropogenic greenhouse gas (GHG) emissions are one of the main reasons for an increasing global temperature. The temperature rise causes a variety of issues: more frequent and severe weather; higher wildlife extinction rates; rising sea levels and higher death rates (IPCC, 2014e). The threshold of a 2 °C temperature increase should not be exceeded according to the Intergovernmental Panel on Climate Change (IPCC). A transgression would lead to an intensification of the previously mentioned issues (IPCC, 2014). As a consequence, the energy demand of polluting sectors has to be reduced drastically or changed from fossil fuels to renewable energy provision to reduce greenhouse gas emissions (EU, 2010). The climate conference in Paris of 2015 promotes an internationally sustainable future to reach this goal (UN, 2015). The building sector stands out as an important contributor of energy demand and environmental impacts. The energy consumption of buildings accounts for up to 40% of total energy consumption, 35% of final energy consumption, and 32% of carbon emissions in the European Union (EU) (EC, 2014). Emissions of the building sector account for 19% of all global GHG emissions (IEA, 2013). A high share of these emissions are indirectly emitted by electricity use (IPCC, 2014c). The figure below shows an overview of total anthropogenic GHG emissions by sectors (IPCC, 2014d).

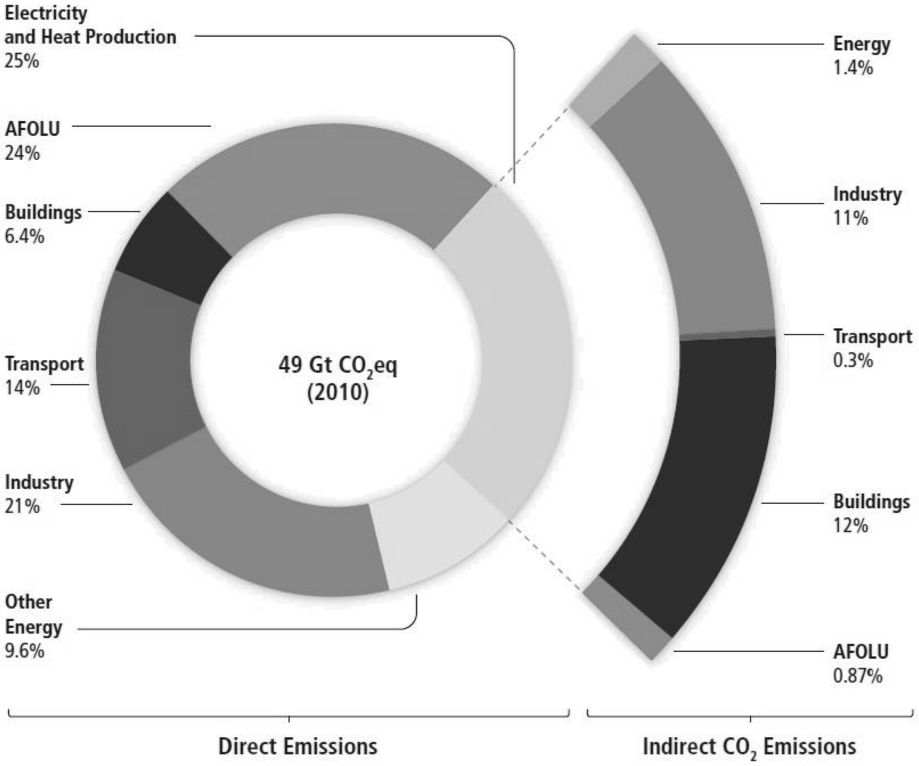

Figure 1 Total anthropogenic GHG emissions in GtCO2eq/y by sector (IPCC, 2014d).

The EU pushes forward towards higher energy efficiency buildings with the building energy directive published in 2010. One of the main goals is to reduce the EU's energy dependency and GHG emissions. The directive demands energy efficiency improvement of existing and new buildings (EU, 2010). The available options to upgrade the energy efficiency of buildings are widely discussed among experts and necessary policy measures, which set the minimum requirements of these options, are debated. New policies are introduced in throughout Europe for each member state. The Dutch government enforced the EU directive by publishing the Dutch building regulation 2012 in August 2011 (BRIS, 2016). The most important set of rules covered are energy efficiency improvements, mandatory safety measures, physical properties, and indoor building climate. The building regulation 2012 was updated in November 2015 and changed at several points to improve even more the energy balance of buildings (BRIS, 2016). When existing buildings undergo major renovations they likewise have to meet minimum energy performance requirements. These requirements have to be net cost-optimal and follow specific guidelines of the directive (EU, 2010). Part of the existing building stock consists of historical buildings, which may be excluded from the performance guidelines by choice of EU member states if an alteration makes unacceptable changes to the appearance and damages the heritage value of the building (EU, 2010). These historical buildings are, generally speaking, pre-war or date before the oil crisis in the 1970s. They account for approximately two-third of the total building stock in the Netherlands. Figure 2 gives an overview with regards to the residential building stock in the Netherlands (CBS StatLine, 2016). The energy performance design is rather poor and has a high need for renovation (Meijer et al., 2009). The number of historical buildings is significant and of high relevance to reduce the environmental impact of the building sector. The stock of historical buildings is especially large in Europe. Approximately 55 million dwellings of E-27's building stock date before 1945 (Eurostat, 2009). A retrofitting of these buildings towards efficiency improvements would result in high energy savings (EC, 2015).

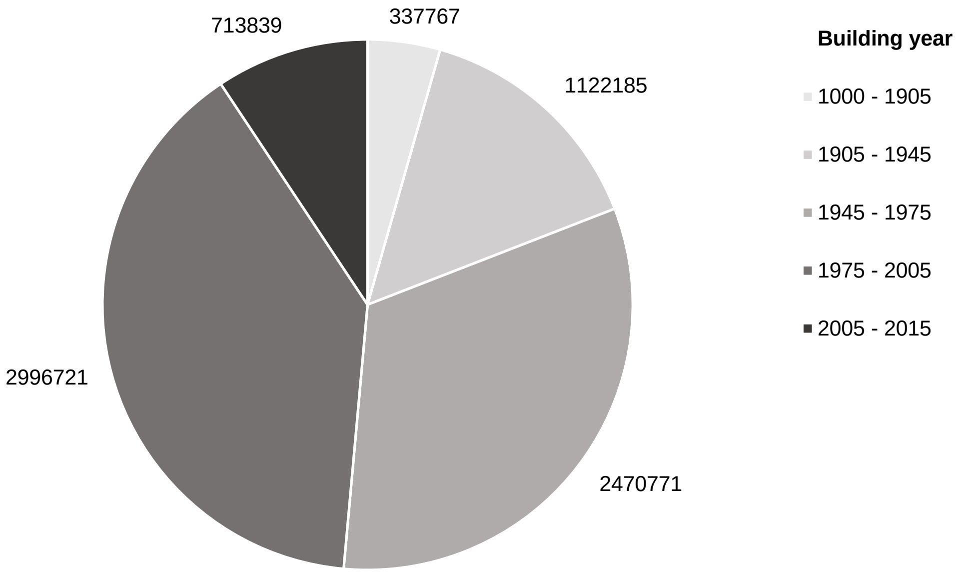

Figure 2 Residential building stock in the Netherlands (CBS StatLine, 2016)

Because of the pressure to build more and more energy efficient buildings, the utilization of energetically improved installations might lead to a loss of heritage value of historical buildings. Therefore, retrofitting measures have to be carefully assessed to ensure that the inherent value of a historical building retrofit is optimally protected (Broström et al., 2014). The Dutch Cultural Heritage Agency protects these buildings. Nevertheless, since 1st of January 2012 alterations and modifications of historical buildings have not required permission if altered substances are not of historical value (CHA, 2011). This rule makes it every project manager's responsibility to individually assess if a substance is of heritage value or not. A set of general rules aids in decision making, but Dutch legislation lacks a systemic approach of how economic and environmental considerations can be weighed against heritage values. All buildings can – and have to – contribute to sustainability targets. But improper retrofitting measures might lead to an irreversible damage of the historical building.

Problem definition

This thesis is a step forward to sustainable historical buildings in the Netherlands. Ways to lower the energy demand and carbon emissions are investigated in the light of heritage values. To achieve this, a case study is conducted. The building under consideration for the case study is a *gemeentelijke* (municipal) monument owned by the *National Spoorwegen* (NS) in Utrecht in the Netherlands (Gemeente Utrecht, 2016a). The NS's goal is to refunction the building to an office space and to retrofit the historical building towards higher energy efficiency and lower carbon emissions to make the building more sustainable. This should include a high efficiency of technology used in the building, an energy coverage by renewable energy sources (RES), and a fulfilment of legal heritage value requirements for historical buildings in the Netherlands. The identified solutions should be cost-effective. The absence of scientific studies dealing with the Netherlands as a problem area, according to our knowledge, exposes issues towards justified energy efficiency and energy supply measures for the building. This research presents a variety of scenarios of how an energy retrofitting for historical buildings can be accomplished and which type of construction should be chosen for the building. A statement is possible concerning emission and economic considerations in combination with the impact on heritage values.

This leads to the following **research question**:

What building retrofit measures are the most optimal in the light of carbon emissions and economic concerns taking into account the impact on heritage values in the Netherlands?

The research has the following **sub-questions**:

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1. Which energetic retrofitting measures are the most appropriate to conserve the heritage value of a historical building in the Netherlands?

Case study

2. Which retrofitting measures are the most suitable to conserve the heritage value of the case study building?
3. What is the demand profile in final and primary energy of a heritage building in the Netherlands?
4. What are the potential energy savings and carbon emission savings of the chosen retrofitting measures and what are the costs of these?
5. Which packages of retrofitting measures are the most optimal to reach minimum carbon emissions, the most economic outcome, and a high share of RES while achieving combinations of aforementioned targets?

Structure of the thesis

Chapter 2 of the thesis elaborates on the necessary methods to answer the above-mentioned research question and its sub-questions. Also, an overview of the used simulation programmes for the case study is given.

Chapter 3 deals with relevant legislative background information and identifies which retrofitting measures are appropriate to conserve the heritage value of a historical building in the case of the Netherlands and, in the end, discusses the possibilities for the case study.

Chapter 4 is the fundamental part of the thesis. It answers the research question, namely the energy simulation of the historical building situated in Utrecht. Here only retrofitting measures are assessed which are approved in the chapter beforehand to not restrict the heritage values and the legislation in the Netherlands. Retrofitting measures concerning final and primary energy and carbon emissions are tested in the simulation. The outcomes are given in absolute values and percentages for each measure separately. On the basis of this, the costs analysis is executed for each measure. Subsequently, the defined targets in the research sub-questions are tested in retrofitting packages for whether they can be fulfilled.

Finally, chapter 5 discusses the results, which includes an uncertainty analysis, implications, limitations and a recommendation for further research. The discussion is followed by a conclusion and a recommendation of which retrofitting package should be implemented.

2. METHODOLOGY

This chapter describes the necessary method to achieve a balance between historical building retrofits and the conservation of their heritage value. First, the overarching approach in form of the *Trias Energetica* is described. The second part introduces the literature review, which gives an overview of the legislative preconditions in the Netherlands and displays applicable retrofitting measures to conserve the heritage value of a Dutch historical building and for the case study. This part of the methodology answers the sub-questions (SQ) 1 and 2. Thirdly, the relevant methods are described with regards to the case study. This includes the introduction of the building simulation software that is used to simulate the case study building (SQ 3), as well as the description of how individual and packaged measures are assessed, the explanation of methodical tools for the economical assessment, and the description of the sensitivity analysis. The methodology answers SQ 4 and 5 with regards to the measure and package assessment.

2.1 Trias energetica

The main focus of this thesis is to reduce the energy demand and produced emissions of historical buildings as much as possible without neglecting their heritage value. One possible method to limit the carbon emissions to the highest degree possible is the *Trias Energetica* approach, which was developed by the Technical University Delft in 1996 (E.H. Lysen, 1996). The framework is applied in the Netherlands and is one of the main strategies for sustainable buildings (Rijksdienst voor Ondernemend Nederland, 2013). The approach represents a guidance towards sustainable buildings and unites efficiency improvement, renewable energy use, and the use of fossil fuels – but only if used as efficient as possible. The first of three parts of the *Trias Energetica* is to reduce the energy demand of the building. Energy which can be saved does not have to be produced and is therefore a good way to reduce carbon emissions and the energy demand. This can be accomplished by several active and passive options. The most common way is to improve the thermal conductance of the building for walls, ceiling, and glazing. Also, the energy demand can be decreased by adjusting the heating and cooling schedule, making the building air tight, and replacing the HVAC system (i.e., heating, ventilation, and air-conditioning) and the lighting system (Şahin et al., 2015). The second step entails the application of RES. Here, the goal is to apply a maximum share of renewable energy. The main systems are wind power systems, photovoltaics (PV), solar thermal energy, and geothermal energy (BDA, 2011). Of special notice is the primary energy factor (PEF) for electricity, which describes the efficiency of electricity delivery to a building. A high share of renewables (PEF = 1) leads to a better combined PEF of the electricity mix. As a consequence, a high share of renewables at the building site leads to a lower PEF (Molenbroek et al., 2011). The last step of the *Trias Energetica* states that the remaining energy needs should be covered by fossil fuels as efficiently as possible.

The principles of the *Trias Energetica* are applied for various SQs in the thesis. The answer to SQ 4 initially follows the first part by identifying those retrofitting measures which are the most suitable to reduce the energy demand of the building. After a successful reduction of the energy demand, the second part intends to find the most appropriate RES to cover the energy demand, which is also part of SQ 4. The remaining energy demand is covered by an efficient application of fossil resources. The combination of the aforementioned parts answers SQ 5 in the form of the packaged measures. The *Trias Energetica* approach heavily influences the selection of the measures by focussing on energy efficiency and energy supply and not on one part individually. This is the main advantage of the approach because it is not limited to one aspect of an energy analysis. The essential principles of the *Trias Energetica* are shown in figure 3.

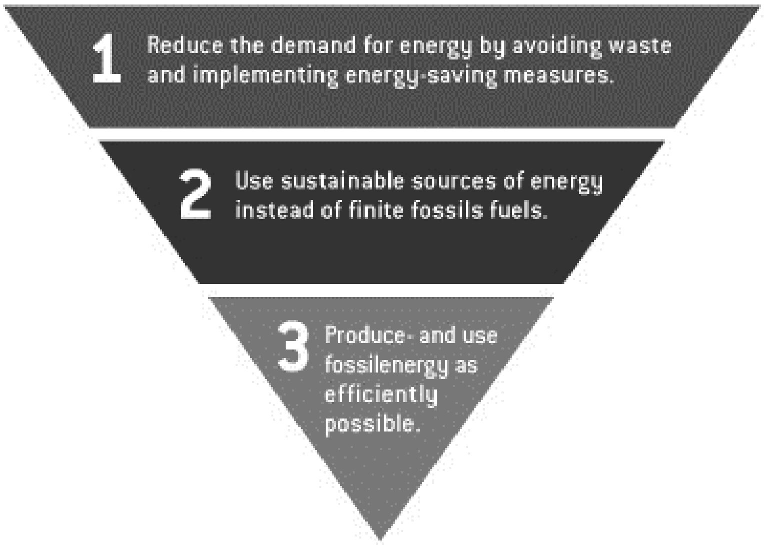

Figure 3 The Trias Energetica framework (Rijksdienst voor Ondernemend Nederland, 2013)

2.2 Literature review

The building retrofit of a historical building is different to the retrofit of a building which does not have a protected status. A variety of regulations need to be taken into consideration before the retrofit can be executed. One very important aspect is the heritage value of historical buildings and to what extent retrofitting measures compromise those. Therefore, a holistic approach is necessary to make justified choices towards an energy efficient building with low emissions. This approach assesses the benefits and weighs them against the heritage values (Grytli et al., 2012). This process should happen in a transparent and systematic manner and should not be assumed (Broström et al., 2014). Therefore, a careful investigation of planning law, heritage law, and scientific literature shows which measures are the most appropriate for a historical building retrofit. Chapter 3 gives a coherent picture of the legislative preconditions, the measures which are the most fitting to conserve the heritage value of a building, and how these measures should be assessed. Also, a heritage value impact assessment for retrofitting measures gives a clear picture of which conservation approaches are the most appropriate in the Netherlands. The assessment is divided into the main categories, based on multiple sources, which are identified in the prior legislative review of chapter 3. The different parts are united into one comprehensive rating for each retrofitting measure. The end of this section discusses which identified retrofitting measures are applicable for the case study. The outcomes of this section answer SQ 1 and 2 and state which energetic retrofitting measures are the most appropriate to conserve the heritage value of a historical building for the Netherlands in general and for the case study building specifically.

2.3 Case study

After a determination of feasible retrofitting measures to conserve the heritage value of a building in the Netherlands, the energy profile of one historical building is investigated in chapter 4. The case study is the main part of the thesis and answers SQ 3, 4, and 5. The retrofitting measures which were previously identified in the literature review are assessed with the help of the case study. This assessment constitutes an energy and carbon emission analysis, an economic analysis, and a combination of all outcomes into a marginal abatement cost curve (MACC) to empower a broad comparability. The sensitivity analysis in the end as part of the discussion describes the influence of selected parameters on the results. All aforementioned methods are elaborated in this section.

The case study building is a workshop and office building which was built in 1892 by the Society for the Exploitation of State Railways and is located on the grounds of the former Central Workshop of the *Nederlandse Spoorwegen* (NS), 2nd Daalsedijk in Utrecht, as shown in figure 4 (Gemeente Utrecht, 2016b). The framed black area on the right displays the part of the building which is considered in the thesis. The client NS wants to refunction the site to an office space in a sustainable manner. The company *Except* was entrusted with this task and is responsible for the entire process. *Except* suggested to refunction the building to a collective office space. The ambition is to make the building as energy self-sufficient as possible, to reach minimum carbon emissions, and to avoid the use of fossil resources. The retrofitting operation has already started in December 2015 at the beginning of the thesis. At the current state, the majority of the building has been dismantled and interior construction work has begun. The goal is to have a functional office space in the beginning of 2017, according to the time planning of the project. The master thesis is part of the energy and carbon emissions assessment of *Except* and has impact on the retrofitting measure selection. The budget for the entire renovation is 1.2 million euro. The retrofit of the technical installations can cost 0.3 million euro and the application of insulation or fenestration has a budget of 0.1 million euro.

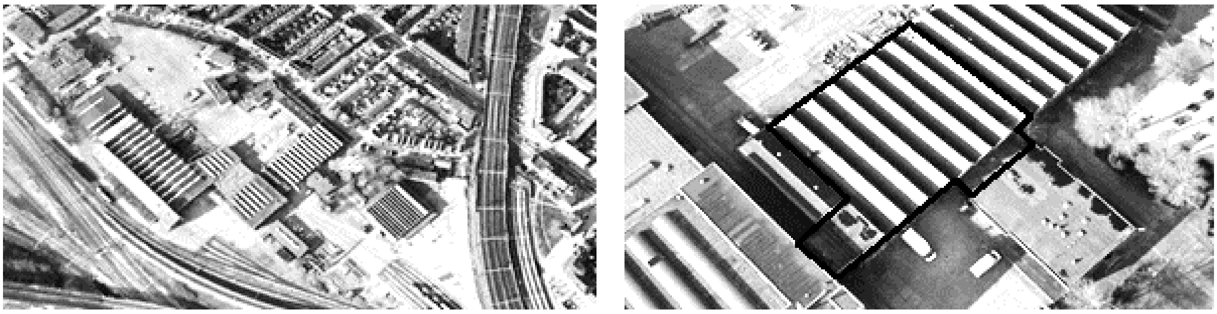

Figure 4 Building site 2nd Daalsedijk, Utrecht (google earth)

2.3.1 Building simulation

In order to achieve an energy demand analysis of the case study and to assess the potential to reduce the primary energy demand and carbon emissions, a simulation program is used wherein all characteristics of the building are modelled. The first step is to simulate the initial situation of the building as a base case. The base case simulation represents the building envelope of the building at the beginning of the master thesis in December 2015. The thermal energy installations and light installations were not present any more at this point in time. This information is complemented by adequate data for the Netherlands. All simulations for the measures and packages build up directly on the base case. The foundation of the energy simulation workflow towards the base case is a 3D perspective of the historical building, which is simulated with the recognized software SketchUp3D, which is available as a plugin for the energy simulation suite OpenStudio (SketchUp, 2016). SketchUp3D is a software to create three-dimensional models. It is used to simulate the building envelope, which is the foundation of the energy simulation. The energy profile of the case study is modelled with the help of OpenStudio, which contains the official building simulation engine EnergPlus of the U.S. Department of Energy (OpenStudio, 2015a;

U.S. Department of Energy, 2016). OpenStudio is a suite of free and open source software applications. It is used for the energy analysis.

Background

Because of the unique architectural design, a comprehensive approach is necessary to determine the initial energy profile for the base case. Firstly, relevant data is collected in an interview with the project manager Mirjam Schmull of *Except* to ensure a proper start of the simulation. Secondly, an extensive independent inspection of the building is conducted to ascertain a clear overview of the initial condition as well as a clear insight of which measures might be achievable to retrofit the building. Thirdly, detailed architectural plans of the building were retrieved from the architecture office ZECC, which is based in Utrecht. The entire background information can be found in appendixB. Next, all previously mentioned data is merged in the simulation software SketchUp3D and OpenStudio to simulate the base case and to assess the identified retrofitting measures and packages. These steps answer SQ 3 by showing the demand profile in final and primary energy of the base case. They are also the foundation for SQs 4 and 5. Subsequently, the necessary phases in the software are described.

3D model of the building using SketchUp3D

The simulation includes the volume and the surface area as well as windows and other surfaces such as doors. The 3D representation of the building in the software is done by drawing the space outline in SI units and by projecting the diagram into a 3D perspective. SketchUp3D is able to recognize the different surfaces present in the model thanks to the link with the energy simulation software OpenStudio. The orientation according to the north axis is simulated; additionally, shading surfaces and other geometries are replicated. The outline which defines the surfaces, the various constructions, the different space types (e.g. office, facility, storage), and the assemblage of spaces in thermal zones is based on the detailed architectural drawings. Each thermal zone in the building has its own heating thermostat schedule and cooling thermostat schedule, so building areas with the same temperature profile are united to one thermal zone to facilitate the simulation process (OpenStudio, 2015b). The definition of those is mainly dependant on the orientation and use of spaces. Areas which have the same orientation and use are united (OpenStudio, 2015b). All of these points are fundamental inputs for the OpenStudio simulation building energy simulation. The outcome of this step shall reflect the geometries of the building as close to reality as possible. It serves as the basis for later steps in OpenStudio, where the simulated geometries of SketchUp3D are the foundation for building envelope definitions.

Modelling of the building perspective and energy demand optimization

The modelling of optimal energy efficiency through passive measures is done through OpenStudio together with the plugin EnergyPlus (EnergyPlus, 2015; OpenStudio, 2015b). OpenStudio is a dynamic energy building simulation program. The dynamic character of the simulation is far more advanced and accurate than a steady-state simulation thanks to the consideration of time-dependant changes (Harrell, 2011). A static simulation would neglect building schedules and weather where a dynamic simulation does not. It would only make a statement about a specific point in time and not a whole time frame (Saelens et al., 2004). OpenStudio is an open source cross-platform suite which unites a variety of software tools to support building energy modelling. Both SketchUp3D and the thermal simulation engine EnergyPlus are components of OpenStudio. The engine does not have a user interface, so OpenStudio is used to make the software accessible. EnergyPlus is established for building energy simulations. It is an appropriate tool to estimate the energy consumption of a building (Fumo et al., 2010). EnergyPlus is able to simulate heating, cooling, lighting, ventilation, and other energy flows as well as water use accurately (Boyano et al., 2013). This is done by simulating heat and mass transfer flows. The building is divided into different thermal zones with specific properties, as described before in the 3D model simulation. Moreover, exact properties like windows, shape of shading surfaces, and building schedules are applied to simulate the building close to reality. OpenStudio incorporates weather data and thermal properties of used products and materials. It is also able to model the thermal behaviour of the building in sub-hourly time steps, which are necessary to make the dynamic simulation accurate. The shift of building schedules in the space of minutes can influence the energy demand directly. The outcomes of these simulations are values for the final energy demand in total per year. Figure 5 shows a typical workflow of OpenStudio. The step by step description can be found in appendix A (OpenStudio, 2015b). More in to depth information is available on the official website of Openstudio (OpenStudio, 2015a).

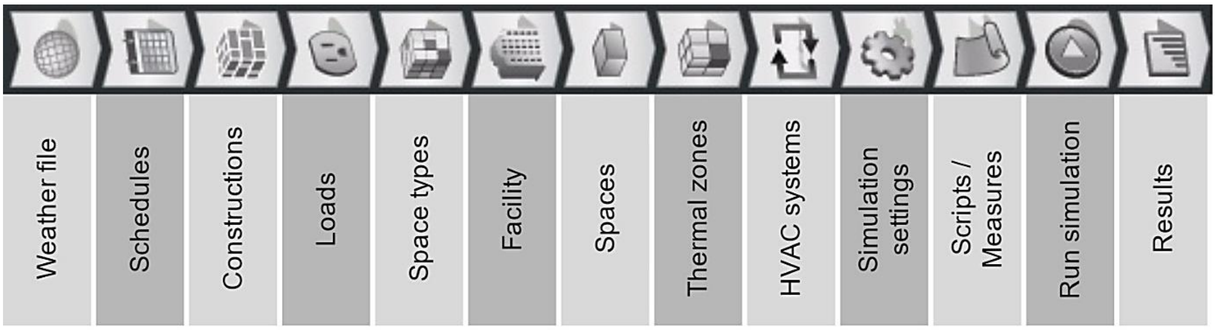

Figure 5 OpenStudio workflow based on the actual structure of the software (OpenStudio, 2015b)

2.3.2 Assessment of individual measures and construction of packages

Before the individual and packaged measures can be assessed, the base case for the simulation was constructed, which is necessary for all subsequent steps. After the successful simulation of the base case, each of the previously identified retrofitting measures towards an appropriate conservation of heritage values is tested. This is done by changing the simulated base case in OpenStudio according to the new parameters of the measure. The general building characteristics stay the same. This includes schedules, geometry, and internal loads. The following measures are under consideration: building envelope insulation, lighting system improvement, window replacement, heat pump installation, ventilation system enhancement, and the coverage of the energy demand by a variety of renewable solutions. The outcomes are recorded in MS Excel for the extensive energy and carbon analysis. The outcomes are also dependant on a variety of parameters such as carbon intensity and the PEF for electricity. After a successful individual assessment, the measures are combined to packages, which also serve to partly answer the research SQs. The following targets are defined as a basis for the packages with regards to SQ 4 and 5: best energy demand reduction, best carbon emission reduction, best economic combinations, and highest share of RES. The following sub-chapters describe each measure group individually.

Building envelope measures

Thermal improvements of the building envelope have the potential to lower the energy demand for cooling and heating significantly. Commonly, walls, windows, and the ceiling are enhanced or replaced with constructions with a better U-value (Şahin et al., 2015). Each of these retrofitting areas is tested with a variety of measures to identify the most appropriate solution for the different targets. Maintaining the indoor climate at preferably low energy demand is the main use for thermal energy. In winter, energy is necessary for heating; in summer, for cooling. The heat transfer rate of buildings surfaces with an outside boundary are expressed in the following formula:

Equation 1 Rate of heat transfer

$$Q = U * A * \Delta\mathrm{T} = \frac{1}{R} * A * \Delta\mathrm{T} = \frac{\lambda}{d} * A * \Delta\mathrm{T}$$

A is the surface area, *U* is the thermal conductance in $\mathrm{W/m^2K}$, *R* is the thermal resistivity in $\mathrm{m^2K/W}$, *d* is the thickness of the construction, λ is the thermal conductivity of the entire construction, and ΔT is the temperature difference between inside and outside boundary of the construction (Andrews et al., 2013).

Fenestration measures

The right choice of fenestration has an important role in a retrofitting process. Up to 60% of the total energy loss of a building can originate from its windows. Therefore, fenestration products with a particularly low U-value have a huge potential to provide energy savings (Gustavsen et al., 2007; Bjørn Petter Jelle et al., 2012). Typical fenestration products are single-glazing and multilayer-glazing, vacuum glazing, electrochromic glazing, solar cell glazing, aerogels, low-emissivity (low-e) coatings, frames, and spacers (Cuce et al., 2015). The thesis focusses on the best available state-of-the-art options with the lowest available U-value and appropriate solar transmittance (Tvis). Glazing can be considered the most important part of the fenestration as it has the highest share in surface area. Thereby, multilayer glazing represents the most advanced commercially available glazing type. Double layered glazing is less competitive with regards to U-values, but it is widespread and very economic. Triple glazing has highly advanced thermal properties, but comes with a higher price. Multi-layered glazing is typically filled with noble gasses, which have advanced thermal properties when compared to air. The overall U-value of a fenestration product is determined by uniting the properties of glass, frame, and spacer and calculated with the following formula (SANCO, 2014):

Equation 2 U-value of windows

$$U_w = \frac{A_g * U_g + A_f * U_f + L_g * \psi}{A_f + A_g}$$

U_w is the overall U-value of the total window construction, A_g is the surface area of the glazing, U_g is the U-value of the glazing, A_f is the surface area of the frame, U_f is the U-value of the frame, L_g is the perimeter of the window, and ψ is the linear heat transfer coefficient of the window. This formula is applied for each fenestration type. An average U_w is determined for the entire building dependant on the fenestration type.

Interior wall-, roof- and floor insulation

The building constructions for historical walls, roofs, and floors are outdated and do not coincide with thermal requirements in the Netherlands (BRIS, 2016). The added U-values range from 1.0 $\mathrm{W/m^2K}$ for the least efficient option to 0.17 $\mathrm{W/m^2K}$ for the thickest insulation with the best thermal performance. The insulation analysis overview focusses on U-values and not on specific product types. Figure 6 shows the considered insulation thicknesses with their specific U-values. Generally, similar insulation properties can be reached by applying different material types in the same thickness with a comparable cost-effectiveness. The thermal conductivity for conventional insulation materials is in the region of 20 to 40 W/mK (Björn Petter Jelle, 2011).

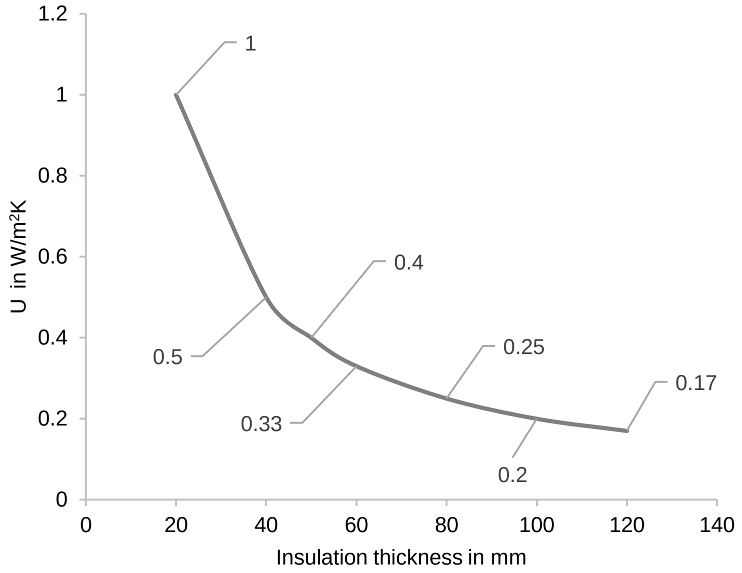

Figure 6 Relation between insulation thickness and the related U-values

<u>Technical installation measures</u>

After altering the building envelope, the next step is to improve the technical installation system of the building. The new values for the energy demand and the carbon emissions are the difference compared to the base case. An overview is shown for lighting and HVAC system that was chosen for this thesis.

Lighting system

The lighting system of the building can be improved by a replacement of the old bulbs by new more efficient solutions. The lighting of an older building has generally a system with a poor luminous efficacy, which is measured in lumens per watt (Pyloudi et al., 2015).

HVAC system

The supply of thermal energy can be achieved with heat engines, which supply work to pump heat or chill into the building. These engines are called heat pumps (Andrews et al., 2013). The device takes advantage of the fact that the temperature level of the ground and to a lesser extent of the air can be maintained relatively constant. The working principle of a heat pump is similar to a refrigerator. A heat pump is able to transform a low surrounding room temperature to a higher temperature level, which can be used for heating and also for cooling. Three main installation options are available: ground, ground water, and ambient air. These three options are available with more variations. The principle of a heat pump is based on the Carnot cycle, which describes the ratio of heat Q and work W, which is called coefficient of performance (COP). An optimal ratio would result in a COP of 10. In practice, however, COPs are typically in the area of 3 to 4.5 (Andrews et al., 2013). Usually ground water heat pumps are much more efficient than ambient air heat pumps because of the more constant temperature level of water compared to air. Ground heat pumps are in between the other two pump types. The application of COP enables a conversion from primary energy to final energy and vice versa.

Renewable energy system measures

After altering the technical installations, the next step is to improve the renewable energy supply of the building. The technologies under consideration are established state-of-the-art systems to show an alternative to burning fossil fuels by following the guidelines of the *Trias energetica*. The technologies included are solar thermal energy, solar photovoltaic (PV), and wind energy. The results for PV and wind energy are calculated with the help of the physical energy content method. This method uses the physical energy content of an energy source as the primary energy equivalent. As a consequence, a efficiency of 100% can be assumed for PV and wind energy (Stoffregen et al., 2014).

Photovoltaics

Solar PV is a direct solar energy form. The emitted energy of the sun gets directly captured by panels and transferred into electrical energy. To reach a maximum output for PV cells, the orientation of the surfaces needs to be to the southeast or the southwest. An angle of incidence with 36 degrees is optimal (Quaschning, 2011). Other angles or a different orientation lead to a lower electricity output. The determination of the PV panel alignment is done according to figure 7. The sheds (visual representation in chapter 4.1.1) of the case study's roof cause shading, which needs to be taken into consideration when determining the position of the PV panels (Agentschap NL, 2010a). In the case study, the orientation of the panels is to the southwest.

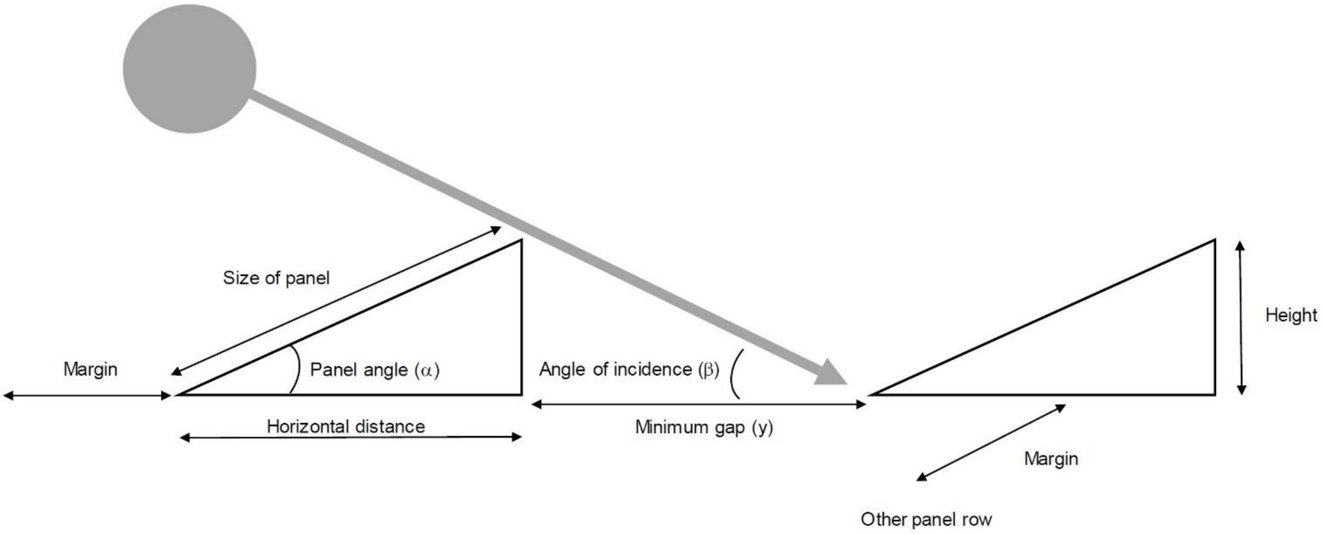

Figure 7 Determination of the minimal PV-panel distance on a shed-roof (Agentschap NL, 2010a)

Solar thermal energy

Solar thermal energy is another direct solar energy form. It can be used for warm tap water, which is not necessary for the case study, and additionally for space conditioning. Although such systems can be considered to provide renewable energy, they are not further assessed in this thesis, because literature shows that solar collectors have a very low cost effectiveness, and the benefit per m^2 of used space is much lower than for PV systems (Lesser et al., 2008).

Wind energy

Unlike the previously described direct solar energy, wind energy is an indirect solar energy form. The influence of the sun causes temperature fluctuations on the earth, which in return cause wind. This energy can be harvested by capturing the natural air flow through wind turbines to produce electricity with the help of power generators (Andrews et al., 2013). Wind energy has much greater power densities than direct solar energy. The maximum solar energy accounts to 1 kW/m^2. By way of contrast, wind energy can reach up to 10 kW/m^2 (Quaschning, 2011). A distinction can be made between large scale and small scale wind turbines. Large scale wind turbines (> 1MW) are not assessed in this report. This is because their overall scale is too big for this project. Additionally, the investment costs are enormous, and the scale of wind turbines is restricted by legislation. Small scale wind turbines do not have these restrictions and can therefore be applied at a historical building retrofit.

2.3.3 Economic analysis

After the assessment of individual measures and construction of packages, the next step is to investigate their economic performance. The first approach of choice within the economic analysis is the use of simple payback periods (SPB) to give a clear and easy accessible first overview of how cost-effective the assessed measures and packages are. It describes the time required for the cumulative savings of a measure to recover the initial investment and other related costs. It does not take into account the time value of money (WBDG, 2016). A discounted payback period would be accurate but is not part of this thesis due to time constraints. The SPB is calculated as follows:

Equation 3 Simple payback period

$$SPB = \frac{I}{S}$$

I = Investment (€)
S = savings (€/y)

The main method in the economic analysis is the determination of the levelized costs of conserved carbon (LCCC). An LCCC is a method to assess the total costs of ownership. It takes into account all investment costs and other annual costs related to a measure (Woodward, 1997). The costs are levelized to show the average costs over a longer timeframe, which means assuming the time value of money (IPCC, 2014a). This reflects a rather simple metric to calculate the costs of carbon emissions. It can be used to compare more measures with each other (IPCC, 2014a). It is of important notice that the outcome can be negative if ΔB is larger than the rest of the numerator. Negative outcomes pay themselves off in the long run and are therefore economic. Positive costs indicate loss and are only worth consideration if the motivation for carbon mitigation is larger than having a financial loss. The LCCC is calculated as follows (IPCC, 2014a):

Equation 4 Levelized costs of conserved carbon

$$C_{specCO_2} = \frac{a * \Delta I + \Delta C - \Delta B}{\Delta M_{CO_2}}$$

I= initial investment
C= annual costs
E= annual energy provision
ΔI= difference of investment costs of energy savings measure compared to base case
ΔB= difference of annual benefits
ΔC= difference of annual costs
ΔMCO_2 = annual GHG emission savings through the implementation of an option
a= annuity factor

The annuity factor, which is part of equation 2, takes into account the lifetime of a technology and the assigned interest rate. It is calculated as follows (IPCC, 2014a):

Equation 5 Annuity factor

$$a = \frac{r}{1-(1+r)^{-L}}$$

r= discount rate
L= technology lifetime

The results of the economic analysis answer sub-question 5. The marginal abatement cost curve (MACC) explained here supplements these results by visualizing them. The construction of MACCs is a tool to summarize the realistic volume and costs of opportunities to reduce carbon emissions (Kesicki et al., 2012). The outcomes of the LCCC, as explained in section 2.3.3, are the basis for this step. The analysis for individual measure LCCCs of best performing packages deducted under 2.3.2 helps to visually compare the contribution of separate measures within the package. These outcomes support the exploration of the best retrofitting solutions with regards to SQ 4 and 5. Each box of figure 8 below shows an individual measure to reduce carbon emissions. The width reflects the potential of carbon reduction within the defined lifetime of the specific measure compared to the base case. The height stands for the average to abate one tonne of CO_2 through that carbon mitigation opportunity. The opportunities below the horizontal axis offer the best potential for financial savings. Those above come at net costs. In this thesis, the most promising retrofitting measures and all packages are assessed with the help of a MACC.

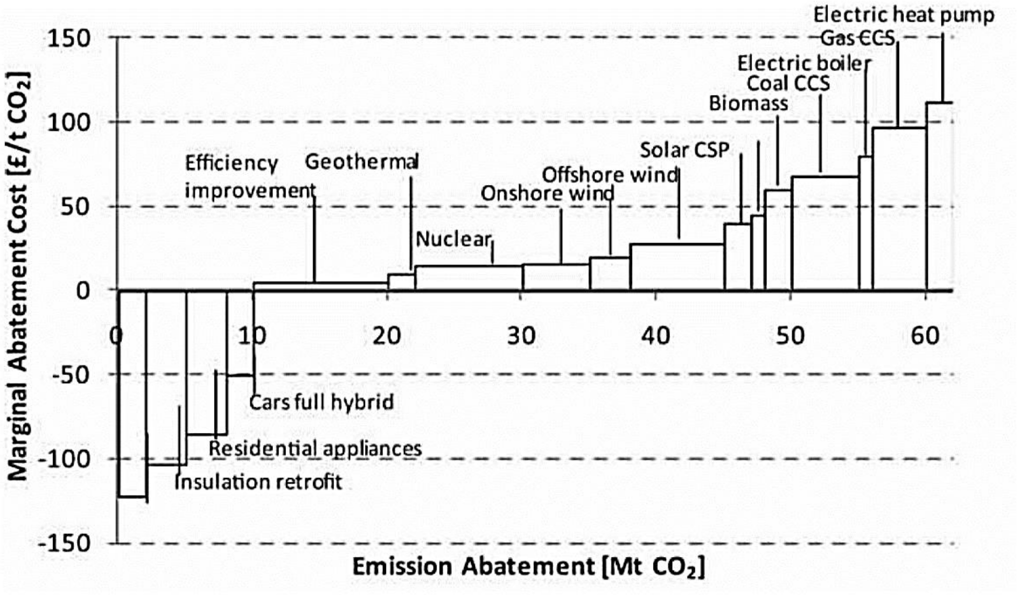

Figure 8 Example for marginal abatement cost curves (Kesicki et al., 2012).

2.3.4 Sensitivity analysis

Another important aspect is to take into account the uncertainty of parameters. Investments in the building sector usually involve an non-neglectable amount of uncertainty with regard to their costs, energy demand reduction, and carbon mitigation (WBDG, 2016). Some of the parameters cannot be set constant. The logical consequence is a sensitivity analysis to see the magnitude of difference if an alternative value is chosen. Consequently, the influence on the outcome, which is dependent on each parameter, can be detected and, building up on these results, the later decision-making and recommendations can be altered or adopted accordingly. One parameter based on the previous methodology under 2.3.3 is the discount rate, which can be analysed in a sensitivity analysis. It makes the cash-flows equivalent that are incurred during the lifetime of an investment time. The chosen rates are either private and therefore higher or public and therefore lower. The highest rate under consideration is 20% as a private rate and the lowest 6% as a public rate (Blok, 2007). The discount rate reflects the opportunity for an investor to make money over time (WBDG, 2016). Hence, the discount rate can be seen as the minimum rate of return for an investment. Therefore, private investors tend to choose higher discount rates to achieve a maximum turnover. In contrary, public investors and other private investors which are not primarily driven by the rate of return but other motives (i.e., lower carbon emissions) generally accept lower discount rates. Other significant parameters which determine the outcomes in section 2.3.2 are carbon intensity and primary energy factors for electricity. Carbon intensity is the emission rate of CO_2 for a certain activity (i.e., tonnes of carbon produced per gigajoule of energy produced). The carbon intensity for primary energy production is assumed to develop according predictions of the European Commission (EC, 2013). The primary energy factor describes the ratio between end-user consumption of electricity and the referred primary energy consumption (Adapt Consulting AS, 2016). It is important to investigate if the assessed measures and packages stay interesting if the aforementioned parameters change.

2.4 Research overview

Figure 9 shows a schematic overview of the research in the form of a flow chart to make the workflow of the conducted research more accessible. All steps are described above in the methods sections.

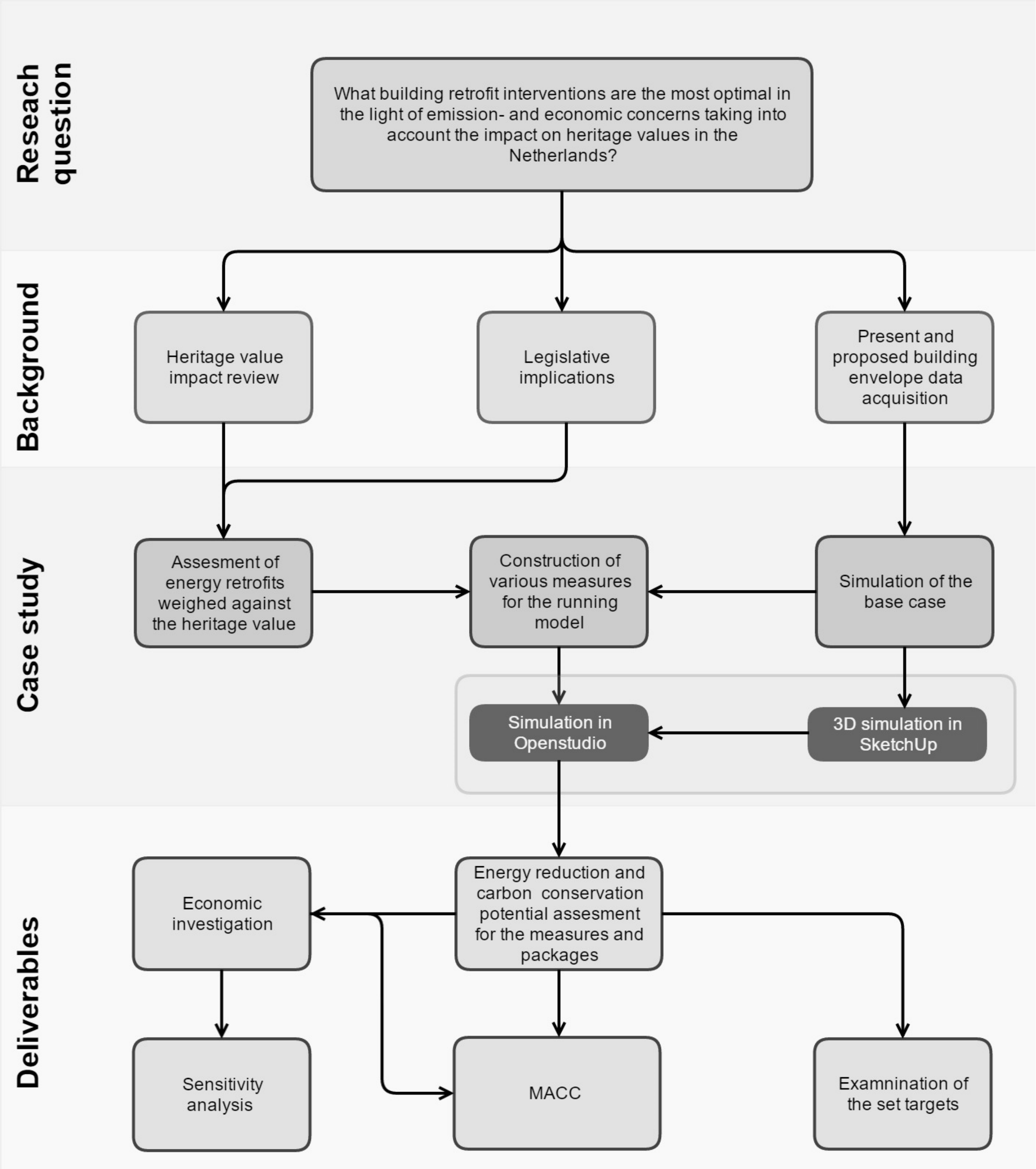

Figure 9 Flow diagram of the conducted research

3. LITERATURE REVIEW

The first part of this chapter deals with relevant legislative background information for historical building retrofits. The review focusses on European and Dutch building and heritage value regulations. It gives a distinct overview of energetic building regulations according to the Dutch building regulations of the year 2012 (BRIS, 2016). The second part identifies appropriate energetic retrofitting measures to conserve the heritage value of a historical building, which follows the regulations in the case of the Netherlands. Based on the previous step, a set of retrofitting measures is discussed in depth, which serve as input for the subsequent building energy simulation.

3.1 Legislation

The performance requirements for building retrofits are determined by the EU energy directive (EU, 2010). All member states have to ensure that the energy performance is upgraded to meet the minimum energy performance requirements if a building undergoes major changes. These have to be feasible in the light of economy, functionality, and technology. The requirements can be determined by the official comparative methodology framework of the directive. The Dutch legislation enforces these guidelines by the publication of own regulations referring to the directive. The Dutch building regulation called *Bouwbesluit* was published in 2012 and updated in November 2015 (BRIS, 2016). It includes regulations for safety, health, usability, energy, and environment. All existing and new buildings must meet these requirements. Member states of the EU can exclude existing buildings from the framework if they are part of a designated environment or because of their special architectural or historical merit. This can only be done if the retrofit to meet minimum energy requirements would interfere with the aforementioned values (EU, 2010). The following section elaborates on the importance of the heritage value of a historical building.

The historic building materials, structures, and methods used for building construction represent an important monumental and historical value. This value should be respected as much as possible so that the history and significance of the building can be understood through pure visibility (O.O.M. Advies, 2011b). A retrofit entails the risk of a total loss of the cultural heritage. Therefore, it is necessary to consider preservation before renovation. The retrofit options need to be assessed according to their benefits, to what extent the value of the building can be preserved, and if, in case part of the value gets lost, changes are justified because of strong advantages (Grunewald et al., 2010). The transformation of a building might also change the functionality and the role of the building. Both these points are of significant value for the character of the building and should be part of any retrofit consideration. The value is often derived of the construction history. Later renovations can make it impossible to esteem the historical construction history as those might have destroyed particular characteristics of the appearance. Therefore, any changes and retrofit options have to be reversible to avoid any later issues with regards to the legislation. A violation can lead to financial penalties or an enforced recovery of the initial status (CHA, 2011).

Furthermore, historical material applications and / or construction methods are not always compatible with contemporary building materials or construction methods. They may cause mechanical, physical, and / or chemical reactions which can subsequently cause damage to the monument. To avoid such impacts, the selection of appropriate techniques should be of special notice (O.O.M. Advies, 2011b).

Innovative solutions should not be directly applied to the retrofitted building. These solutions have to prove themselves beforehand in the conventional building sector, and they need to be certified. In case of doubt, the proposed solutions should not be applied. The main official Dutch regulation states that the appearance of the historical building should not be altered (CHA, 2012; O.O.M. Advies, 2011a, 2011b). Since 1st January 2012 alterations and modifications of a historical building have not required permission if altered substances are not of historical value (CHA, 2011). Before this date, every modification or alteration of a municipal historical building required a permit. A similar situation exists for national monuments. Project managers and planners must decide independently if a retrofit measure needs a permit. If the changes are not in line with the legislation, a permission of the Dutch *Cultural Heritage Agency* is necessary to assess if proposed retrofit options are acceptable (CHA, 2016). All aforementioned arguments will be taken into account in the following assessment of retrofitting options.

3.2 Heritage value assessment

This section deals with the general assessment of retrofit measures for the Netherlands in general and for the case study specifically. Subsequently, retrofitting measures are selected that are the most appropriate for the case study. Several choices are discussed and a recommendation with a measure set is made for the building energy simulation.

3.2.1 Building envelope measures

Several downsides need to be considered for technical improvements which enable a better energy performance for monumental buildings. The implementation of modern technical solutions might lead to catastrophic consequences for the technical state of a monumental building (O.O.M. Advies, 2011a). The subsequent implementation of insulation can lead to an evolvement of thermal bridges, which as a consequence leads to condensation of water and damages the building substance dramatically (Grytli et al., 2012). Wood in particular is affected. Thus, buildings which were in good state for more than 100 years can deteriorate within a short time period. These problems demand a distinct regulation of monumental building retrofits (CHA, 2011). The following section gives a short and comprehensive overview of building retrofit options and their impact on the heritage value of a historical building. The guidelines are based on the recommendations of several official reports and scientific articles[1]. The assessed technologies are limited to solutions which are feasible in the case of the Netherlands, e.g., technologies like nuclear power and hydro power are excluded due to not being feasible in a small scale or because of environmental concerns. Furthermore, the selected measures are limited to the preconditions of the case study building. For instance, floor measures for a basement are excluded as there is no basement in the building. Information about more retrofitting measures can be retrieved in the literature stated in the footnote.

Table 1 gives an overview of the impact assessment on the heritage value for refitting measures. The summary includes different approaches for fenestration and insulation constructions for all exterior surfaces of a building. Based on section 3.1, the main limitations to consider are: the appearance should stay the same as much as possible, the changes have to be reversible if the appearance changes, and the measures have to be selected carefully to avoid irreversible damage to be building. Alterations might cause problems or even a loss in the light of the cultural heritage of the building. Affected areas are

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[1] Sources for the heritage value impact assessment: #1 - (BDA, 2011); #2 - (Broström et al., 2014); #3 - (Grunewald et al., 2010); #4 - (O.O.M. Advies, 2011a); #5 - (Şahin et al., 2015). These sources are used in table 1.

surfaces in general, details, windows, and others parts of historical value (O.O.M. Advies, 2011a). All measures are assessed according to the legislative categories mentioned above based on a five step scale from very low to very high. The colour scheme of the heritage value conservation rating for each retrofit option gives an indication of how high the aggregated impact would be. White has the lowest impact (corresponds to a score of very low or 1), with a scale up to black with the highest impact (corresponds to a score of very high or 5). Irreversibility potentials without a rating do not require the possibility to reverse the measure. This is the case if the measure has no impact on the appearance. Below the table is a detailed description for each retrofitting measure group.

Table 1 Heritage value impact assessment for retrofitting measures

Type	Measure	Impact on appearance	Irreversibility risk	Damage potential	Heritage value conservation rating	Sources
Building envelope measures						
Fenestration	Window construction overhaul or sealing	Very low	/	Very low / low	□ ░	#1, #2, #3, #5
	Attachment of foils	Low	Medium	Low	░	#1, #3
	Insulation glasses	Medium	High	High	▓	#1, #3, #4, #5
	Extra layer of glass	Medium	High	Medium	▒	#1, #3, #4
	Replacement of fenestration	Very high	Very high	Very high	■	#1, #2, #3, #4, #5
	Replacement of fenestration, similar appearance	High	Very high	Very high	▓	#1, #3
Walls	Overhaul	Very low	/	Very low	□	#1, #2, #3, #5
	Interior wall insulation	Medium	Low	Medium	▒	#1, #2, #3, #4, #5
	Exterior wall insulation	High	High	High	■	#1, #2, #3, #4, #5
Roofs	Overhaul	Very low	/	Very low	□	#1, #2, #3, #5
	Above, in between or under insulation of pitched roofs	Medium	Low	Medium	▒	#1, #2, #3, #4, #5
	Insulation of flat roofs	Very low	Low	Very low	□	#1, #2, #3, #4, #5
Floors	Floor insulation without basement	Medium	Low	Medium	▒	#1, #3, #4, #5

Type	Measure	Impact on appearance	Irreversibility risk	Damage potential	Heritage value conservation rating	Sources
Technical installation measures						
	Lightning systems	Low	Very low	Low	░	#1, #3
	Groundwater heat pump	Very low	Very low	Very low	□	#1
	Ground heat pump	Very low / High	Very low / Medium	Very low / Medium	□ ▒	#1, #2, #5
	Ambient air heat pump	High	Medium	Medium	▒	#1
	PV, solar thermal, and wind energy	Very low / Medium / High	Very low / Medium / High	Very low / Medium / High	□ ▒ ■	#1, #3, #5
	District heating	Very low	Very low	Very low	□	#1, #3

Fenestration

Fenestration is a significant part of the architecture and plays a significant role in the look of the historical building (BDA, 2011). They fulfil multiple tasks like day lighting, insulation, solar gain, acoustic protection, sun protection, etc. All these requirements led to a specific development of tailored systems in the past. The retrofit of historical building fenestration has an explicit demand for thickness and appearance of the construction. A window overhaul or sealing tries to reach a prior performance rate of the construction (Grunewald et al., 2010). This can be done by general overhauling work like painting, repair works, rebating, and maintenance of closing mechanisms. The impact on the historical value is rather small or not existing, thanks to minimum alterations on the exterior appearance (BDA, 2011). A subsequent attachment of foils or a glass coating are good measures to achieve a slight energy improvement. By applying this method, the solar gain and day lighting values might change, which has a direct impact on the historical value and the appearance (Grunewald et al., 2010). Another approach is to replace the historical glass with insulation glass, which depends heavily on the frame construction of the window. A too thin frame will not allow the installation of an insulation glass. These glasses are thicker than a common single-pane window (O.O.M. Advies, 2011a). With this approach, the impact on the heritage value of the building is rather large. The appearance differs, the retrofit option might be irreversible, and the window properties change significantly so that the interior light values and solar gain interfere with the character of the building. By adding an extra layer of glass (either insulation or common glass), a better performance can be achieved. Nevertheless, this method underlies the same restrictions as the prior approach. The impact is almost the same as with the application of insulation glasses, but the interior light values will not change as much and the appearance will be closer to the prior state. A replacement of the fenestration by a state of the art system is generally not applicable because the appearance changes significantly and it is, in most cases, irreversible (Broström et al., 2014). It can only be done by extreme wear of the windows and if the new windows preferably have the same or a similar appearance as the original construction (CHA, 2012).

Wall insulation

Wall construction is one of the fundamental substances of a historical building. It is proof of the construction era of the building and therefore of significant value. Furthermore, it is a testimony to phenomena like age, stylistic era, historical events, building phases, craftsmanship, and applied materials (BDA, 2011). In general, the exterior surface maintains the appearance of the building. A wall construction overhaul adds no extra insulation and the exterior appearance is maintained. Afterwards, the building should be more air tight and thermal bridges should be removed. The historical value will not be influenced because there are no changes to the exterior surface (Şahin et al., 2015). Weather stripping is one of the main approaches available. The addition of interior insulation allows a thermal improvement without compromising the historical appearance of the building from the outside (Grunewald et al., 2010). Nevertheless, this approach has a direct impact on the interior and has to be applied carefully to make it reversible. The subsequent installation of exterior insulation means the total loss of the architectural appearance and, as a consequence, the historical value of the building. This approach is not in line with the Dutch legislation and therefore must not be supported (CHA, 2011).

Roof and floor insulation

Roofs are integral parts of a historical building as they are directly linked to the typological and building-historical background of the building. They are proof of the building technique and the architectural design of the historical era (Grunewald et al., 2010). The first applicable retrofitting approach is an overhaul. It follows the same guidelines as the wall insulation. If installed above, in between, or under a pitched roof, the insulation does not interfere with the exterior appearance of a building. Nevertheless, the interior appearance is altered and influences the heritage value (BDA, 2011). Lastly, a flat roof insulation mostly does not interfere with the heritage value of a building. Generally, the application of floor insulation has no impact on the heritage value of the historical building. Nevertheless, a distinction between a building with or without a basement needs to be made. The application of insulation to the historical floor without a basement should not destroy any floor covering of value. It must be clarified if the floor can be changed. Even so, this method interferes only with the interior appearance of the historical building (Şahin et al., 2015).

Technical installations

In addition to the building materials, the technical installation can also be replaced. The installation of new lights is generally of low impact if the same sockets are used. Most historical buildings already have updated installations, so an improvement of these systems with state-of-the-art products is feasible without compromising the current heritage value (CHA, 2011). A ground water heat pump has almost no impact on the heritage value of a historical building. The required wells can be placed in the surrounding area of the building. The implementation of such a system is more restricted by hydrological parameters and legislation than by historic preservation (BDA, 2011). A ground-sourced system can be applied in two different ways: the heat source is either achieved through deep drilling or a surface collector. The first approach has a relatively low or no impact on the heritage value. The second option does, because a specific surface area requirement is given dependant on the specific heating and cooling demand, which has a direct impact on the appearance of the building. The ambient air heat pump option can directly influence the exterior look of a building. The location for the technical installations needs to be carefully chosen and hidden as much as possible (BDA, 2011). The impact on the historical substance is rather small, nonetheless, the system has to be combined with other systems due to their inefficiency in winter. The necessary installations might have an impact on the historical substance.

Renewable energy sources

The options for RES have three levels of impact (Grunewald et al., 2010). Under consideration are PV, wind energy, and solar thermal energy. The technology is either installed in the surrounding area of the building and, therefore, has no direct impact on the building. The other possibility is to install the RES not visible on the historical building. This leads to an impact on the building substance. Nevertheless, the effect on the appearance stays small. The third variant represents a visible installation which, of course, has a direct impact on the appearance. Finally, district heating results in a low requirement for in-building services and accordingly requires only a low amount of constructive measures.

3.2.2 Measure discussion

This section deals with selection of appropriate measures for the subsequent case study simulation. The measures introduced in the previous section are discussed and a retrofit selection for the case study is made in the end. It is necessary to treat the choice of retrofitting measures with utmost caution owing to the characteristic cultural and heritage value of the building, which is of special interest because of the inherent value for the railway history in the city of Utrecht. The building has a distinctive and detailed design. Some rails are still remaining, which contribute to the value even more. The building served as a railway workshop (Gemeente Utrecht, 2016b) and is listed as a municipal monument. The latter means that, as a consequence, it falls under specific retrofitting regulations in the Netherlands, as described in section 3.1. The measure discussion is based on information of the municipality of Utrecht, a site visit, and an interview with the case owner (Gemeente Utrecht, 2016b).

The characteristic design of the windows makes it hard to maintain the heritage value during a retrofit. The windows are usually iron rods with a thin single-pane glazing. Their thin profile makes it not feasible to add an extra layer of glass or to replace the existing glass by an insulated glass. These options might have had the best outcome with a combination of energy demand reduction and the conservation of the heritage value. Options with almost no impact on the heritage value are an overhaul of the windows or the attachment of foils to control the thermal gain indoors. Nevertheless, these two options show little energetic improvement, but should be always considered for a retrofit because of their cost effectiveness. The last option is a replacement of the windows. This step is drastic and would almost completely destroy the inherit value. However, manufactures are able to copy the appearance of existing windows and a replacement would result in a much better energy performance.

Roofs, walls and floors perform similar in the heritage value assessment. The first approach of choice for all three is a general overhaul of the construction to recover the original state. There is virtually no impact on the heritage value of the building. The roof construction of the building consists of thirteen sheds, whereas the building retrofit has a restriction to an area with seven sheds. The southern end of the building is, instead of a shed roof, partially constructed with a flat roof and partially with a gable roof. The addition of insulation performs very well energetically while, at the same time, not compromising the heritage value drastically. The flat roof insulations are of no concern and the shed roof insulations interfere only with the interior appearance of the building. The exterior wall consists of brick. Its patina and the characteristic assembly is of great importance for the appearance and the character of the building. An exterior insulation would compromise these valuable features. An interior insulation maintains the appearance from the outside and only alters the inside. Also, the addition of insulation to the interior concrete floor has no influence on the exterior and follows the same argumentation line as for the roof and wall insulations.

The replacement of the old lighting system almost does not interfere with the heritage value of the building. The case study building has relatively modern sockets. The installed light sources can be replaced with more efficient ones without any impact. The building was heated by a gas boiler connected to a forced-air heating system before the renovation. Cooling was done through a steam-driven chiller. A replacement of these systems with a modern source of heating and cooling is only beneficial. The energetic performance increases and the character of the building is not disturbed. This is mainly thanks to the invisibility of the installations. Only an ambient air heat pump and a ground heat pump with a heat source close to the surface would interfere with the look of the building. Thus, a groundwater or a ground heat pump with deep drilling are preferable. The application of district heating for the building has no impact on the heritage value because only distributive equipment is required at the site. An RES system, both PV and wind, is generally applicable. The main criterion for the RES system is to make the installations invisible. The interior technical equipment for all systems can be installed in the existing technical rooms.

The recommended measures for the case study building are (as an answer to SQ 2):

➢ **Fenestration**	Overhaul, attachment of foils, or replacement of the single-pane windows with insulated windows, if the appearance can be maintained
➢ **Roofs**	Overhaul, addition of insulation at shed and flat roofs
➢ **Walls**	Overhaul, addition of insulation on the interior at walls with an outside boundary condition
➢ **Floor**	Overhaul, addition of insulation on top of existing concrete plate
➢ **Lighting system**	Replacement of outdated fluorescent lighting system
➢ **Heating & cooling system**	Preferably groundwater or a ground heat pump; an ambient air heat pump or district heating are also applicable
➢ **RES**	PV, solar thermal energy and wind energy are applicable if the appearance is not negatively affected

4. CASE STUDY

The first section of this chapter is concerned with the initial simulation as the base case of the analysis, including relevant background information for the case study and elementary simulation inputs for all simulations. It also gives an overview of the climatic conditions. The second section shows the energy simulation outcomes in form of energy demand and carbon emissions. The third section addresses a variety of retrofitting options and independently investigates the energy demand improvement and carbon emission reduction for each measure. All these measures are also economically investigated in the light of SPBs and LCCCs for each measure. The last section covers the measure packages to investigate which combinations are best to tackle each of the set targets. The assessment of packaged measures applies the same methodology as the measure assessment.

4.1 Base case of the simulation

This section is the basis for most of the defined research goals. The first step is to create a functional and accurate base case. This is done by merging relevant data into the initial building simulation with the software. The required steps are described to create the building envelope representation in SketchUp3D, which is the foundation for the subsequent energy simulation in OpenStudio. The second step in this section describes the necessary data input in OpenStudio for the base case simulation. The product of this section is a functional simulation. The related outcomes are further presented in 4.2.

4.1.1 Building envelope representation

The first step to make the case study successful and to make the energy simulation possible is to perform the 3D simulation of the building. Figure 10 and 11 show the initial building simulation in SketchUp3D. The geometries of the envelope are simplified to ease the process. The window shape has no impact on the simulation outcome yet alone the surface area, so the handiest geometry is chosen to reflect the real situation. The temperature profile of neighbouring structures can be assumed to be similar to the areas where the building is connected to other buildings. These are defined as an adiabatic surface area.

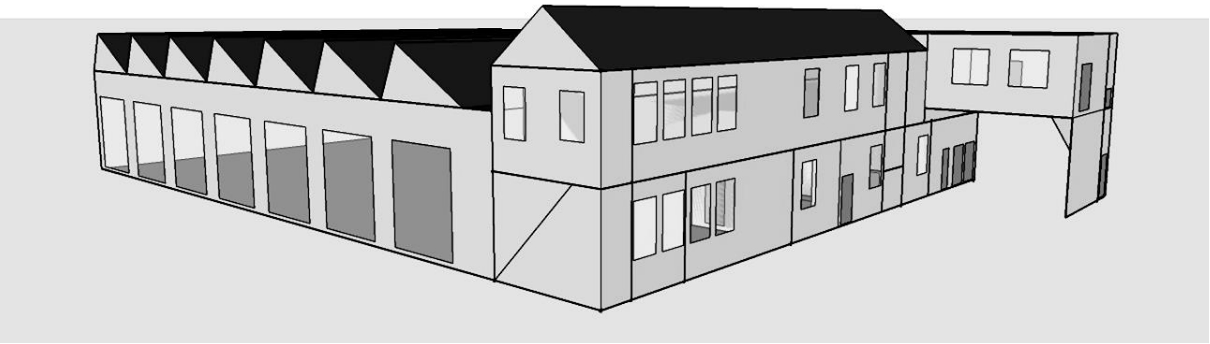

Figure 10 3D simulation output of SketchUp3D - view from northwest

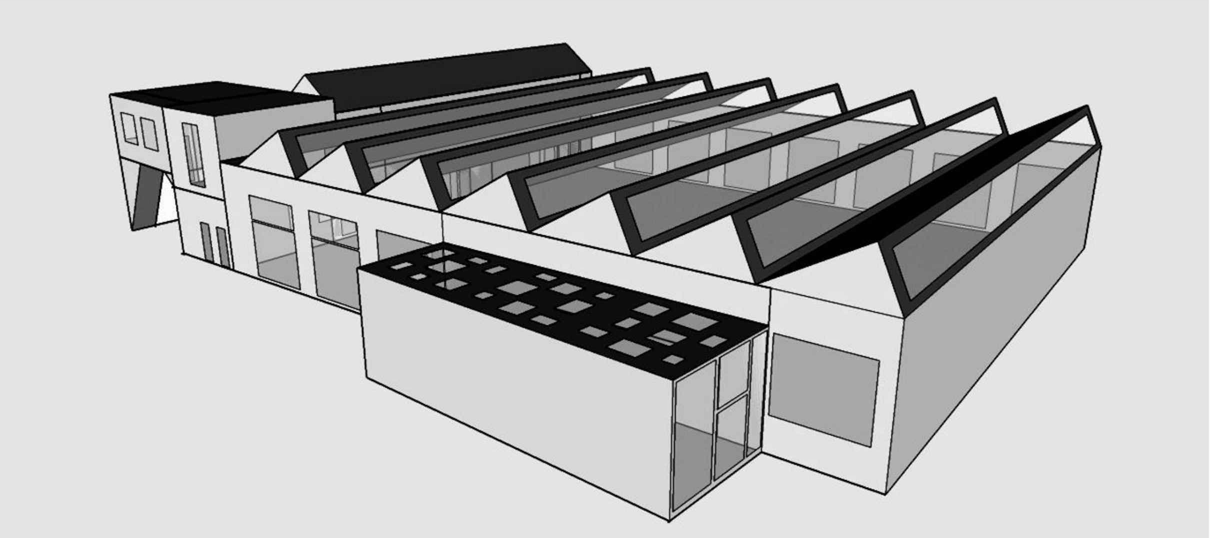

Figure 11 3D simulation output of SketchUp3D - view from the east

The thermal zones are defined according to OpenStudio guidelines (OpenStudio, 2015b). Each space was assigned to a separate zone if necessary. Figures 12, 13, and 14 show the setup of thermal zones in 2D for both stories and in 3D to give a complete overview. The main open office space is defined as one thermal zone according to the orientation and space utilization rules. Both these criteria do not allow to unite the area with other areas of the building, although they have a similar temperature profile. The closed office thermal zones in both the first and second floor on the southeastern side are united owing to the same orientation and the same use. The same scheme was applied to all other space types.

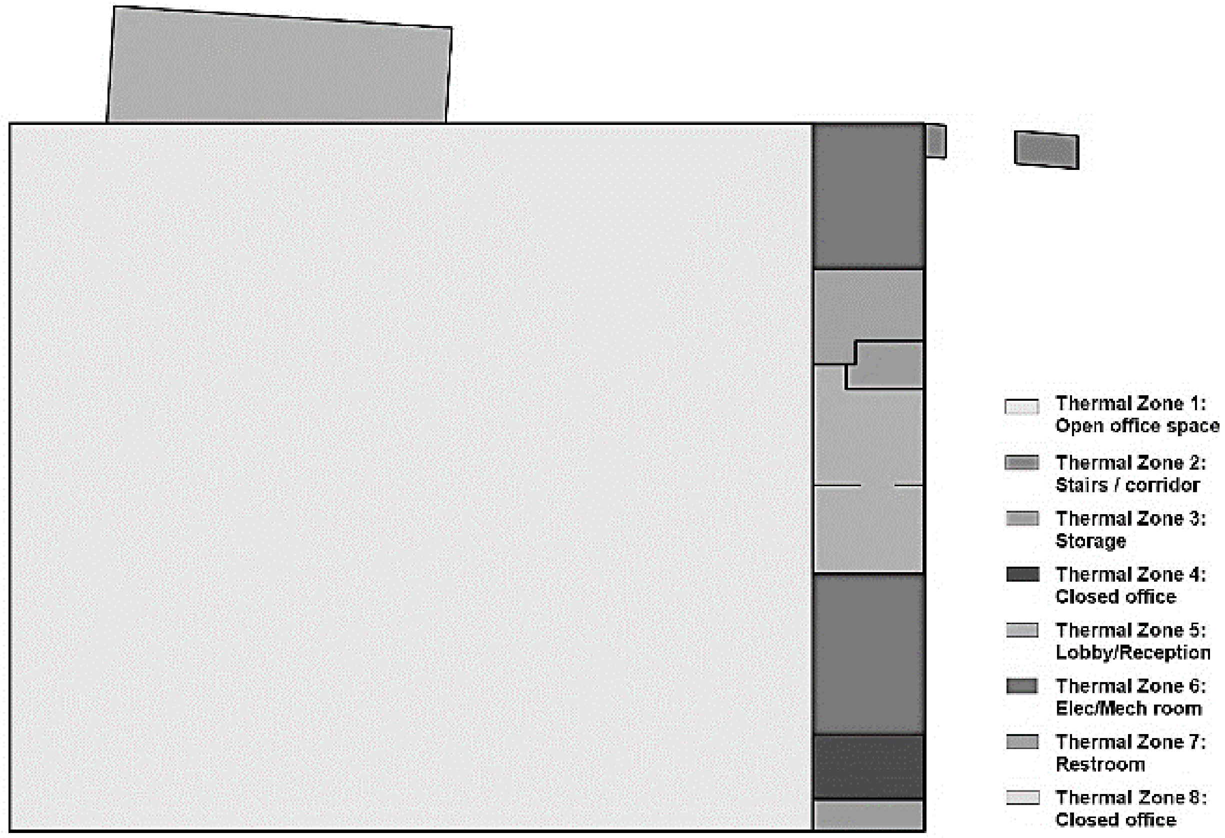

Figure 12 Thermal zones of the first floor

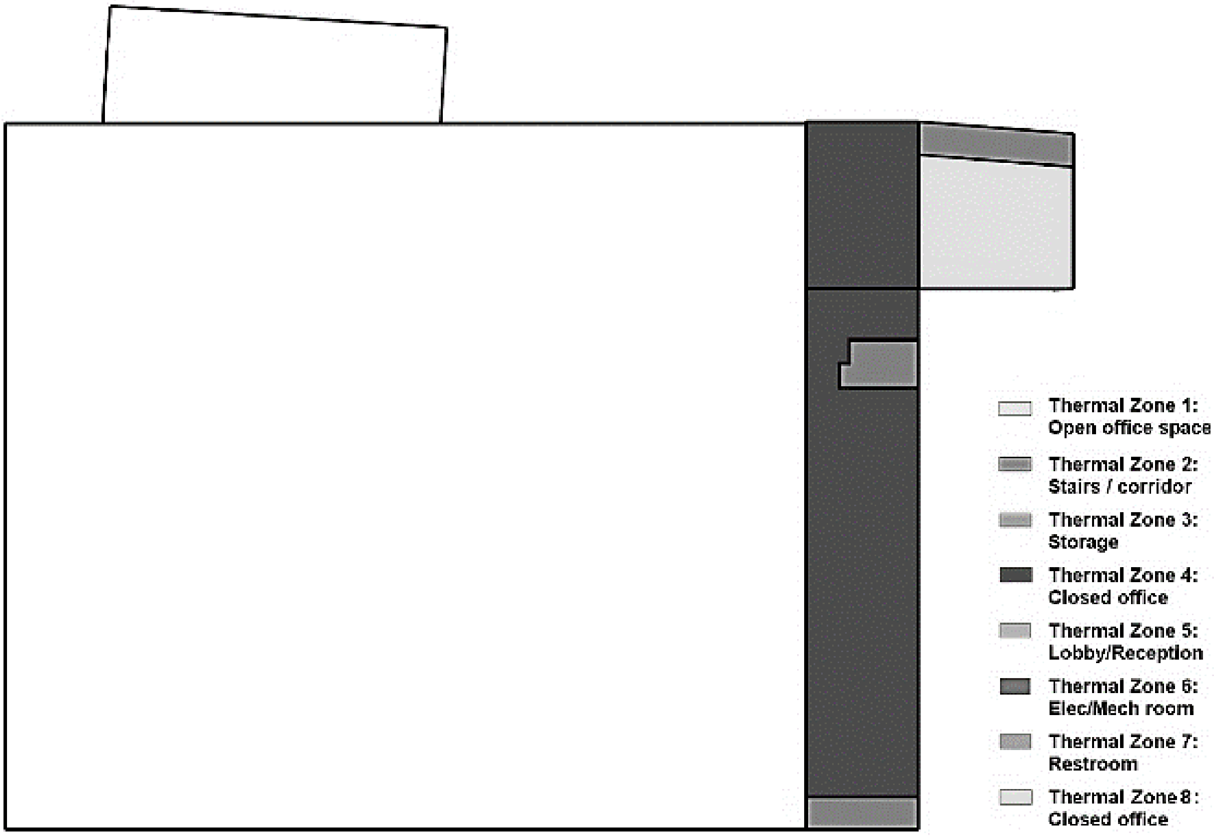

Figure 13 Thermal zones of the second floor (white areas are part of the first floor)

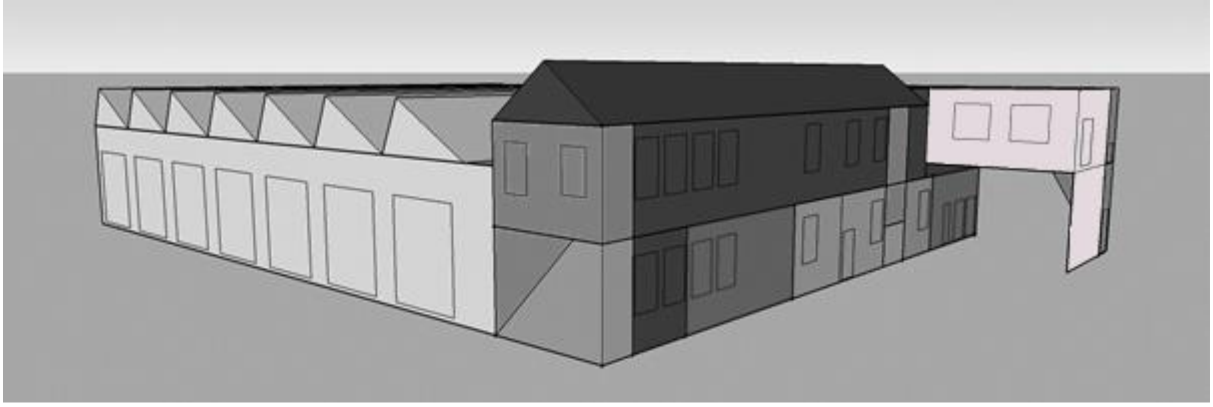

Figure 14 Thermal zones represented in SketchUp3D

4.1.2 Simulation data input

In order to make the energy simulation possible in form of energy demand and carbon emissions and to enable a comparability between different building measures, a base case approach was chosen. The initial base case simulation serves as the basis for all consecutive building envelope measures to improve the performance. Table 2 gives an overview of building envelope inputs and the technical installations in use for the simulation software OpenStudio.

Table 2 General, building envelope, and technical installation data for the base case

General data	
Total floor area	1742.32 m2
Gross wall area	1575.68 m2
Gross window wall ratio	39.98%
Ceiling height, main hall	6.10 m
Ceiling height, lower and upper floor	2.9 m
Occupation	Main hall: 1 person / 20 m^2
	Other rooms: 1 person / 10 m^2
Internal temperature conditions	Day: 22 °C – night: 16 °C
Internal heat gains per person	70 W/m^2
Clothing insulation (CLO) factors	Summer clothing: 0.7
	Winter clothing: 0.9
Electrical equipment internal heat gains	10 W/m^2
Building envelope	
Air infiltration	2 dm^3/s per m^2 (ISSO 51)
Infiltration type	Natural ventilation
Lighting internal heat gains	33 W/m^2
Exterior surface constructions	
Walls	U = 2.96 W/m^2K, building brick
Floors	U = 6.96 W/m^2K, uninsulated concrete floor
Sloping roofs and flat roofs	U = 8.93 W/m^2K, roof underlay without insulation
Sub surface constructions	
Fenestration	U_w = 5.33 W/m^2K, single pane
Doors	U = 1.72 W/m^2K, hard wood
Technical installation	
Heating / cooling system	Gas fired boiler / steam driven chiller
Output system	Hydronic radiant system
Lighting system	Fluorescent lighting with 33 W/m^2 internal heat gain
Hot water system	Not installed

The general data input is maintained throughout the energy analysis, except the internal heat gain for lighting, which changes due to the lighting systems, and the data replaced by measures or packages in the later analysis in chapter 4.2. The geometric data input is based on architectural plans of the site which can be found in appendix B (from page 65 onwards). The majority of the floor ground plan is the main hall, whose planned use is an open office space. The building geometry is shown in chapter 4.1.1. The occupation profile of the building and the internal temperature conditions are defined based on the information of the interview with Mirjam Schmull, which can also be found in appendix B (pages 63 and 64). Table 3 shows the time schedules for the technical installations and the utilization of the building. The remaining schedules and exact profiles for all schedules can be found in appendix B (pages 70 and 71).

Table 3 Time schedules for the case study

Technical installations	Monday to Friday inclusive – 06:00-20:00
Utilization of the building	Monday to Friday inclusive – 08:00-18:00 The profile has a dip during midday.

The internal heat gain per person is based on a building simulation conducted by NiemanValk (Nieman, 2016). An important factor with regards to the internal heat gain per person are clothing insulation factors. They are based on standardized factors of the *Kennisinstituut voor Installatietechnik* (ISSO) and directly influence the heat gain dependant on different types of clothing (ISSO, 2012). Winter clothes for example have a higher CLO and result in a lower heat gain. The internal heat gain for electrical equipment is based on Energy Star guidelines. The variable is set constant due to the poor plannability of electrical equipment usage because each person working in the office uses different appliances. 10 W/m^2 reflects an appropriate choice as an average value (Energy Star, 2013).

The construction dates back to a time before first building regulations were enacted for buildings in the Netherlands and the EU. As a consequence, no insulation or other energetic conservation constructions were initially in use for the entire building envelope. Consequently, the entire building envelope is without insulation. The inputs for the exterior and sub-surface constructions are based on the site visit and the interview. The air infiltration value is based on guidelines of the Dutch ISSO. As soon as a building does not fulfil the requirements of the Dutch building regulation, the value has to be set at 2 dm^3/s per m^2 (ISSO, 2012). This is due to the current poor energy performance.

The technical installations were not present anymore during the site visit. As a consequence, the base case is simulated with a conventional gas fired boiler with an efficiency of 75% based on the higher heating value (HHV) and a steam driven chiller with a COP of 1.11 (duurzaam thuis, 2016; Energy Star, 2013). Both values represent an inefficient value for the Netherlands and are therefore used to represent the technical state before the renovation. The distribution of thermal energy is done by a forced air heating system (Gemeente Utrecht, 2016b). A hot water supply is not installed and, accordingly, not simulated. The lighting is based on an inefficient fluorescent light which was installed before the renovation works started. The default ASHRAE value of OpenStudio is used for air leakage at 50 pascals throughout the result simulation so that the outcome is not compromised. A blower door test to determine the air leakage was not feasible due to the lack of time and budget.

The climate zone definition is based on ASHRAE classifications (ASHRAE, 2016). The predominant climate in the Netherlands is temperate maritime and is influenced by the North Sea and Atlantic Ocean. The summers are generally cool and the winters are moderate. Temperatures during the day reach from 17 °C to 20 °C in summer and from 2 °C to 6 °C in winter. There is little variation of the climate from region to region in the Netherlands due to the small size. The climate zone is 5C according to international climate zone definitions (EnergyPlus, 2016). This is transferred to EnergyPlus standards by application of an ASHRAE weather file (ASHRAE, 2010; EnergyPlus, 2016). Appendix B (pages 72 and 73) shows precise climatic information for Amsterdam in the Netherlands, based on IWEC (ASHRAE, 2016). Precise weather data for Utrecht is not available within the EnergyPlus database, which is why Amsterdam was chosen as an appropriate replacement (EnergyPlus, 2016). The climate differences are small because of the minor distance between the two cities.

All aforementioned parameters are incorporated in the software OpenStudio and enable the initial base case simulation.

4.2 Simulation results

This section presents the simulation results for the base case, the building envelope measures and the technical installation measures, and the measure selection. Answers are given to SQ 3, 4, and 5. The demand profile of the case study is specified and the potential energy and carbon savings of the retrofitting measures are shown.

The results of the simulation are given in primary energy to avoid a neglect of carbon emissions. The end uses of thermal and electric energy are given in final energy. A distinction is made for thermal energy given in GJ/y and electrical energy given in kWh/y. OpenStudio initially delivers an output in final energy. As a consequence, the outcomes were converted into primary energy with the help of specific conversion factors. The conversion of primary energy to final energy and vice versa is dependent on the COP for the heat pump systems, the physical energy content method for the renewable energy supply, the PEF and the energy conversion efficiencies for heating and cooling. The PEF for electricity in buildings is 2.56 for the energy mix in the Netherlands in 2011 (Molenbroek et al., 2011). The final energy for both heating and cooling is converted with the help of the energy conversion efficiencies described in chapter 4.1.2. The emission calculation is based on 56 kg CO_2/GJ for natural gas and 0.48 kg CO_2/kWh for the average electricity mix in the Netherlands (CBS StatLine, 2016; IPCC, 2014b). The reprocessing of data shows the most promising measures for each retrofitting field. Supporting data for some measure groups can be found in appendix C (page 74). The mentioned information is limited to data which is not included in the methods or results.

4.2.1 Results of the base case simulation

The total site primary energy demand for the base case is 3826.74 GJ/y for heating, cooling, and electricity. This value answers SQ 3. The demand for electricity is converted from GJ to kWh. The respective carbon emissions are 309.07 t CO_2/y. The exact values for the primary energy demand and the related final energy demand of heating, cooling, and electricity are shown in table 4 below. The emission conversion factors in combination with the primary energy conversion factor for electricity result in an almost twofold share of carbon emissions for the electricity consumption of fans, lighting, and equipment.

Table 4 Outcomes of the base case simulation for primary energy demand and carbon emissions

		Energy demand for thermal energy in GJ/y		Share of total primary energy in %	Emissions in t CO_2/y	Share of total carbon emissions in %
		Primary	Final			
Heating		2437.96	1828.47	63.71	136.53	44.17
Cooling		163.33	147.14	4.27	9.15	2.96
	Sum	2601.29	1975.61	145.68	145.68	
		Primary energy demand for electricity in kWh/y				
		Primary	Final			
Fans		70090.60	27379.14	6.59	33.64	10.89
Lighting		139477.33	54483.33	13.12	66.95	21.66
Equipment		130837.33	51108.33	12.31	62.80	20.32
	Sum	340405.27	132970.81	100.00	163.39	100.00

The figures 15 and 16 below show a breakdown of final energy consumption and carbon emissions. The left side shows the components for heating, cooling and total electricity. On the right is a distribution of the total electricity outcome divided into three sub-items. The percentage of carbon emissions for electricity is significantly higher than the corresponding final energy share. This is because of the different carbon emission factors for electricity and natural gas.

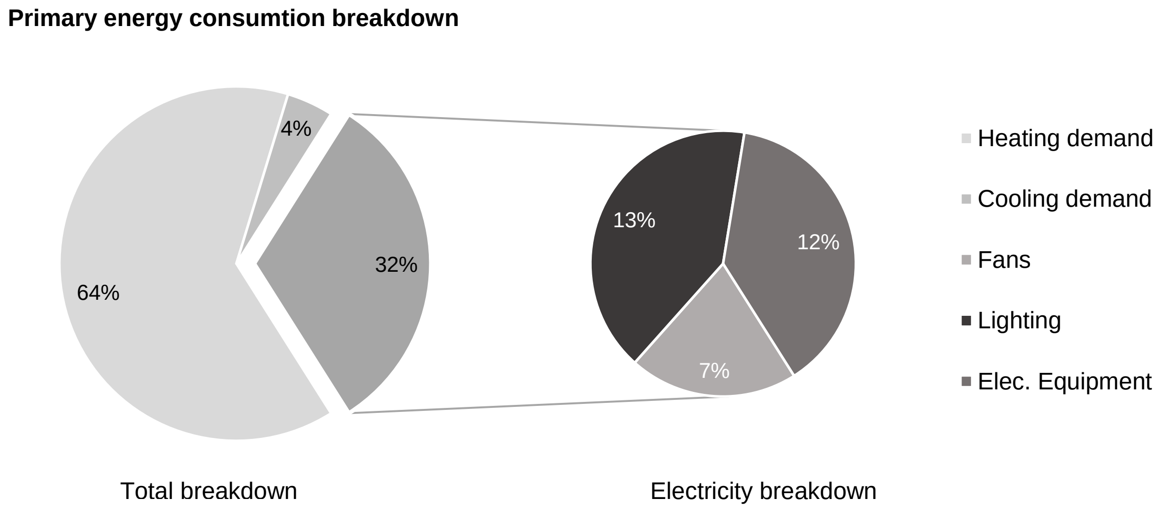

Figure 15 Base case breakdown of primary energy consumption

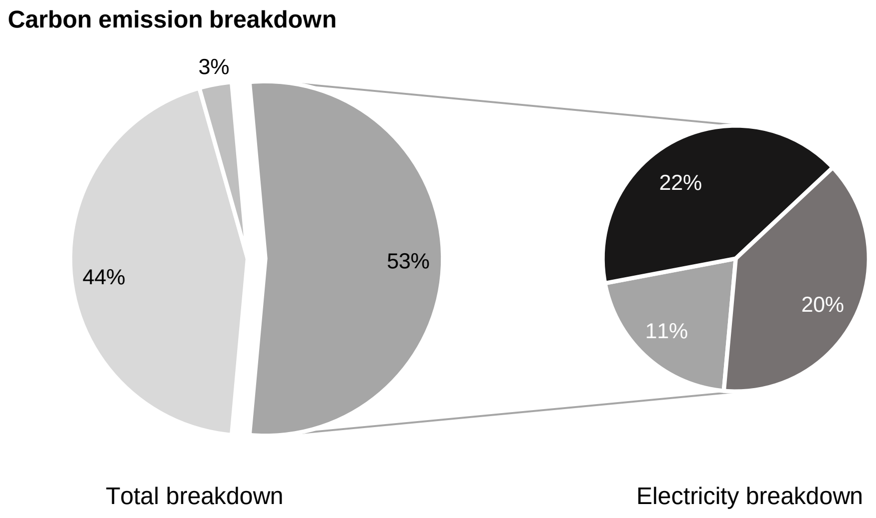

Figure 16 Base case breakdown of carbon emissions

4.2.2 Measure results

The main goal is to minimize the energy demand and the carbon emissions of the case study in the most economic manner without compromising the heritage value of the building. To achieve this, a variety of retrofitting areas and concrete measures are recommended in chapter 3.2.3. They are assessed individually in the simulation software with the base case simulation as the foundation of the simulation together with its fundamental input data. Supplementary data for fenestration, heat pump system and small scale wind power plants can be found in given in appendix C (page 74).

Overview of most promising measures

Table 5 and 6 show the most promising retrofitting measures for both energy demand reduction and energy supply based on the individual measure group analysis. The most promising measures were selected according to the magnitude of energy and carbon emission reduction. Measures with a higher reduction are preferred over other measures in the same group. However, if a measure which reaches a better energy and carbon performance shows only marginally small improvements by adding a high amount of extra insulation, the measure of choice is a thinner insulation because of the expectably better cost-effectiveness. In some groups more measures are included owing to an expected high difference in costs. The cost analysis is given later in this section for the most promising measures. The summary shows the best measures for fenestration, interior wall insulation, roof insulation, floor insulation, lighting, HVAC systems, PV, and wind power systems. The assessment is also limited to the most promising solutions with regards to a retention of the heritage value of the building as described in section 3.2.3.

Table 5 Overview of the most promising thermal and electricity demand reducing retrofitting measures for the case study compared to the base case

Measure	Total energy demand in GJ/y		Thermal final energy demand in GJ/y		Reduction of thermal final energy demand in %	Final energy of electricity in MWh/y	Reduction of final energy of electricity in %	Total carbon emissions in t CO_2/y	Reduction of carbon emissions in t CO_2/y	Reduction of t CO_2/y in %
	Primary	Final	Heating	Cooling						
Base case	3827	2454	1828	147	/	133	/	309.07	/	/
Triple glazing, Krypton, no sun protection	3594	2285	1679.68	135	8.14%	130	1.68%	294.48	14.59	4.72%
Wall insulation 0.05mm; U=0.4	3746	2398	1764.43	157	2.70%	132	0.56%	304.04	5.03	1.63%
Roof insulation 0.05m; U=0.4	3255	2039	1463.08	117	20.01%	127	4.12%	273.19	35.87	11.61%
Floor insulation 0.05m; U=0.4	3625	2323	1618.93	232	6.31%	131	1.30%	296.58	12.49	4.04%
LED TL T8 27W	3492	2343	1874.75	142	-2.10%	90	31.90%	260.11	48.96	15.84%
TL5 HE 14W	3553	2367	1874.75	142	-1.89%	97	26.91%	268.26	40.80	13.20%

Table 6 Overview of the most promising thermal energy and electricity supply measures for the case study compared to the base case

Measure	Total remaining energy demand after own supply in GJ/y		Thermal final energy supply of the heat pumps [2] in GJ/y		Reduction of thermal final energy compared to base in %	Final energy demand of electricity for the heat pumps in MWh/y	Reduction of final energy of electricity compared to base case in %	Total carbon emissions in t CO_2/y	Reduction of total carbon emissions in t CO_2/y	Reduction of t CO_2/y in %
	Primary	Final	Heating	Cooling						
Groundwater heat pump	1658	904	1579	490	86.38%	117	-88.90	221.11	87.96	28.46%
Ambient air heat pump	1820	1066	1579	490	86.38%	188	-108.39	242.74	66.32	21.46%

Measure	Total remaining energy demand after own supply in GJ/y		Thermal final energy supply in GJ/y	Reduction of thermal final energy compared to base in %	Final energy supply of electricity in MWh/y	Reduction of final energy of electricity compared to base case in %	Total carbon emissions in t CO_2/y	Reduction of carbon emissions in t CO_2/y	Reduction of t CO_2/y in %
	Primary	Final							
Solar PV (max. based on roof area)	3012	2136	0	0.00%	88	132.64%	89.80	84.66	48.53%
Solar PV (100% elec. coverage)	2032	1754	0	0.00%	195	292.58%	-12.28	186.74	107.04%
Vertical turbine - Tulipo	3789	2440	0	0.00%	4	5.90%	299.35	9.72	3.14%

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[2] System parameters: Groundwater heat pump (200kW heating, COP=4.5; 130kW cooling, COP=7); Ambient air heat pump (200kW heating, COP=4; 130kW cooling, COP=2.6)

The figure below shows the previously shown selection of measures and gives an overview for carbon emission reduction compared to the base case.

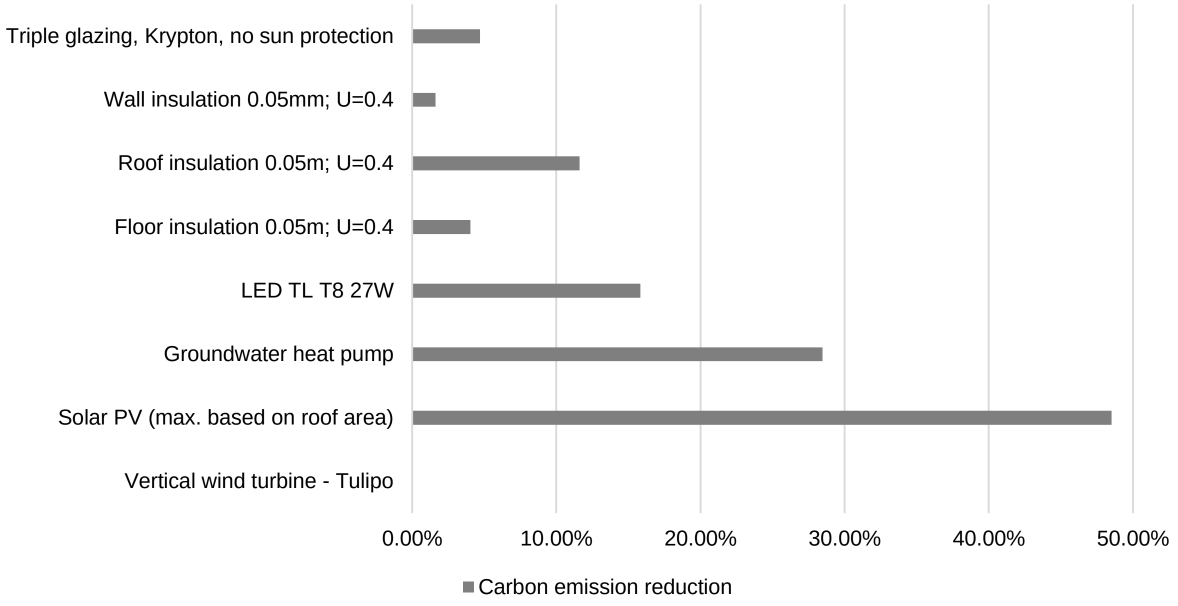

Figure 17 Carbon mission reduction in % compared to the base case for the most promising measures

The following section describes the results in relation to the initial construction of the base case for each measure group.

Fenestration results

The present state of the assessed case study building has a single-pane fenestration of 3 mm with a steel frame. The whole construction is outdated and energetically inefficient. A replacement is standing to reason, so a variety of measures are chosen. Included are double glazing and triple glazing. Both types have different gap fillers. Double glazing is assessed with an air (L) and argon (AR) filling. Triple glazing includes argon and krypton (KR) fillings. Krypton has a better thermal performance than argon, but it is still economically feasible. Finally, a krypton triple glazing with sun protection (triple zero) is tested. All values are based on fenestration material of SANCO (SANCO, 2016). Other producers have comparable product characteristics. Upcoming technologies like aerogel and vacuum glazing are excluded due to their cost, which is so far not competitive (Bjørn Petter Jelle et al., 2012). The application of foil or glass coating or adding extra glass to the window is excluded because of the low energetic performance (Bjørn Petter Jelle et al., 2012).

Although the U_w-value for fenestration can be improved by approximately 75% in the worst profile with 4-16L-4, the total primary energy demand to maintain the defined internal climatic conditions can be only reduced by 5.05% or 193.29 GJ/y. The CO_2 emissions can be reduced by 3.93% or 12.14 t CO_2/y. The energetic best profile triple krypton, which is also the most promising measure, reduces the primary energy demand by 6.07% or 211.66 GJ/y primary energy and the CO_2 emissions by 4.72% or 14.59 t CO_2/y. The simulation with sun protective glazing results in worse outcomes than the triple krypton setup. The cooling in summer can be reduced, but the heating demand in the winter rises by roughly 9 GJ/y compared to the triple krypton case. The emission performance is almost alike in all cases.

Interior wall insulation results

Brick walls with a thickness of 27 mm are common for exterior wall surface constructions of historical buildings in the Netherlands and are also the main construction of the case study. Usually, no insulation is installed in historical buildings, which is also the situation for the present case. The bricks themselves have a high age of more than 100 years and do not have to achieve specific U-values as they are regulated in the present. However, the influence of the brick layer on the overall insulation performance is rather small. As a consequence, it is necessary to add one or more insulation layers to the construction to enhance the insulation values. This can be done by adding an extension to the brick walls in the form of an interior retention wall to improve the insulation values and by maintaining the exterior heritage value. The same approach is necessary for floor and roof insulation.

The profile with 50 mm insulation and 27 mm brick wall as the outside layer results in a U-value improvement of approximately 88%, based on 0.35 W/m^{2}K for the retention wall construction with 50 mm insulation and 2.96 W/m^{2}K for the bare brick wall. Nevertheless, the primary energy savings account for 2.10% or 73.54 GJ/y. The option with the lowest U-value reaches 1.65% primary energy reduction and the highest U-value with a construction thickness of 120 mm reaches 2.36%. The emission performance reaches from a 1.28% (3.96 t CO_2/y) reduction for the thinnest insulation option to 1.83% (5.66 t CO_2/y) for the thickest option. The overall best performing measure with regards to the relation between insulation thickness and performance is the insulation with 50 mm. Constructions with thicker insulation amount to only marginally small improvements with much higher investment costs.

Roof insulation results

The new roof construction setup with a 50 mm thick insulation, a roofing felt and a hardboard plate reaches a U-value of approximately 0.40 W/m^{2}K. This value reveals an improvement of ~95% compared to a construction without insulation (U-value = 9.01 W/m^{2}K). The primary energy savings for this option account for 520 GJ/y or a primary energy consumption reduction of 14.92%. The option with the lowest U-value reaches 12.63% primary energy reduction and the highest U-value with a construction thickness of 120mm reaches 15.99%. The emission performance reaches from 9.83% (30.37 t CO_2/y) reduction for the thinnest insulation option to 12.44% (38.46t CO_2/y) for the thickest option. The measure of choice here is the insulation with 50mm thickness. It shows the best outcomes in relation to performance and insulation thickness.

Floor insulation results

The results of the floor energy simulation are lower than the roof insulation outcomes. Nevertheless, the worst option assessed here achieves an energy reduction of 5.12% compared to the base case. Here, the original concrete floor is extended with insulations constructions of different thicknesses for each measure. The best option is slightly better with 5.60%. The reduction of carbon emissions follows a similar trend. The emissions can be reduced by 3.93% (12.16 t CO_2/y) with the worst option and by 4.31% with the best option (13.31 t CO_2/y). The U-value increase compared to base case is similar to the roof and wall insulation. The insulation with a U-value of 0.42 W/m^{2}K (50 mm) shows the most promising outcome.

Lighting

The new lighting systems replace the old fluorescent installations. Next to LEDs, which are the preference of *Except*, a highly efficient fluorescent TL5 light is assessed. All lighting systems are based on the same socket. The outcomes for the LED and the fluorescent TL5 light lamps are all in a similar range. The best system (LED) achieves a reduction for final electricity demand of 31.90% and a carbon emission reduction of 15.69%.

HVAC systems

This sections shows a variety of HVAC systems to provide the heating and cooling demand of the case study building. The assessment is limited to the technologies identified in section 3.2.3. The heating and cooling simulation is based on operating hours (retrieved from the base case): 2193 h/y for heating and 1046 h/y for cooling. On-site fossil-based technologies are excluded here due to the motivation of the client to reach a self-sufficient sustainable energy supply by exclusion of fossil resources. The choice of the heat pump systems is based on the experience of an engineer office (Nieman, 2016). An overview of the applied heat pump installations can be found in table 7.

The outcomes are directly related to the COPs of each system. The installation with the highest performance indicator has the best outcomes for primary energy and carbon emission reduction. The other systems are in a similar range. The ambient air heat pump performs about 10% less for primary energy reduction and approximately 7% less for carbon emission reduction. The best system, namely the ground water heat pump, is able to reduce the primary energy demand by 56.67% and the carbon emissions by 28.46%. The almost twofold percentage difference of both assessment criteria is because of the higher electricity demand of the heat pump measures compared to the base case. The carbon emission factor for electricity per kWh is much than the factor for gas. The primary energy demand of the heat pump systems is determined through an on-site or close-to-site RES energy supply. Off-site energy provision would lead to a non-economic feasibility because of the primary energy factor of 2.56. Therefore, the PEF is set to 1 (based on an on-site electricity supply with renewables). The heat pump system of choice is the groundwater system because of the outstanding energetic and emission results. Also, this type of installation shows the best potential to deliver a stable energy supply. Groundwater has a more consistent temperature profile than air and is therefore preferable.

Photovoltaics

After altering the technical installations, the next step is to improve the renewable energy supply of the building. The technologies under consideration are established state-of-the-art systems as an alternative to burning fossil fuels by following the guidelines of the *Trias energetica*. The results for both PV a wind energy are based on the physical energy content method. The outcome for solar PV is higher in this case with 100% electrical coverage thanks to extra supply which can be achieved with an extra PV surface besides the own roof surface of the case study. The case based on the maximum available roof surface area is limited to a roof surface of 144.56 m^2 of the seven sheds and an additional 69.11 m^2 of the roof at the southwest of the building. Each PV panel has a measurement of 1.7 m x 1.53 m. The most optimal distribution on the roof surfaces, which also considers shading of other sheds, results in an amount of 415 PV panels for the case study building. An additional 401 PV-panels are necessary to achieve a coverage of the total electricity demand of 194,52 MWh/y. The rated power of one system is 250 Watt peak (Wp). The solar gain in the Netherlands is 850 kWh/y/Wp, based on a panel orientation of southwest (Agentschap NL, 2010a). The results for this case exceed a 100% reduction owing to the consideration of extra electricity demand due to the heat pump system, which are neglected here to show the outcome for the PV system alone. A combination of both systems is shown later in the packaged measure results in chapter 4.7. The high amount is carbon emission conservation is due to the PEF and the physical energy content method, which leads to an efficiency of 100%.

Wind energy systems results

Both vertical and horizontal solutions are included. A variety of small scale wind turbines are available. Their usual lifetime is 20 years. However, only a part of the turbines shown below are active for several years (Agentschap NL, 2010b). The yield estimation for the Netherlands is approximately 200 kWh/m^2 for small wind turbines (Agentschap NL, 2010b).

The horizontal wind power plant Tulipo yields the best outcomes for carbon emission and primary energy reduction. One turbine is able to lower the primary energy demand by 0.98% and the carbon emissions by 3.14%. This suggests an installation of additional systems to cover more of the energy demand and to mitigate further carbon emissions. Wind energy system results are for one system only. Higher savings can be achieved by installing more systems. One system alone is able to save 10.01 MWh/y primary energy if the RES primary energy factor of 1 is compared to an off-site production with a factor of 2.56. About 34 Tulipo wind turbines would be required to cover the total primary energy demand of the base case for the entire case study building.

Results for the economic investigation

In this part of the thesis, the focus lies on the economic performance of each measure presented in the previous sub-chapter by an investigation of the SPB and the LCCC. The first step is to utilize investment cost information for each of the measures by consultation of relevant producers or scientific literature information. The next step, after a successful analysis, is the construction of a MACC to visualize the gathered information. This step completes the answer to SQ 4.

The investment and operational costs can be seen in the table below for each measure group. The investment costs were collected from appropriate firms in the Netherlands and include both the costs for acquisition and installation. The operational costs for electricity and gas, which are part of the SPB and LCCC, are based on statistical information of Eurostat. One kWh of electricity costs € 0.0712 and one kWh natural gas costs € 0.0638. Both values are for the Netherlands and exclude VAT and other recoverable taxes and levies (business rate) (Eurostat, 2016). Investment costs are also excluding VAT to make the calculation coherent. All values in GJ thermal energy are converted to kWh to enable an accessible comparability. The lifetime of each technology is also of importance, which is, next to the discount rate, a variable for every measure to determine the annuity factor for each measure. The discount rate for the analysis is set at 15% owing to the use of a private perspective on the investment (Blok, 2007). The later sensitivity analysis shows the differences if other discount rates are chosen. The table gives an overview of the lifetime, costs per unit, total investment costs, SPB, and LCCC for each technology.

Table 7 Investment & operational costs, lifetime, SPB and LCCC for listed measure under 4.4.3

	Measure	Investment & operational costs (€) (excl. BTW) [3]	Total Investment costs in € (excl. BTW)	Lifetime in years	SPB	LCCC; 15%
		Unit = m^2				
#1	Triple glazing, KR, no sun protection	338.47	219589	50	53.71	1979.37
#2	Interior 0.05 mm; U = 0.4	33.94	24964	50	17.64	464.01
#3	Roof 0.05 m; U = 0.4	33.94	74911	50	7.45	-62.79
#4	Floor 0.05 m; U = 0.4	40.00	59274	50	16.74	429.09
		per socket				
#5	LED TL T8 27 W	33.00	14380	51.17	2.65	-66.73
#6	TL5 HE 14 W	2.65	4917	24.56	1.11	-89.65
		per unit				
#7	Groundwater heat pump	170000	170000	25	6.03	-21.51
#8	Ambient air heat pump	60000	60000	25	2.81	-182.14
		Unit = Wp				
#9	Solar PV (max. based on roof area)	1.20	124500	20	9.32	30.12
#10	Solar PV (100% elec. coverage)	1.20	274619	20		30.12
		per unit				
#11	Vertical turbine - Tulipo	19000	19000	20	31.99	648.81

The outcomes reveal a big gap between some measures with regards to their cost-effectiveness. The wind energy system, the fenestration, the interior wall insulation, and the floor insulation show high SPBs and, because of that, are not economically viable for most investors. The same is true for the outcomes of the LCCCs. On the other hand, some measures perform well. The roof insulation, the lighting systems, and the ambient air heat pump convince with a low SPB and a negative LCCC. The PV systems and the ground water heat pump show competitive outcomes. The range of SPB is interesting for investors. The LCCC proves the validity with regards to the cost-effectiveness. Of special notice for the outcomes of the heat pump systems is the neglecting of operation-related electricity costs. They source their electricity demand from the site or close to the site at no costs.

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[3] Investment costs were retrieved from: Agentschap NL, JOSKO GmbH, Lampdirect, Hornbach BV, Energieheld GmbH; Nieman – RAADGEVENDE INGENIEURS, milieucentraal

The next step is to visualize the best performing results in a MACC to make them more accessible. The curve below shows the relation of all measures assessed above related to the LCCC. The measures below the x axis perform the best and have the potential to pay themselves back over the lifetime of the measure. Other measures above the x-axis require an unrecoverable investment to mitigate carbon emissions. The heat pump system and the lighting system perform well. The remaining measures are partially connected to very high costs for a low amount of carbon mitigation. Measures with a relatively low positive cost are PV and the roof insulation. The measure numbers can be retrieved from table 7. Only measures which can be implemented consecutively are shown. A combined simulation in OpenStudio is part of the following chapter.

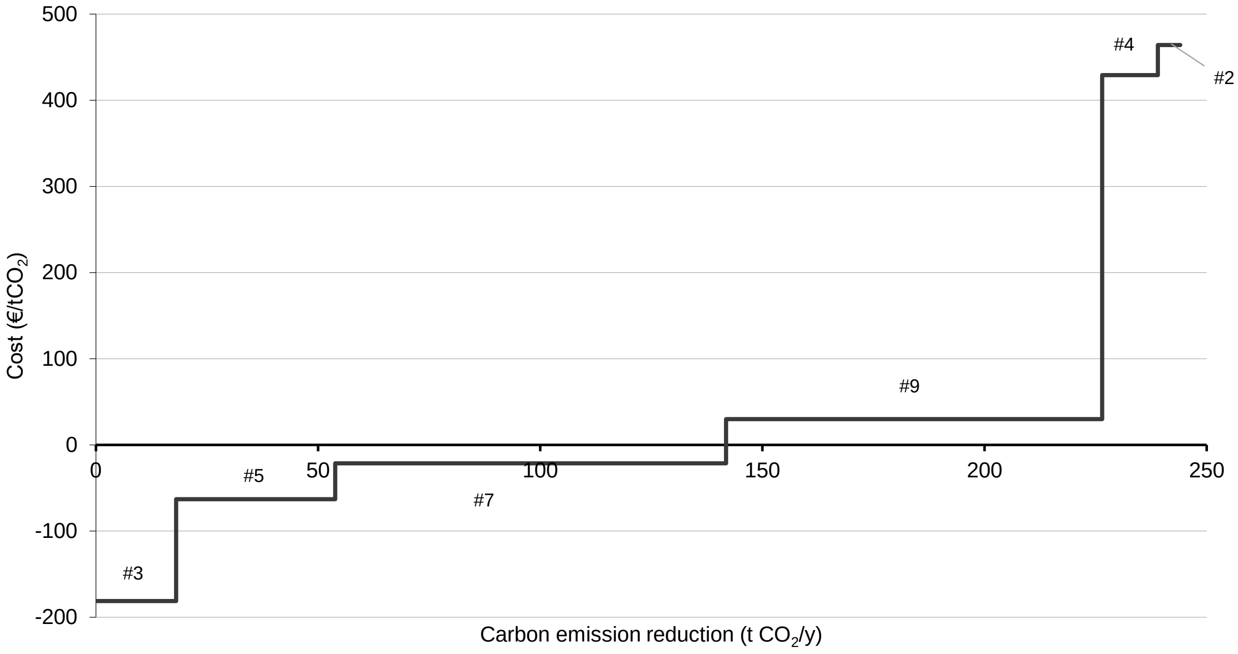

Figure 18 MACC of a consecutive combination of the most promising measures with a discount rate of 15%

4.2.3 Packaged measure results

This part of the thesis assesses if the defined targets of SQ 5 can be reached. Also, packages to show the energy simulation for the Dutch building legislation are included, and if the benchmark of a net-zero energy building (NZEB) or a zero energy building (ZEB) can be accomplished (BRIS, 2016). A MACC is incorporated for the best performing package to show the carbon mitigation potential for each consecutively implemented measure of the package. The following technology packages are assessed in the simulation software with regards to their energy performance, carbon emission, and economic performance. They are based on the outcomes of the previous section with regards to their energy, carbon emission and cost output. The packages under consideration are:

➢ **Package 1**	Best demand reduction (envelope)
➢ **Package 2**	*Bouwbesluit 2015* (envelope)
➢ **Package 3**	Most cost-effective
➢ **Package 4.1**	Best demand, HVAC
➢ **Package 4.2**	Best demand, HVAC and RES measures (extra PV) (ZEB)
➢ **Package 5**	Best demand, HVAC and RES measures (without extra PV)
➢ **Package 6**	Most cost-effective, demand, HVAC and RES measures
➢ **Package 7.1**	Best demand reduction and heritage value
➢ **Package 7.2**	Best demand reduction, heritage value, HVAC and RES
➢ **Package 8**	Recommendation

The assembly of measures is based on the previous outcomes where individual measures are simulated separately in section 4.4.2. The first package utilizes all building envelope measures which prove to be the best options for energy and carbon emission reduction. It consists of floor, roof, and wall insulation. Also, the best lighting option is included. The Dutch building regulation (*Bouwbesluit*) package contains measures to fulfil the legal minimum thermal requirements for retrofitted buildings. These are: R = 2.5 m^{2}K/W for floor insulation, R = 1.3 m^{2}K/W for wall insulation, and R = 2.0 m^{2}K/W for floor insulation (NEN, 2012). Package 3 does not fulfil the Dutch building regulations. It uses measures which have too low R-values, but the most cost effective performance. Package 4.1 focusses on the HVAC system. It is based on the best demand reduction energy simulation and the heat pump system with the best performance with regards to energetic and carbon emission (groundwater heat pump).

The subsequent step includes an RES energy supply, which can be provided by own resources. In this case a theoretical extra roof area or ground surface in the surrounding area of the case study is utilized to show if the benchmark status of a ZEB can be reached. A ZEB is typically defined as a building which can meet all its energy requirements through cost-efficient, locally available or from the own site, non-polluting RES. The building can acquire the status of an NZEB if all energy requirements are sourced on-site (Torcellini et al., 2006). Package 5 limits the RES supply to own space resources by utilizing only the own roof of the building and no extra space next to the site or from other buildings’ roofs. The next package focusses on the most cost effective measures for all measure groups. Here, the RES supply is also based on the own resource capacity of the case study. Also, a combined heritage value assessment package (7.1), based on the assessment framework of the literature review, is included. This assessment takes into account the heritage value conservation performance of each measure used in the package and weighs them against each other to a total heritage value impact. Package 7.2 reveals the best outcomes in relation to the heritage value of the building in consideration of best demand reduction, HVAC, and RES measures. Package 8 is the recommendation.

Overview of package results

This section gives an overview of all retrofitting packages presented above. It follows the same methodology as the measure results under 4.2.2. Package 1 reveals the best combination of measures for both most optimal energy efficiency and carbon emission reduction (limited to the building envelope). The second package relates to the Dutch building regulation and package 3 shows the most cost-effective measure combination. The economics of all packages will be further elaborated in section 4.3.2. The best package purely related to optimal energy efficiency and carbon emission reduction is package 4.2, except for the fact that this package needs extra land resources for PV installation besides the own roof surface of the case study. The package is able to cover the entire energy demand itself and has the capability to lower the carbon emissions by 100%. If the energy provision could be achieved with own space, the benchmark of a NZEB would be accomplished (Torcellini et al., 2006). In this particular case, the building can only reach the status ZEB due to measures next to the actual building site. The best packages with regards to the heritage value are the packages 6 and 7.2. The score here is 2 out of 5 for both cases, where 5 is the worst and 1 the best. Package 5 has the same setup as the energetic most optimal package 4.2. The difference here is an on-site PV installation, which is out of sight and therefore scores higher for the heritage value rating. Package 7.2 shows the best combined outcomes for primary energy reduction and carbon emission reduction. The recommendation builds up on package 7.2 by implementing the best available measures. Here, floor and wall insulation are excluded due to their poor energetic and heritage value performance. However, this package does not fulfil the regulations for the minimum U-values of the Dutch building regulation (BRIS, 2016). As a consequence, a permit of the Dutch Cultural Heritage Agency is necessary to not implement the obligated retrofits (CHA, 2016). The result would be a retrofit with a very good combination of energy reduction, carbon mitigation, and conservation of heritage value. The outcomes below in table 8 give the answer to the research question and the related sub-questions.

Table 8 Energy simulation results for the measure packages

Measure package	Total remaining energy demand after own supply in GJ/y		Thermal final energy demand in GJ/y		Reduction of thermal final energy demand in %	Own final thermal energy supply in GJ/y [4]		Total final energy demand of electricity in MWh/y	Own RES electricity supply in MWh/y	Reduction of final energy of electricity in %	Total carbon emissions in t CO_2/y	Reduction of carbon emissions in t CO_2/y	Reduction of t CO_2/y in %	Impact on heritage value (white (1) = best; black (5) = worst)
	Primary	Final	Heating	Cooling										
Base case	3827	2454	1828	147	/	/	/	133	/	/	309.07	/	/	/
Package 1 Triple glazing KR, floor, roof, and wall insulation with 0.12 m, LED TL T8 27 W	2110	1362	875	207	45.22%	/	/	78	/	41.64%	173.44	135.62	43.88%	▒▓
Package 2 Wall = 0.02 m, roof = 0.04 m, floor = 0.05 m	2913	1813	1133	232	30.92%	/	/	125	/	6.37%	251.87	57.20	18.51%	▒
Package 3 Roof = 0.04 m, floor = 0.05 m, LED TL T8 27 W	2679	1770	1269	201	25.54%	/	/	83	/	37.59%	209.18	99.89	32.32%	░▒
Package 4.1 Triple glazing KR, floor, roof, and wall insulation with 0.12 m, LED TL T8 27 W, ground-water heat pump	1793	700	875	207	45.22%	1579	490	195	/	-46.29%	239.03	70.04	22.66%	▒
Package 4.2 Triple glazing KR, floor, roof, and wall insulation with 0.12 m, LED T8 27 W, Groundwater heat pump, extra PV	0	0	875	207	45.22%	1579	490	195	195	100.00%	0.00	309.07	100.00%	▒▓

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[4] System parameters: Groundwater heat pump (200kW heating, COP=4.5; 130kW cooling, COP=7); Ambient air heat pump (200kW heating, COP=4; 130kW cooling, COP=2.6)

Measure package	Total remaining energy demand after own supply in GJ/y		Thermal final energy demand in GJ/y		Reduction of thermal final energy in %	Own final thermal energy supply in GJ/y [5]		Total final energy of electricity in MWh/y	Own RES electricity supply in MWh/y	Reduction of final energy of electricity in %	Total primary carbon emissions in t CO_2/y	Reduction of primary carbon emissions in t CO_2/y	Reduction of t CO_2/y in %	Impact on heritage value (white (1) = best; black (5) = worst)
	Primary	Final	Heating	Cooling										
Package 5 Triple glazing KR, floor, roof, and wall insulation with 0.12 m, LED TL T8 27 W, groundwater heat pump, PV	980	381	875	207	45.22%	1579	490	106	88	20.03%	130.66	178.40	57.72%	▓
Package 6 Roof = 0.04 m, floor = 0.05 m, LED TL T8 27 W, ambient air heat pump, PV	1395	545	1269	202	25.54%	1579	490	151	88	-13.87%	186.05	123.01	39.80%	▓
Package 7.1 Wall = 0.02 m, roof = 0.05 m, floor = 0.05 m, LED TL T8 27 W	2573	1696	1182	219	29.09%	/	/	82	/	38.32%	202.52	106.54	34.47%	░▓
Package 7.2 Wall = 0.02 m, roof = 0.05 m; floor = 0.05 m; LED TL T8 27 W; groundwater heat pump, PV	980	383	1182	219	29.09%	1579	490	106	88	20.03%	130.66	178.40	57.72%	░
Package 8 Roof = 0.05 m, LED TL T8 27 W, groundwater heat pump, PV	785	307	1521	112	17.37%	1579	490	113	88	14.30%	118.52	190.55	61.65%	□░

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[5] System parameters: Groundwater heat pump (200kW heating, COP=4.5; 130kW cooling, COP=7); Ambient air heat pump (200kW heating, COP=4; 130kW cooling, COP=2.6)

Figure 19 shows the total primary carbon emissions for each package. The base case is included to make a comparison easier. Package 4.2 performs the best thanks to the extra PV installations next to the own roof surface. It is able to achieve a positive carbon balance. However, this package has a much greater impact on the heritage value of the building compared to well-performing packages like package 7.2 or the recommendation, package 8. The recommendation package is able to reduce the total primary carbon emissions by 61.65% compared to the base case.

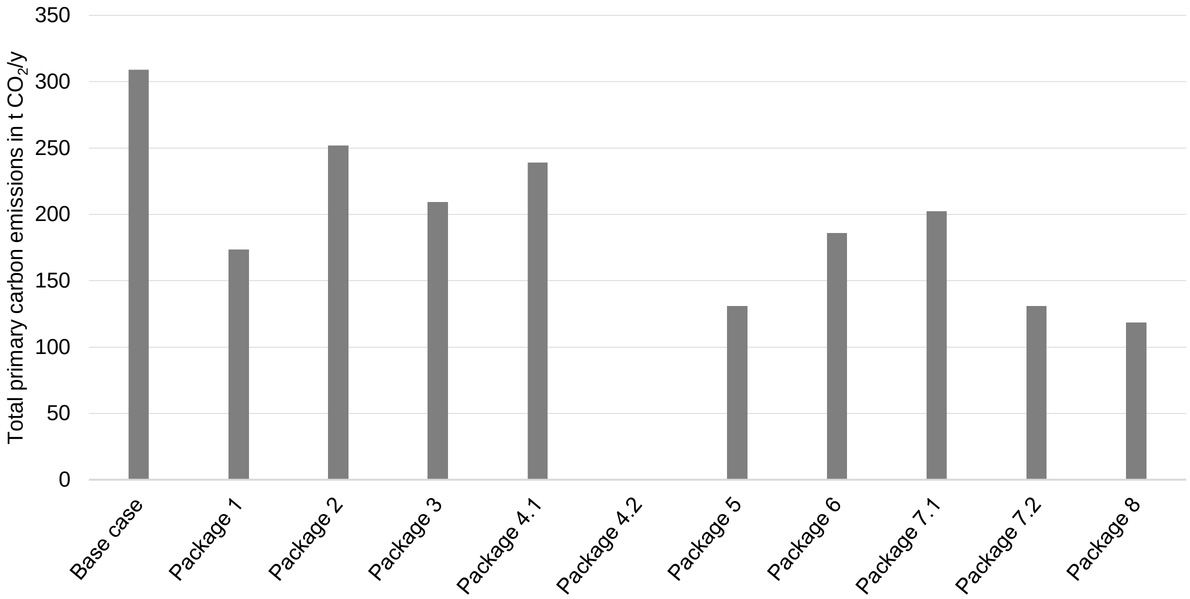

Figure 19 Total primary carbon emissions for each package and the base case

<u>Results for the economic analysis</u>

This section presents the results of the economic analysis of the packages in table 8. The procedure is in line with the previous measure analysis in chapters 4.4.2 and 4.4.4. Table 9 shows the economic outcomes for each package. The individual investment and operational costs, lifetimes, annuity factors, and amount of conserved carbon for each measure are basis of the calculation. They are then combined to a comprehensive outcome in form of the packages.

Table 9 Investment & operational costs, lifetime, SPB, LCCC in €/tCO$_2$ with a discount rate of 15%

Measure package	Investment & operational costs (€)	SPB	LCCC; 15%
Package 1	393480	13.21	216.04
Package 2.1	130980	8.14	62.48
Package 3	123294	6.24	-12.38
Package 4.1	563480	15.32	693.91
Package 4.2	838100	12.65	203.85
Package 5	687980	13.72	309.02
Package 6	307794	7.11	35.57
Package 7.1	147671	6.83	5.15
Package 7.2	442171	7.84	66.87
Package 8	360831	7.37	37.61

The economic package 3 performs the best for investment costs, SPB, and LCCC. However, the performance in the sections before – for energy reduction and carbon mitigation – are not as good as for the other packages. Packages which show a comparable performance in the economic assessment are the following: package 7.1, package 7.2, package 2, and package 8. The other options reveal very high discounted costs. The worst option is package 4.1 with € 693.91 per tCO_2. The remaining packages perform better, but they still come at high net costs. Figure 20 gives an overview of all packages and their LCCCs. Package 8 is within the budget for the retrofitting project (€ 300000 for technical installations and € 100000 for extra insulation).

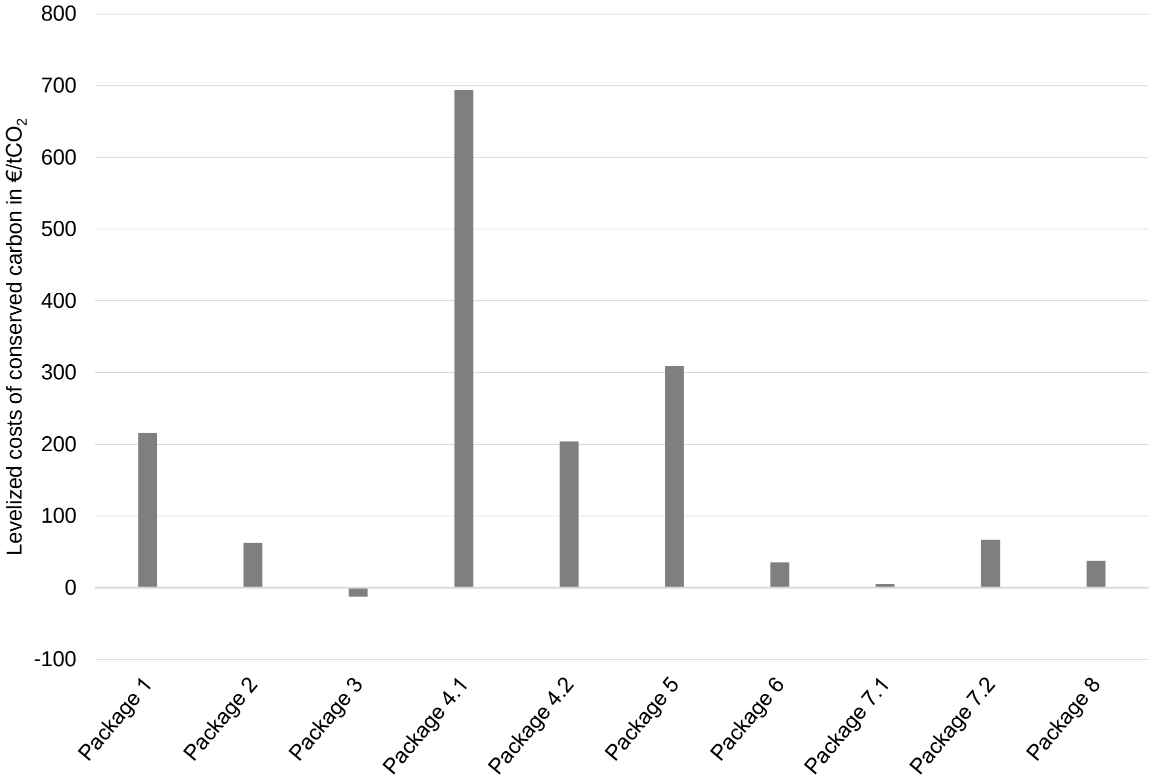

Figure 20 Levelized costs of conserved carbon for all packages in €/tCO_2

The following figure shows the MACC for the best performing package number 8 as described above. The implementation order is: #1 – LED TL T8; #2 – roof insulation 50 mm; #3 – groundwater heat pump; #4 – PV, own roof surface. The order is based on the outcomes of the individual measure results in section 4.2.2 and on the methodology of the *Trias Energetica*. All measures are simulated consecutively to avoid a double counting of energy reduction and carbon conservation. All measures are below the x-axis and therefore have the potential to pay themselves back over the lifetime of the measure.

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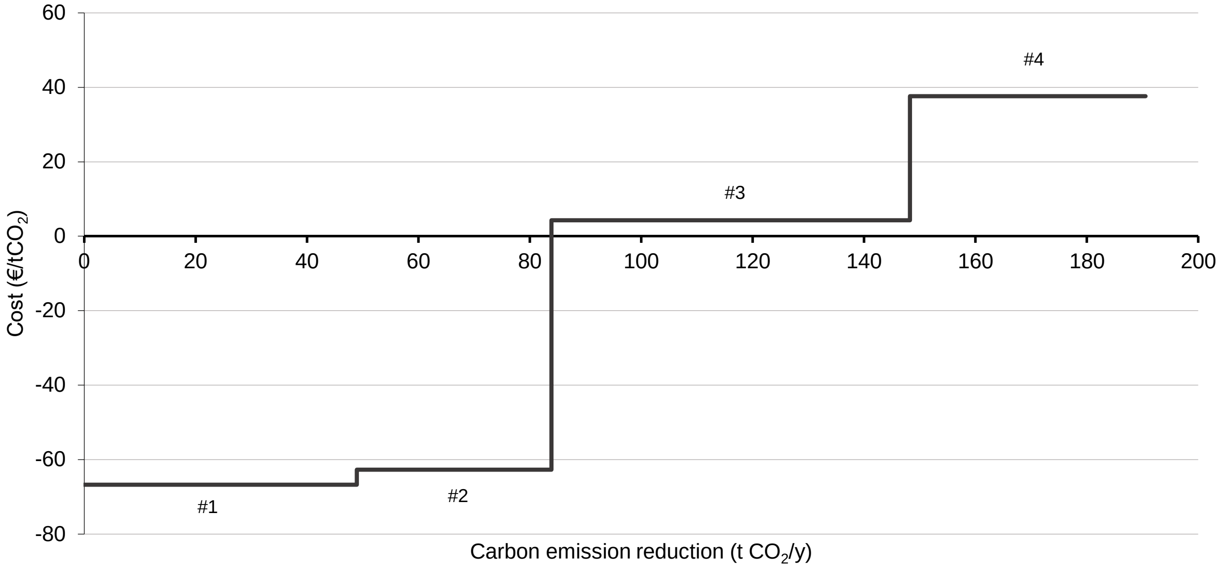


Figure 21 MACC for package 8 with a discount rate of 15%. Measure implementation order: #1 – LED TL T8; #2 – roof insulation 50 mm; #3 – groundwater heat pump; #4 – PV, own roof surface

5. DISCUSSION

The fifth section reflects on the findings of the previous section with regard to the research question and the sub-questions. The first part deals with the questions formulated in chapter 1 and discusses the results accordingly. In the second part, the findings are investigated further and discussed in the light of an uncertainty analysis. The third part deals with the implications of the research for practice and science. Finally, the limitations of the study and the potential for future research are stated.

5.1 General discussion

The goal of this thesis is to reveal the most optimal retrofitting options in the light of emission and economic concerns and thereby taking into account the heritage value of historical buildings in the Netherlands. The main research question and the related sub-questions are:

What building retrofit measures are the most optimal in the light of carbon emissions and economic concerns taking into account the impact on heritage values in the Netherlands?

The research has the following **sub-questions**:

1. Which energetic retrofitting measures are the most appropriate to conserve the heritage value of a historical building in the Netherlands?

Case study

2. Which retrofitting measures are the most suitable to conserve the heritage value of the case study building?
3. What is the demand profile in final and primary energy of a heritage building in the Netherlands?
4. What are the potential energy savings and carbon emission savings of the chosen retrofitting measures and what are the costs of these?
5. Which packages of retrofitting measures are the most optimal to reach minimum carbon emissions, the most economic outcome, and a high share of RES while achieving combinations of aforementioned targets?

The first part of the thesis deals with energetic retrofitting measures which are the most suitable to conserve the heritage value of a building. To answer SQ 1 and 2 a literature review was done. The findings show that the heritage value of the site can be conserved in most of the measure groups since most retrofitting groups have at least one option to not interfere with the heritage value of the building. Overhauls represent such an option for building envelope measures. They are a great tool to restore the original state of the construction. Nonetheless, the energy reduction potential would still be inadequate and was therefore not assessed in this study due to time constraints. Mostly, a higher energy reduction is connected with a greater impact on the heritage value of the building. Most building envelope measures cannot perform better than a score of three. Such a score does usually not interfere with the exterior appearance. But, either the changes are to some extent irreversible, or the interior appearance is altered. Fenestration scores the worst for the building envelope measures. The measure in this group, which is able to achieve the best energy results, leads to a score of 5 because the historical windows would have to be replaced in that particular case. New technical installations are also assessed. They are mainly dependant on whether they are visible or not. A groundwater heat pump has an excellent score because the equipment can be installed in a manner which is in line with the heritage value. On the other hand, an ambient air heat pump has visible equipment and scores less well. The implementation of RES is dependent on different factors: if the measure is installed close to the building (good), on the building but not visible (average), or on the building and visible (poor). PVs are a great option to install if it can be done without being visible. The main prerequisite is an appropriate orientation of the building. Small scale wind turbines can be installed off-site but would stay visible in any case. The retrofitting recommendations for a historical building in the Netherlands in general and for the case study in particular can be found in section 3.2. The best options for the case study were interior insulation for walls, roofs and floors, replacement of the lighting system, the application of a groundwater or ground heat pump, photovoltaics and construction overhauls. To make a fast assessment if a measure intervenes with the heritage value the outcomes of the literature study can be transferred to any historical building type and are not limited by location thanks to an international review – here outcomes are given in particular for the case study.

The next part of the thesis focusses on a building in the Netherlands to answer SQ 3. The revealed demand profile of the case study served as the base case for the subsequent analysis to answer the remaining SQs. The total annual energy demand of the old train workshop is 2454 GJ and the related total carbon emissions are 309.07 tonnes of carbon per year. The uncommon architecture of the building makes it not feasible to compare the outcomes with scientific literature. However, the engineer office *Niemann Raadgevende Ingenieurs* conducted a building energy simulation of the case study in October 2015 to give an initial overview to the client Except whether a NZEB building could be achieved (Nieman, 2016). Unfortunately, the results of this simulation could not be used for this master thesis. The measures and packages could have not been tested in same way. To validate the simulation outcomes, one simulation in OpenStudio is entirely based on the simulation of the engineering office. An exact replica is made in terms of surface constructions, schedules, loads, and other building definitions. Figure 22 below shows the outcomes of the validation simulation. The outcomes overlap almost completely. The left shows the outcomes of the engineering office and the right gives an overview of the test simulation in OpenStudio. Only the heating and cooling demand reveal a bigger gap. The differences can be explained by the application of different energy different simulation software, although both programmes are dynamic building simulations. The engineering office used *Vabi Elements* (Vabi Elements, 2016).

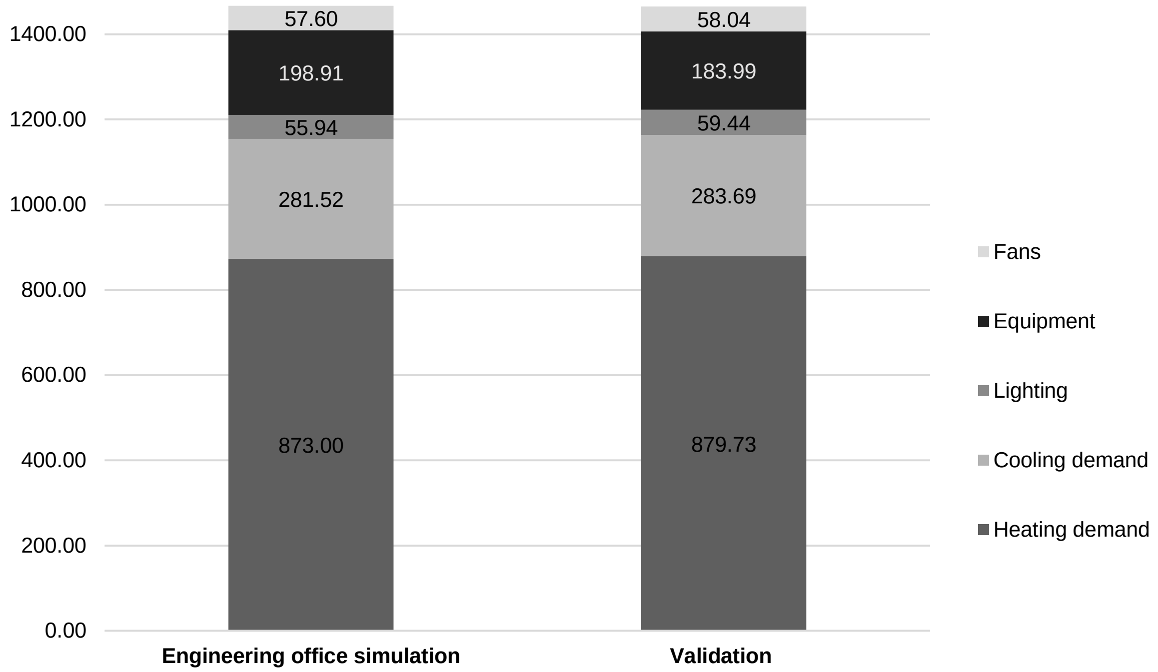


Figure 22 Validity simulation outputs in GJ/y primary energy

The next part of the general discussion deals with the sub-questions 4 and 5. The simulation outcomes show that a variety of measures have great potential for reducing the energy demand and, at the same time, the carbon emissions in the case of the case study building. The energy and carbon reduction potential is manifold for all measures. Roof insulation stands out within the building envelope measures with a carbon conservation potential of 11.61%, compared to the base case. The remaining building envelope measures such as floor insulation, exterior wall insulation, and fenestration fall short in the carbon mitigation analysis (4.04%, 1.63% and 4.72% respectively). Their energy reduction potential for both final and primary energy is only a fraction of the roof insulation measures. Likewise, the most cost-effective measure is also roof insulation. Although costs are in the same range for all building insulation measures, roof insulation performs much better thanks to the advanced outcomes for energy reduction. The investment costs are similar but the savings are much higher. The fenestration measures are the least economic due to their high investment costs and comparatively low energy reduction potential. The best performing fenestration measure has a SPB of 53.71 y. In comparison, the best roof insulation measure has a SPB of 7.45 y.

The technical installation measures also play also significant role in the energy demand reduction and carbon conservation. Lighting measures and photovoltaics have a great potential to reduce carbon emissions. Owing to a sourcing off site with a primary energy factor of 2.56, electrical savings are much more significant than savings from thermal energy (here the carbon conversion is based on natural gas). This correlation affects all technical installations which use electrical energy. The simulation reveals also a major difference between two diverse lighting types. LEDs cost more per unit than an efficient fluorescent light, nevertheless they perform slightly better for energy reduction and carbon emission mitigation of about 2 percentage points. The heat pump systems perform very well for thermal energy reduction but in return they demand a high amount of electrical energy. This leads to a high energy reduction and comparatively low carbon emission mitigation. Electrical energy causes more carbon emissions compared to natural gas sourced energy. The best system for both energy and carbon emission performance is the groundwater heat pump. This system shows also the best continuity in temperature due to the most stable source of energy (groundwater). It has a carbon conservation potential of 28.46% and a thermal energy reduction potential of 86.38%. The cost analysis for these measures reveal economic outcomes for all of them. The ambient air heat pump performs best due to the comparatively low investment costs (no borehole required). The other types require extra preparations next to the investment in the actual device. The majority of the costs for the groundwater heat pump are due to the required borehole. The SPB is 6.03 y for the groundwater heat pump and 2.81 y for the ambient air heat pump. The PV systems perform well in the entire analysis. To potential to reduce carbon emissions is high and the technology is able to cover a high demand of electrical energy on site. This is due to the efficiency of 100% and the PEF of 1 which influences directly the primary energy savings and the related carbon emissions. The PV installation which is based on the own roof surface of the case study reaches 48.53% for carbon emission reduction and is able to provide about one-third more electricity than is needed for the base case. In combination with the heat pumps, the electricity production on site is a benefit due to the high electricity demand. An off-site sourced electricity would lead to much higher carbon emissions. The economics of the PV system performs well. The outcome is not as good as for lighting or the heat pump installations, however the SPB (9.32 y) and the costs per conserved carbon are within borders to make the technology interesting for private investors. The potential of wind energy is very low compared to the other option PV. They are in direct competition for the land resources. Keeping that is mind it is much more valuable to install PVs.

The results of the packaged measures build up on the results of the measures section. Packages do well if they incorporate well performing measures. Package 8 – recommendation proofs this statement The package can be found in chapter 4.2.3. Only measures are implemented consecutively which perform the best. These measure are roof insulation, LED lights, groundwater heat pump and PV based on the own roof surface. This leads to a primary energy reduction of 80% and almost two third in carbon emission reduction. This package does not fulfil the Dutch building regulation. As a consequence, a permission is necessary of the Dutch Heritage Agency. The performance is similar to the other packages, but it comes at much lower costs for a building system which includes an own thermal energy and electricity supply. Packages perform economically better if the focus is limited to purely the building envelope, or if less stable thermal energy supply technologies like the ambient air heat pump are chosen. Generally: If packages include solely building envelope measures the thermal performance improves; The implementation of a better lighting system leads to a lower electricity demand and influences slightly the thermal energy demand due to the internal heat gain of the lighting system; Heat pump system reduce the thermal energy demand profoundly, but lead to a much higher electrical energy demand; The installation of PV does not influence the thermal energy but is able to reduce the electrical energy demand from the grid utterly by own provision. The carbon emission performance per technology is directly related to this energetic behaviour dependant on the carbon emission factor per technology. Electricity related technologies influence the overall carbon emissions the most due to the higher carbon emission factor. Other technologies are able to lower the primary energy demand but are not able to reduce carbon emissions as much due to the lower carbon emission factor for natural gas.

5.2 Uncertainty analysis

This part of the discussion investigates a variety of parameters for the measure and package results in chapter 4.2 to gain a deeper insight into their behaviour and to support the findings of a conclusion for

SQ 4 and 5. The chosen method is a sensitivity analysis. The first parameter under investigation is the chosen discount rate of 15% in the levelized cost of conserved carbon (LCCC) analysis. It is likely that the time-equivalent cash flows are directly affected. Several discount rates are assessed to quantify if an assessment stays interesting if the cash flow changes. A primary energy factor and two carbon intensities are added to show their impact on the results of the LCCC. Table 10 and table 11 show the outcomes of the sensitivity analysis for the measure analysis and packages. The same measures and packaged measures are assessed as in the result section in 4.2 and 4.3.

Table 10 Sensitivity analysis outcomes for most promising measures for LCCC in €/tCO2 for several discount rates, primary energy factor of 2, and several carbon intensities

	Measure	Base with discount rate of 15%	LCCC; 20%	LCCC; 10%	LCCC; 6%	Primary energy factor - 2	Carbon intensity - 2.1%	Carbon intensity - 3.4%
#1	Triple glazing, KR, no sun protection	1979.37	2730.12	1237.71	674.62	2064.09	2039.12	2141.24
#2	Interior 0.05 mm; U = 0.4	464.01	711.72	219.30	33.50	483.11	477.49	500.46
#3	Roof 0.05 m; U = 0.4	-62.79	9.46	-134.15	-188.34	-65.47	-64.68	-67.92
#4	Floor 0.05 m; U = 0.4	429.09	665.90	195.15	17.54	445.66	440.79	460.63
#5	LED TL T8 27 W	-66.73	-52.07	-81.22	-92.26	-86.99	-80.03	-116.85
#6	TL5 HE 14 W	-89.65	-83.95	-95.00	-98.83	-117.30	-107.79	-158.43
#7	Groundwater heat pump	-21.51	70.14	-107.57	-169.31	-21.42	-19.51	-17.01
#8	Ambient air heat pump	-182.14	-139.24	-222.43	-251.32	-181.19	-153.47	-122.89
#9	Solar PV (max. based on roof area)	30.12	56.30	5.83	-11.56	38.55	35.69	50.43
#10	Vertical turbine - Tulipo	648.81	879.01	435.23	282.37	648.81	768.87	1086.63

Table 11 Sensitivity analysis outcomes for packaged measures for LCCC in €/tCO2 with several discount rates, primary energy factor of 2, and several carbon intensities

Measure package	Base with discount rate of 15%	LCCC; 20%	LCCC; 10%	LCCC; 6%	Primary energy factor - 2	Carbon intensity - 2.1%	Carbon intensity - 3.4%
Package 1	216.04	360.76	73.06	-35.51	242.67	234.40	270.77
Package 2	62.48	176.71	-50.37	-136.05	65.07	64.30	67.42

Measure package	Base with discount rate of 15%	LCCC; 20%	LCCC; 10%	LCCC; 6%	Primary energy factor - 2	Carbon intensity - 2.1%	Carbon intensity - 3.4%
Package 3	-12.38	49.19	-73.22	-119.42	-14.30	-13.69	-16.46
Package 4.1	693.91	1089.26	308.95	21.18	561.31	593.78	483.52
Package 4.2	203.85	333.95	79.03	-13.08	230.51	222.19	259.03
Package 5	309.02	496.05	128.37	-5.73	321.94	318.13	333.68
Package 6	35.57	154.85	-78.36	-162.10	34.20	34.58	33.12
Package 7.1	5.15	74.29	-63.16	-115.04	5.91	5.67	6.75
Package 7.2	66.87	185.16	-45.89	-128.43	82.86	68.84	72.20
Package 8	37.61	127.08	-46.91	-108.23	40.33	39.05	41.56

The outcomes show a direct relation between the choice of discount rate and the LCCC. If a lower value is chosen for the discount rate, the LCCCs are also lower and make a measure more economically viable. Higher values result in higher LCCCs. Of special notice are the much lower LCCC outcomes for all measures and packaged measures with a discount rate of 6%. Half of the calculations show negative outcomes and therefore reflect an opportunity for financial savings. This is the case for both measure and packaged measures.

The next step is to visualize a part of the sensitivity analysis results in a marginal abatement cost curve (MACC) to make them more accessible. Figure 23 depicts a MACC in relation to the MACC in section 4.3.2. Here the discount rate of 6% is chosen instead of 15%. The implementation order stays the same. All measures are below the x-axis and have the potential to pay themselves back over the lifetime of the measure. Nevertheless, a shift in order of the best performing measures is revealed. With a discount rate of 15%, the LED lighting performs best. In this case, it falls short and performs less well compared to the other three measures. One parameter which can explain the outcome is a much higher investment cost for the other measures. A low discount rate favours high investments and, as a consequence, renders the LCCC more negative. The even lower LCCC, compared to the case with a discount rate of 15%, makes the measure package very interesting for private investors. The measure package is a good way to mitigate carbon emissions even if parameters are changed. This is confirmed by the recommendation package in section 4.2.3.

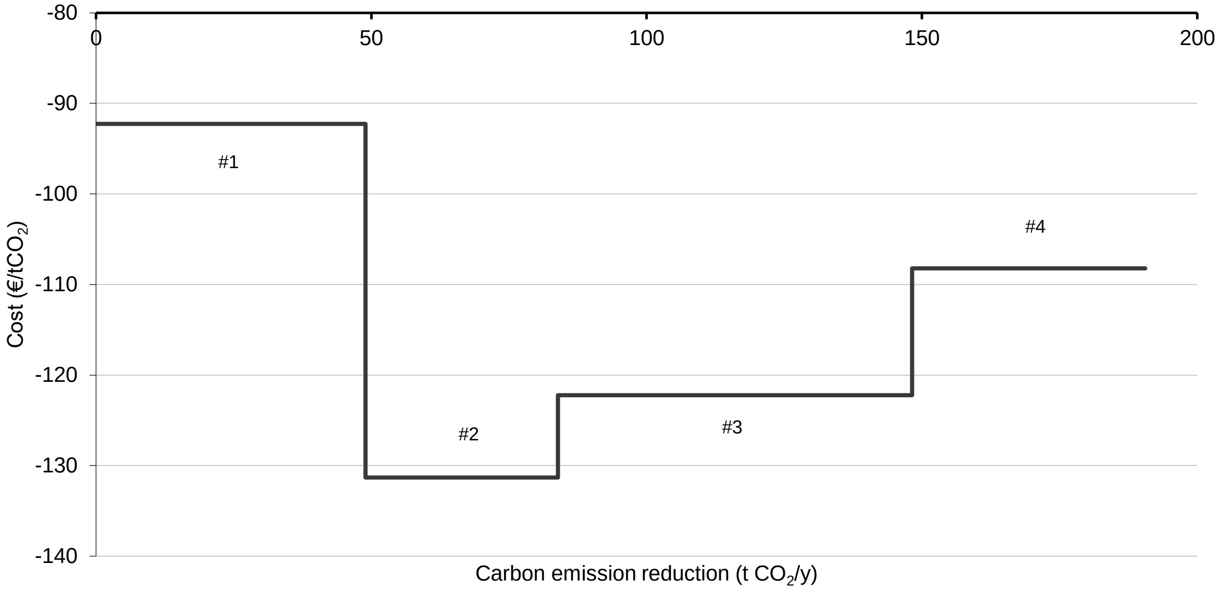


Figure 23 MACC for package 8 with a discount rate of 6%. Measure implementation order: #1 – LED TL T8; #2 – roof insulation 50 mm; #3 – groundwater heat pump; #4 – PV, own roof surface

The second parameter under consideration for a sensitivity analysis is the primary energy conversion factor of electricity generation. A high share of renewable energy makes this factor more efficient and reduces losses. Generally, the primary energy conversion factor can be set to 2.56 for the average energy mix in the Netherlands (Molenbroek et al., 2011). The high share of renewables and electricity generation of combined heat and power plants in the Netherlands results in approximately 2.00 for the primary energy conversion factor (Molenbroek et al., 2011). Based on the trend that a higher share of RES improves the site to source conversion factor, it stands to reason to test even higher shares of RES. The impact on the total primary energy demand for the simulation measures and packages can be significant. In this case, the outcomes are marginally small for most of the measures and packaged measures. Only technologies which are highly dependent on electrical energy are affected to a larger scale. The differences compared to the base case and to the other primary factor of 2 are within approximately 3%. An exception are the results for the lighting system. These results do not base their electricity on-site, as do the heat pump systems, therefore, changes of ±40% are the consequence. Nevertheless, the impact on the results stays small and does not, by any means, reach the magnitude of the discount rate.

The same approach can be tested with regards to the carbon intensity factor. Owing to changes in the energy mix, the carbon intensity for electricity will be lowered by about 2.1% in 2020 and 3.4% until 2030 according to the European Commission (EC, 2013). The analysis for carbon intensity shows a high dissimilarity for electricity-based measures. Others have a maximum change of approximately 7%. This implies a reduction of cost-effectiveness for measures which are based on electricity. The reduction of the carbon mitigation potential might be misleading.

The geometry of the building is also a parameter which directly influences the results of the simulation. Usually, the retrofit of a roof does not perform as well as in this study. The performance can be explained by the geometry of the building. The extraordinary ceiling height of the main hall results in a particular thermal situation, which makes the implementation of roof insulation even more significant. Usually, roofs only have the second largest heat loss for a typical building. Most of the losses can be observed through the exterior walls (Andrews et al., 2013). This matter is tested by changing the ceiling height in the building energy simulation in OpenStudio. A lower ceiling height in the simulation reveals less reduction for roof measures but greater potential for wall and floor insulation. Therefore, the geometry of the case study building directly influences the energy results.

5.3 Implications

This section reveals important implications based on the results and aforementioned discussion. The Dutch building regulation should be altered in relation to required retrofits and the actual benefits of it. The thesis shows a discrepancy between installation of insulation, energetic benefits and the impact on the heritage value. The results show that an implementation according to the building regulation has a very low benefit for energy reduction and carbon mitigation. However, these low improvements come at very high costs. It should be possible to exclude retrofits if their positive impact is too low to be justified for a high investment or an impact on the heritage value. The outcomes of the sensitivity analysis reveal a carbon emission reduction potential for most measures and packages if the discount rate is lowered. This leads to the thought that a more public point of view is necessary to further mitigate carbon emission. Currently, high discount rates avoid the investment for many building retrofits which results in a lost chance for carbon conservation.

5.4 Limitations & future research

Although the effort was done to conduct the research as accurate as possible, some limitation areas can be revealed where the results might fall short or where they are restricted. The model of the building and the later energy conversation simulation underlie a variety of constraints. In general, building simulations try to copy reality as close as possible, although an exact replica of reality is not possible due to unpredictable conditions of nature and the data density of reality. Another important area to consider in the simulation is that the weather file in use is from Amsterdam. Precise climate data for Utrecht is not available, however, climate data for both Amsterdam and Utrecht is almost the same. The energy simulation can be done more accurately by collecting relevant weather data for Utrecht. Nevertheless, the impact on the final results will be negligible. Furthermore, the complete HVAC system was not simulated in OpenStudio due to time constraints. The energy demand of the system and the distribution of thermal energy to the thermal zones is simulated, but, the complete setup and energy demand is covered with MS Excel (based on simulation of the manufacturers). Also, the supply of hot water is neglected due to a lack of demand. Moreover, the method of choice to give a quick overview of the payback period is the SPB. This approach does not discount the costs over the lifetime of a technology. On the other hand, a discounted payback period does, but this approach was neglected because a SPB is sufficient for an initial overview of profitability and it is not as time-demanding as a discounted payback period. Besides, the later marginal cost analysis for carbon discounts the costs. A complete LCCC was not feasible in the case study. Development and end-of-life costs were excluded due to data unavailability and time constraints. However, both these cost areas are comparatively small related to investment and operating costs, which are both considered for all measures and packages. Next to a complete LCCC, a life-cycle analysis for all measures and packages should also be conducted to reveal all life-cycle related emissions and other environmental impacts. The current outcomes give a clear overview of carbon emission reduction. Nevertheless, other emissions and other impacts are not part of this study and should be assessed into depth with regard to the heritage value in future research. Also, the analysis is limited to the specific geometry of the case study. To grasp the potential of the measures and packages for the average historical building in the Netherlands, another study should be conducted with a simulation of a constant case, which represents all buildings to show the potential and the impact on the heritage value. Further research should investigate into depth: life-cycle analysis and life-cycle cost analysis of all measures and packages in relation to the heritage value assessment; Inclusion of all available retrofitting options in the heritage value literature review and the energy analysis; Testing of measures and packages in a normalized building to shows the average potential for each option.

6. CONCLUSION

This research investigated the potential of energy and carbon emission reduction in combination with conservation of the heritage value of a building. For this purpose, a building in Utrecht was assessed as a case study. Also, the cost-effectiveness was determined through the calculation of a simple payback period (SPB), levelized costs of conserved carbon (LCCC), and the use of marginal abatement cost curves as a visualization tool.

6.1 General conclusion

The results of both the literature review and the building energy simulation show that a building in the Netherlands can be retrofitted towards a balance between heritage value and carbon emissions. A variety of measures is feasible. Nevertheless, high carbon reductions can, in most cases, only be achieved if the appearance of the building is altered.

The best performing measures with regards to the inherent heritage value of a building are overhauls; however, these have only a minimum effect on the performance. Most insulation measures, technological installations, and renewable energy sources can be achieved with an average score of 3 (scale from 1 = best to 5 = worst). This score is more or less neutral and has an acceptable or no impact on the exterior building appearance. The replacement of windows is not recommended due to the irreversible impact on the building with a score of 5. The most favourable retrofitting measures to conserve the heritage value of the case study building in the Netherlands are: overhauls with a score of 1, interior insulation for walls, roofs and floors (score = 3), replacement of the lighting system with a score of 1, the application of a groundwater or ground heat pump (score = 1), and PV (score = 2).

The energy analysis and economic analysis for each measure show a great potential for carbon reduction for roof insulation, LED lights, groundwater heat pump, and PV. The percentages of potential carbon conservation were 11.61%, 15.84%, 28.46%, and 70.15% respectively. The other measure fields have an acceptable outcome for carbon reduction, but fall short in cost-effectiveness by discounting the costs over the specific lifetime of each measure. The outcomes show that a higher investment leads to higher carbon savings; however, the LCCC are performing less well than the most cost-effective solutions. This immediately suggests that, if the motivation of the investor to reduce carbon is greater than having a more cost-effective solution, the measure with a higher carbon reduction should be preferred above cost-effectiveness. E.g., the groundwater heat pump system saves 21.34 t CO_2/y more than the ambient air system. Nevertheless, the SPB is 2 years longer (3.87 y) and the LCCC still performs very well. The rest of the measures are more straight-forward. The best results in carbon savings also lead to the best outcomes for LCCC and mostly also for SPB. The SPB for the aforementioned best performing individual measures is 7.45 y, 2.65 y, 6.03 y and 9.32 y respectively. The LCCC is cost-effective for all four measures. PV alone reveals positive costs and is not as cost-effective. The combination of the best performing measures to packages reveals the possibility to reach a zero energy building. A net zero energy building is not feasible because it is not possible to cover the entire electricity demand on-site. This would mean a primary energy and carbon reduction of 100%. By using only the roof surface with an appropriate orientation for PV, a total of 87.50% energy demand reduction can be achieved for the best package, including an own energy supply and 61.55% carbon reduction.

6.2 Recommendation

The recommendation given is based on the outcomes packaged measure section in 4.2.3. The most promising packages are *Package 7.2 – Best demand reduction, heritage value, HVAC & RES* and *Package 8 – Recommendation.* Both packages combine energy and carbon reduction with the conservation of the heritage value of the building. Package 8 reduces carbon emissions by 190.55 t CO_2/y, the investment costs are € 360831, and the cost effectiveness is more than adequate with an SPB of 7.37 y and a negative LCCC of 108.23 based on a discount rate of 6%. The heritage value conservation score is 1.5 and the electricity coverage by RES is 77.88%. Package 8 is within the budget of € 300000 for technical installations and € 100000 for extra insulation. This is the best available option by combining carbon mitigation with a conservation of heritage value.

References

Adapt Consulting AS. (2016). Determining primary energy factors for electricity.

Agentschap NL. (2010a). Leidraad Zonnestroomprojecten.

Agentschap NL. (2010b). Praktische toepassing van mini-windturbines.

Andrews, J., & Jelley, N. (2013). Energy Science - principles, technologies and impacts. *Oxford University Press*.

ASHRAE. (2010). Supplement Energy Standard for Buildings Except Low-Rise Residential Buildings (Vol. 8400).

ASHRAE. (2016). International Weather for Energy Calculations. Retrieved September 7, 2016, from https://www.ashrae.org/resources--publications/bookstore/international-weather-for-energy-calculations

BDA. (2011). Richtlinie: Energieeffizienz am Baudenkmal.

Blok, K. (2007). Introduction to ENERGY ANALYSIS. *Techne Press.*

Boyano, a., Hernandez, P., & Wolf, O. (2013). Energy demands and potential savings in European office buildings: Case studies based on EnergyPlus simulations. *Energy and Buildings*.

BRIS. (2016). Bouwbesluit 2012 | BRIS Bouwbesluit Online. Retrieved August 29, 2016, from http://www.bouwbesluitonline.nl/Inhoud/docs/wet/bb2012

Broström, T., Eriksson, P., Liu, L., Rohdin, P., Ståhl, F., & Moshfegh, B. (2014). A Method to Assess the Potential for and Consequences of Energy Retrofits in Swedish Historic Buildings. *The Historic Environment*.

CBS StatLine. (2016). CBS StatLine - Voorraad woningen; woningtype, bouwjaar, oppervlakte, regio. Retrieved September 9, 2016, from http://statline.cbs.nl/Statweb/publication/

CHA. (2011). Vergunningvrij - Informatie voor professionals.

CHA. (2012). Monumenten en beschermde gezichten Vergunningvrije werkzaamheden.

CHA. (2016). Cultural Heritage Agency of the Netherlands | Rijksdienst voor het Cultureel Erfgoed.

Cuce, E., & Riffat, S. B. (2015). A state-of-the-art review on innovative glazing technologies. *Renewable and Sustainable Energy Reviews*.

duurzaam thuis. (2016). HR-ketel verwarming. Efficiënt, duurzaam, milieuvriendelijk je huis verwarmen. Overzicht voor- en nadelen. Retrieved September 28, 2016, from http://www.duurzaamthuis.nl/energie/verwarming/hr-ketel

E.H. Lysen. (1996). The Trias Energica: Solar energy strategies for developing countries. *Proceedings of the Eurosun Conference*.

EC. (2013). EU Energy, Transport and GHG Emissions: Trends to 2050 - Reference Scenario 2013.

EC. (2014). European Energy Security Strategy. *European Commission Website*.

EC. (2015). Buildings - European Commission. Retrieved December 8, 2015, from https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings

Energy Star. (2013). Source Energy - Energy Star portfolio manager.

EnergyPlus. (2015). Getting Started with EnergyPlus.

EnergyPlus. (2016). Weather Data by Location | EnergyPlus. Retrieved September 7, 2016, from https://energyplus.net/weather-location/europe_wmo_region_6/NLD//NLD_Amsterdam.062400_IWEC

EU. (2010). Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). *Official Journal of the European Union*.

Eurostat. (2009). Sustainable development in the European Union - 2009 monitoring report of the EU sustainable development strategy.

Eurostat. (2016). Energy price statistics - Statistics Explained. Retrieved September 18, 2016, from http://ec.europa.eu/eurostat/statistics-explained/

Fumo, N., Mago, P., & Luck, R. (2010). Methodology to estimate building energy consumption using EnergyPlus Benchmark Models. *Energy and Buildings*.

Gemeente Utrecht. (2016a). Monument, vergunning. Retrieved January 5, 2016, from https://pki.utrecht.nl/Loket/prodcat/products/getProductDetailsAction.do?id=402

Gemeente Utrecht. (2016b). Monumentenkaart. Retrieved March 24, 2016, from http://objectdesk.gemgids.nl/Publication/Site/298

Grunewald, J., Will, T., & Pohl, M. (2010). Energetische Sanierung von Baudenkmalen.

Grytli, E., Kværness, L., Rokseth, L. S., & Ygre, K. F. (2012). The impact of energy improvement measures on heritage buildings. *Journal of Architectural Conservation*.

Gustavsen, A., & Jelle, B. P. (2007). State-of-the-Art Highly Insulating Window Frames – Research and Market Review. *Sintef*.

Harrell, C. (2011). Simulation Basics. *Simulation Using ProModel*.

IEA. (2013). World Energy Outlook 2013. *IEA Publications*.

IPCC. (2014a). Annex II: Metrics & Methodology. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1281–1328.

IPCC. (2014b). Annex III: Technology-specific cost and performance parameters. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

IPCC. (2014c). Buildings.In: Climate Change 2014: Mitigation of Climate Change: Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

IPCC. (2014d). Climate Change 2014: Mitigation of Climate Change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

IPCC. (2014e). Climate Change 2014 Synthesis Report Summary Chapter for Policymakers.

ISSO. (2012). ISSO-publicatie 19 Thermisch binnenklimaat. Retrieved September 18, 2016, from http://kennisbank.isso.nl/docs/publicatie/19/1991

Jelle, B. P. (2011). Traditional, state-of-the-art and future thermal building insulation materials and solutions - Properties, requirements and possibilities. *Energy and Buildings*.

Jelle, B. P., Hynd, A., Gustavsen, A., Arasteh, D., Goudey, H., & Hart, R. (2012). Fenestration of today and tomorrow: A state-of-the-art review and future research opportunities. *Solar Energy Materials and Solar Cells*.

Kesicki, F., & Ekins, P. (2012). Marginal abatement cost curves: a call for caution. *Climate Policy*.

Lesser, J., & Puga, N. (2008). PV vs. Solar Thermal. *Public Utilities Fortnightly*.

Meijer, F., Itard, L., & Sunikka-Blank, M. (2009). Comparing European residential building stocks: performance, renovation and policy opportunities. *Building Research & Information*.

Molenbroek, M., Stricker, E., & Boermans, T. (2011). Primary energy factors for electricity in buildings Toward a flexible electricity supply.

NEN. (2012). NEN 1068 - Thermische isolatie van gebouwen - Rekenmethoden. *Thermische Eigenschappen van Gebouwen*.

Nieman. (2016). Nieman Raadgevende Ingenieurs. Retrieved September 7, 2016, from http://www.nieman.nl/contact/

O.O.M. Advies. (2011a). Toolkit Energieduurzaamheid voor Historische bebouwing.

O.O.M. Advies. (2011b). Toolkit Energieduurzaamheid voor Historische bebouwing Uitgangspunten en toelichting.

OpenStudio. (2015a). OpenStudio. Retrieved December 16, 2015, from https://www.openstudio.net/

OpenStudio. (2015b). *OpenStudio SketchUp Plug-in How to Use this Guide*.

Pyloudi, E., Papantoniou, S., & Kolokotsa, D. (2015). Retrofitting an office building towards a net zero energy building. *Advances in Building Energy Research*.

Quaschning, V. (2011). Regenerative Energiesysteme. *München, Hanser*.

Rijksdienst voor Ondernemend Nederland. (2013). Infoblad Trias Energetica.

Saelens, D., Hens, H., Van der Veken, J., & Verbeeck, G. (2004). Comparison of Steady-State and Dynamic. *Ashare*.

Şahin, C. D., Arsan, Z. D., Tunçoku, S. S., Broström, T., & Akkurt, G. G. (2015). A transdisciplinary approach on the energy efficient retrofitting of a historic building in the Aegean Region of Turkey. *Energy and Buildings*.

SANCO. (2014). SANCO-Glasbuch. Retrieved March 31, 2016, from http://www.sanco.de/glasbuch/glasbuch-online-lesen.html

SANCO. (2016). SANCO - Isolierglas für die Wärmedämmung, Wärmeschutzlas. Retrieved March 31, 2016, from http://www.sanco.de/produkte/waermedaemmung.html

SketchUp. (2016). SketchUp | 3D for Everyone. Retrieved February 5, 2016, from https://www.sketchup.com/

Stoffregen, A., & Schuller, O. (2014). Primary Energy Demand of Renewable Energy Carriers - Part 1: Definitions, accounting methods and their application.

Taylor, S. (2012). The ranking of negative-cost emissions reduction measures. *Energy Policy*, *48*, 430–438. http://doi.org/10.1016/j.enpol.2012.05.071

Torcellini, P., Pless, S., & Deru, M. (2006). Zero Energy Buildings : A Critical Look at the Definition Preprint. *ACEE Summer Studay*.

U.S. Department of Energy. (2016). Building Technologies Office: EnergyPlus Energy Simulation Software. Retrieved September 7, 2016, from http://apps1.eere.energy.gov/buildings/energyplus/

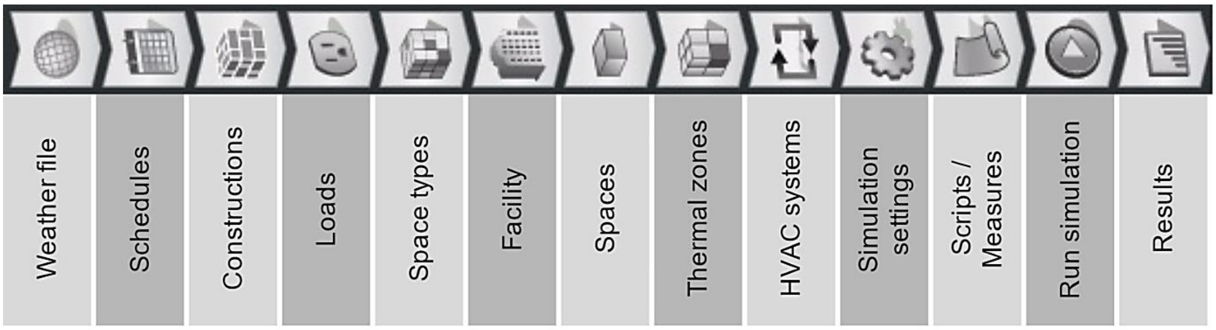
UN. (2015). UN Climate Change Conference Paris 2015. Retrieved December 16, 2015, from http://www.un.org/sustainabledevelopment/cop21/

Vabi Elements. (2016). Vabi Elements - 3D rekensoftware voor installateur & adviseur. Retrieved September 12, 2016, from https://www.vabi.nl/producten/vabi-elements/

WBDG. (2016). Life-Cycle Cost Analysis (LCCA). Retrieved September 7, 2016, from https://www.wbdg.org/resources/lcca.php?r=rpi

Woodward, D. G. (1997). Life cycle costing—Theory, information acquisition and application. *International Journal of Project Management*.

Appendix A – OpenStudio workflow



OpenStudio workflow based on the actual structure of the software (OpenStudio, 2015b)

I. Weather file: The first step is the choice of an appropriate weather file from the EnergyPlus database (EnergyPlus, 2016). The weather data is based on the *American Society of Heating, Refrigeration and Air-conditioning Engineers'*s (ASHRAE) *International Weather for Energy Calculations* (IWEC) (ASHRAE, 2016).

II. Schedules: Secondly, the building schedule for activities and elements is defined. This includes the following: hours of operation, number of people, people activity defined in W, lighting operation times, electric equipment operation times, air infiltration rates in m^3/s.

III. Constructions: This part of the workflow focusses on the building constructions. They depend on the various surface types and can be defined in multiple layers with different materials. This includes a distinct definition of thermal variables of all construction features for wall, ceiling, and floor insulation, and fenestration.

IV. Loads: The internal load specifications define the thermal radiation of people, lights, luminaires, and electric equipment. They are given in W/m^2.

V. Space types: Here, the predefined spaces are adopted from the previously conducted SketchUp3D simulation. Each of the spaces is assigned to particular default construction set, default schedule set, design specification outdoor air, and space infiltration flow rate. The parameters are retrieved from previous simulation inputs. Also, specific loads are assigned to each of the defined space types dependant on schedule and definition.

VI. Facility: This part defines the nominal floor and ceiling height and the number of stories. Also, the north axis can be defined if not done with the help of SketchUp3D. If necessary, exterior equipment, shading, and stories definitions can be included here.

VII. Spaces: The seventh step gives an overview of all relevant space specifications. Each of the surfaces and sub-surfaces (fenestration and doors) can be modified individually where necessary.

VIII. Thermal zones: Here, heating thermostat schedules, cooling thermostat schedules, and their relevant sizing parameters are defined (design supply temperature, supply humidity ratio, air flow).

IX. HVAC systems: The HVAC system is defined by inclusion of multiple components in the designed system. These are: cooling cycle, heating cycle, fan system, distribution for each thermal zone.

X. Simulation settings: The most important settings are: date range of the simulation, hourly time steps, and sizing factors.

XI. Scripts / measures: This step gives the possibility to manipulate or optimize the original simulation by adding programmed features to make the results more accurate. For instance: clothing insulation factors/schedules, air velocity schedules, work efficiency schedules, ground temperature schedule adjustments (instead of default programme settings if precise temperatures are available).

XII. Run simulation and results: The final result of the energy efficiency simulation step answers several SQs by showing the annual energy consumption as a total energy demand (GJ/y) of the building. In relation to the energy consumption, the carbon emissions can be calculated with specific parameters. The results are divided in heating demand, cooling demand, electrical energy demand for lights, electrical energy demand for fans, and electrical energy demand for equipment. This outcome is the basis fof all further steps, namely validation of the software and the assessment of individual measures and measure packages.

Appendix B – Building simulation background

Interview with Mirjam Schmull and site visit information

The interview data was collected with the help of a google document. It was completed at the 23rd of April. Unavailable data was determined through a site visit.

General

	current	planned
Year of construction	1892	
What are the planned time schemes? (Weekdays and weekend)	24-hour availability of the space	
How many people will be in the office space? In person/m² (If necessary distinction between room types)	Maximum of 230	
What are the desired temperatures during the day and in the night?	18-25	

Building insulation

	current		**planned**	
		R - value in m^2K / W		R - value in m^2K / W
Roof (materials)	Roofing felt with a hardboard of wood	0.11	Roofing felt with a hardboard of wood and EPDM or Bitumen	0.11
Roof insulation	No insulation	/	PiR	5.00
Floor (materials)	Concrete	0.14	Concrete	0.14
Floor insulation	No insulation	/	PiR	2.50
External walls (materials)	Building brick	0.34	Building brick with a retention wall	0.34
External walls insulation	No insulation	/	PiR	4.50
Door (type)	Hard wood	0.41	Solid wood	0.41
Door frame (type)	Hard wood	0.41	Solid wood	0.41
Glass door (type)	Single pane	0.17	HR++	0.91
Glass door frame (type)	Steel frame	0.25	Wooden frame	1.00
Windows (type)	Single pane	0.17	HR++	0.91
Windows frames (type)	Steel frame	0.25	Wooden frame	1.00
Use of carpet?	No		No	

Heating

What system is used for heating?	**current**	**planned**
Which fuel is used? (e.g. oil, natural gas)	Natural gas boiler	No use of fossil fuels
Total power (kW)	Not available due to construction on site	200kW
Other heat sources (e.g. geothermal)	/	Heat pump
Which fuel is used?	Gas	/

Space conditioning

	current		**planned**	
Use of space air conditioning?	Heating? Yes	Cooling? Yes	Heating? Yes	Cooling? Yes
Total power (kW)	Not available		Not available	
What type of system is used for space conditioning?	Central heating system		Floor heating (low temp)	
Fuel	Gas		Solar	
Which type of ventilation is used?	Natural		Natural + adiabatic cooling	
Where?	All spaces		All spaces (except for the new built appendix)	
If mechanical: Total power (kW)	Not available		Not available	
Are fans used for cooling?	no		no	

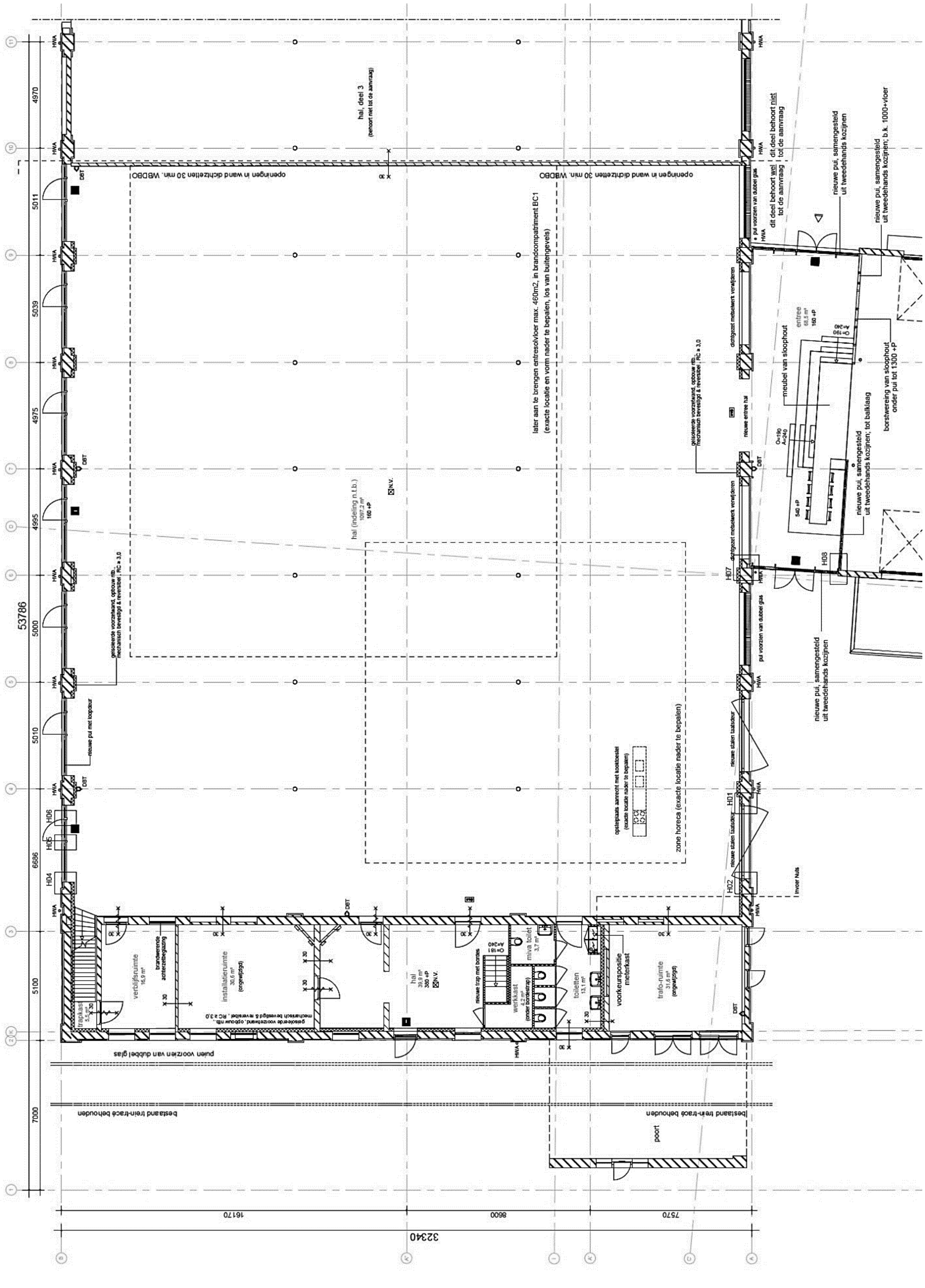
Hot water supply

	current	**planned**
Individual boiler	No hot water	No hot water
Which type of boiler is used?	/	/
What is the capacity of the boiler in litres?	/	/

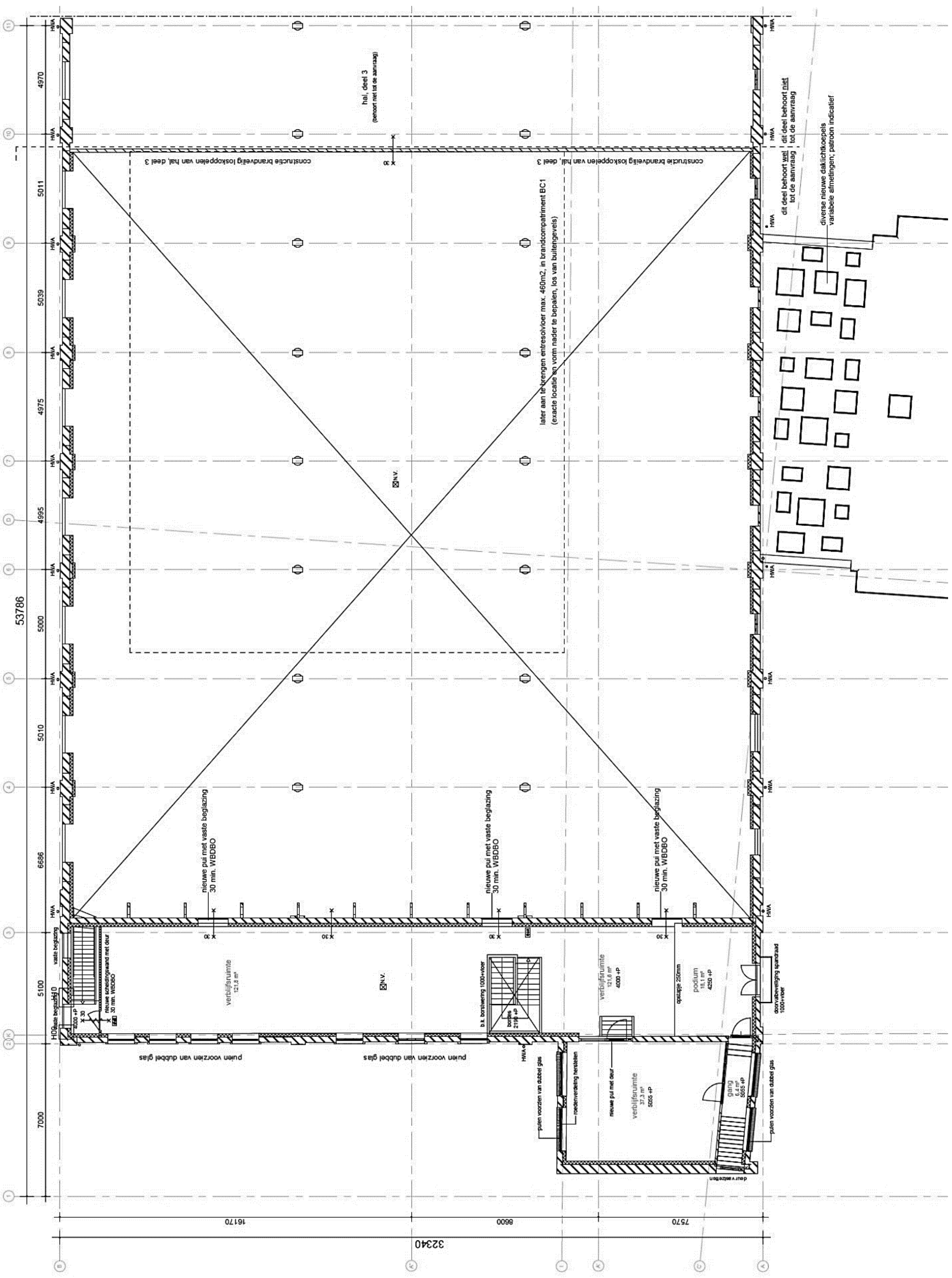
Lighting and other

	current	**planned**
Which light bulbs are used?	TL	LED with high efficacy
Type	Bulbs with a thermal radiation of 33 W / m^2	Not defined yet
Space	Not available due to construction on site	No light plan yet
Amount	Not available due to construction on site	No light plan yet

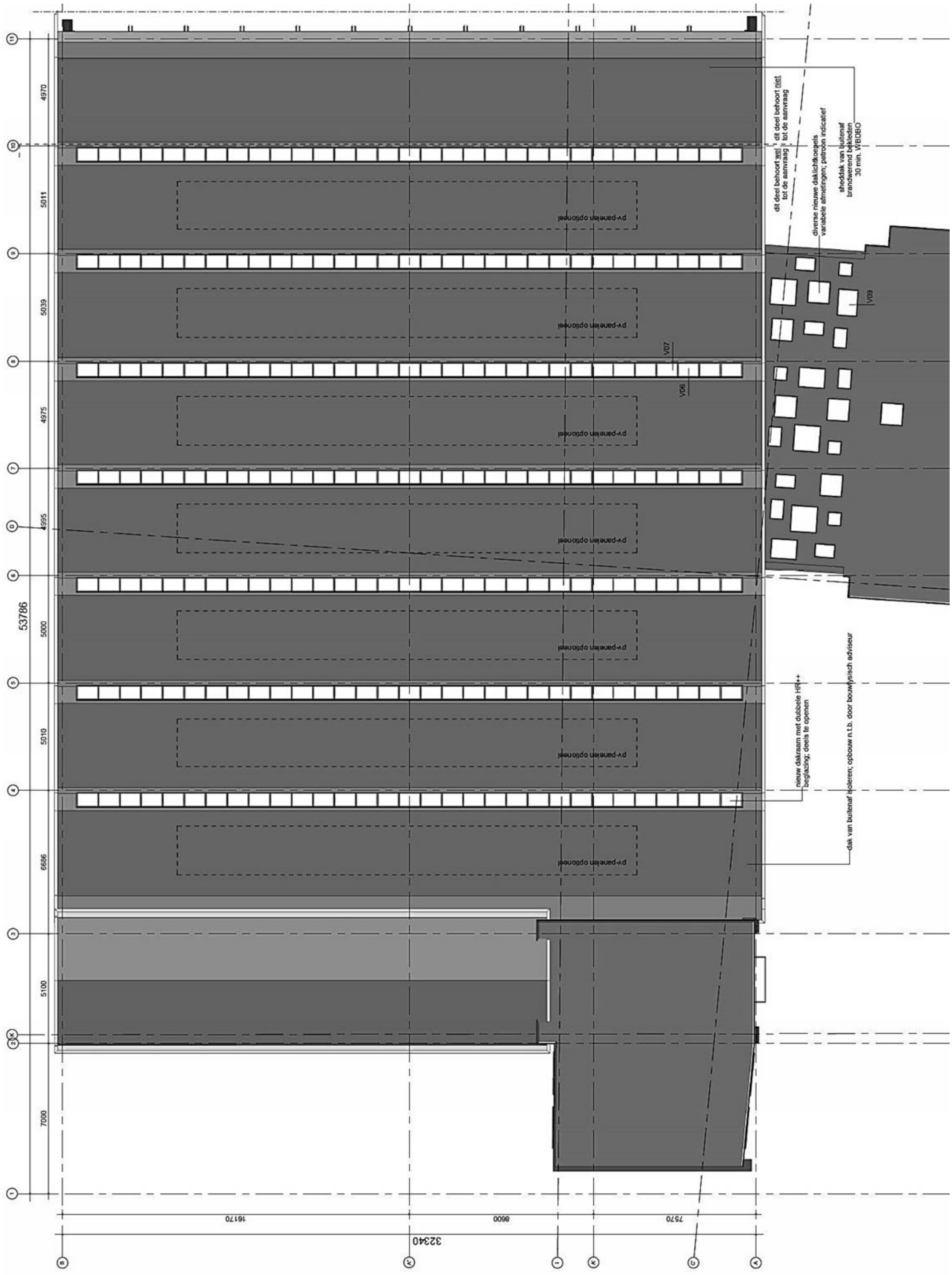
Architectural plans



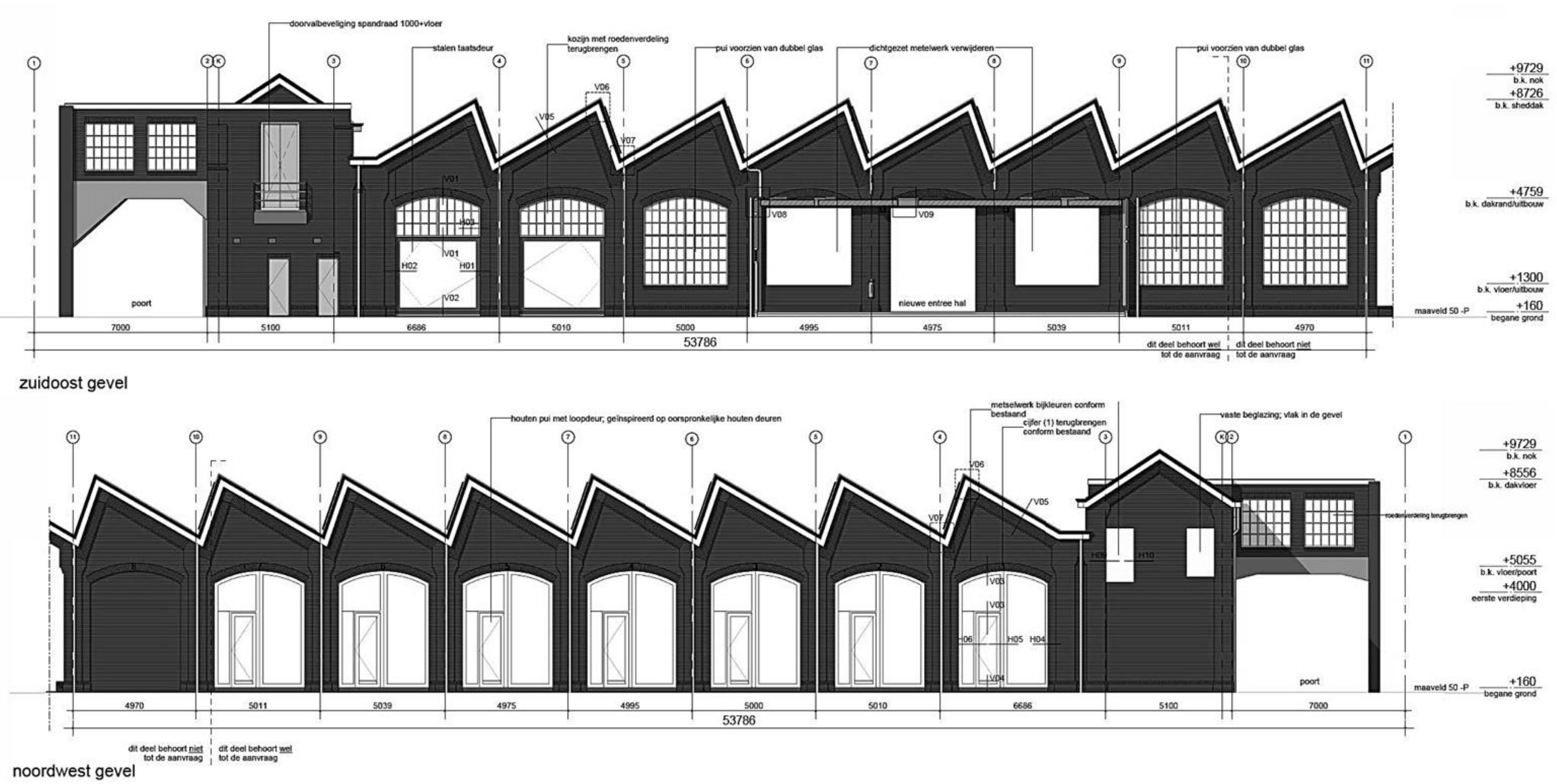
Appendix B Ground floor



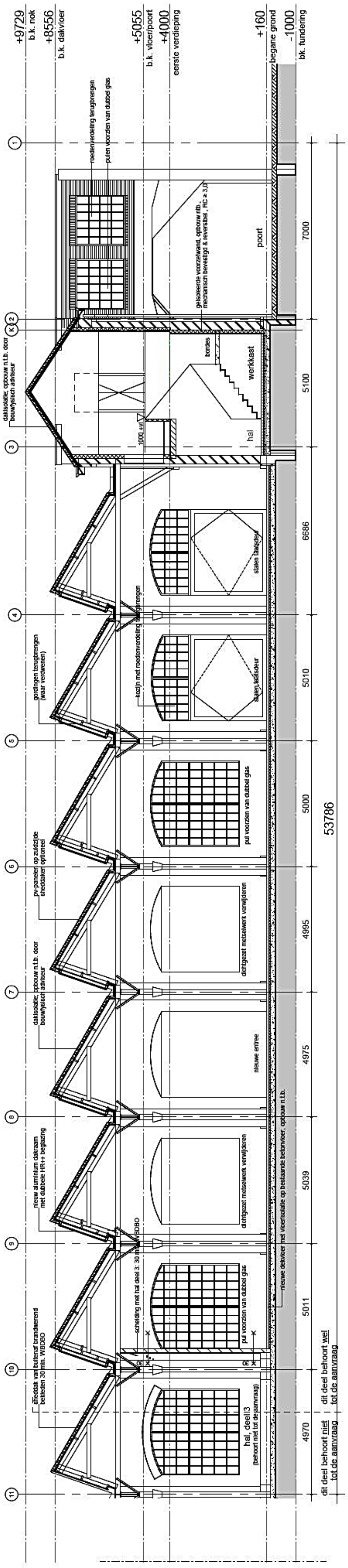
Appendix B First floor



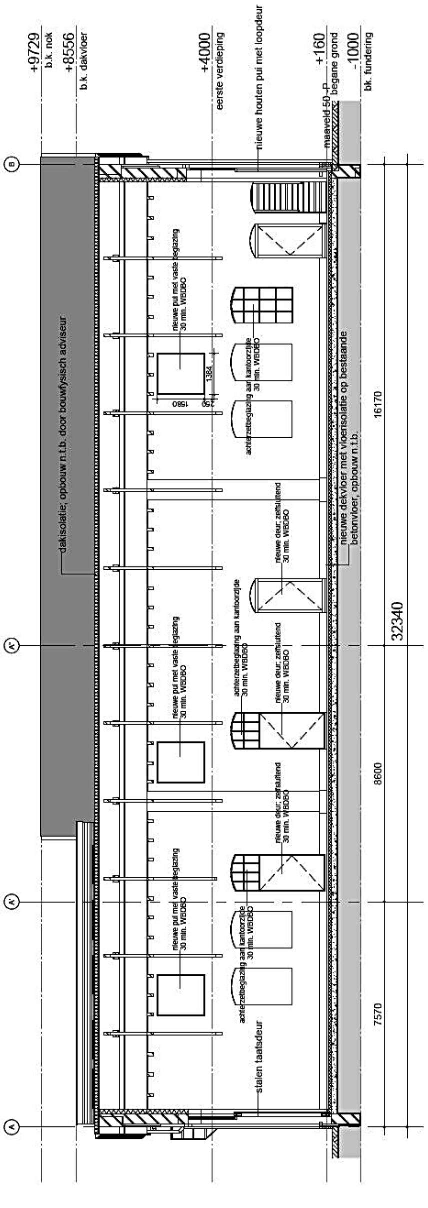
Appendix B View from above



Appendix B Southeast and northwest views of the exterior walls



doorsnede B-B



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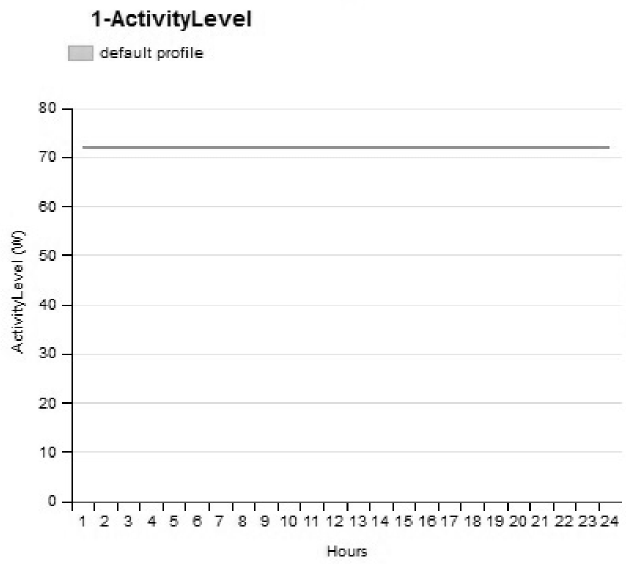
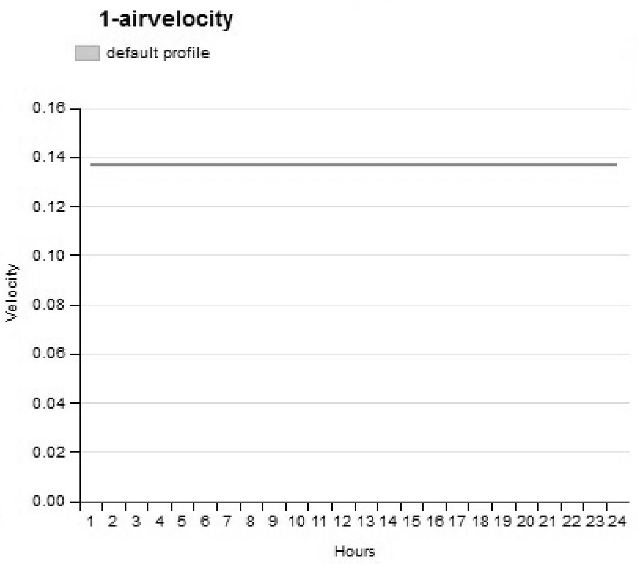
Building schedules


1-ActivityLevel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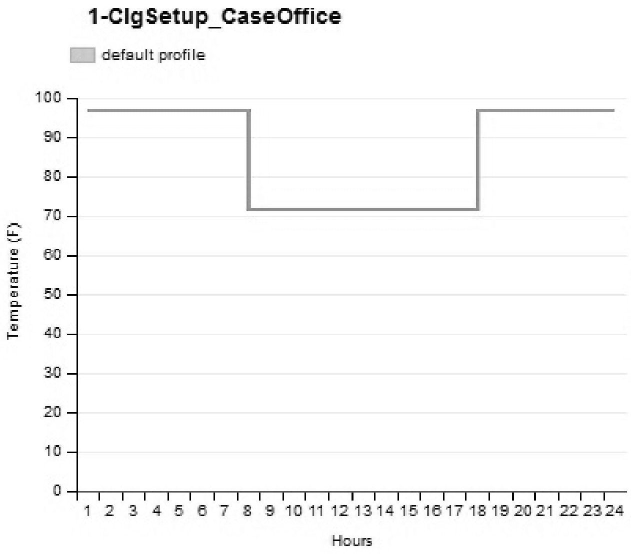
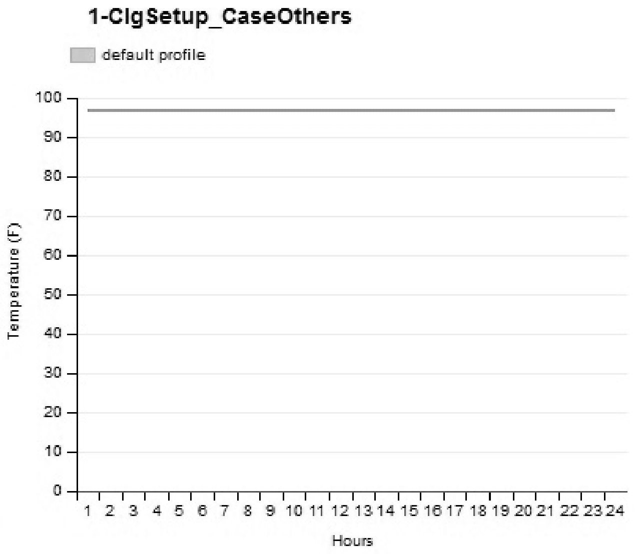
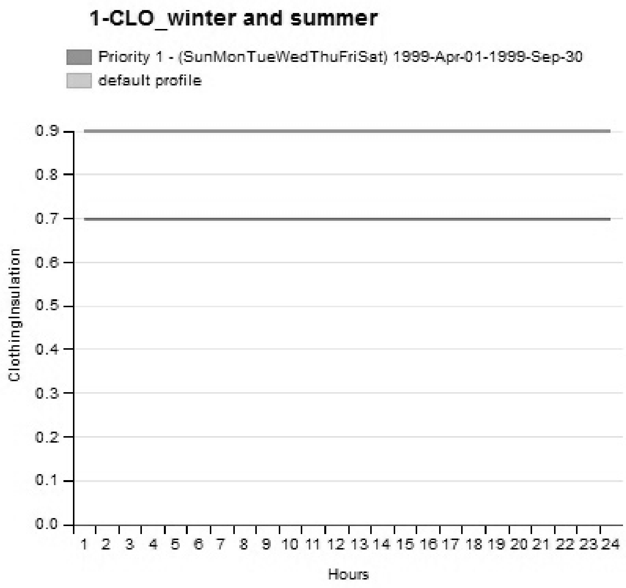
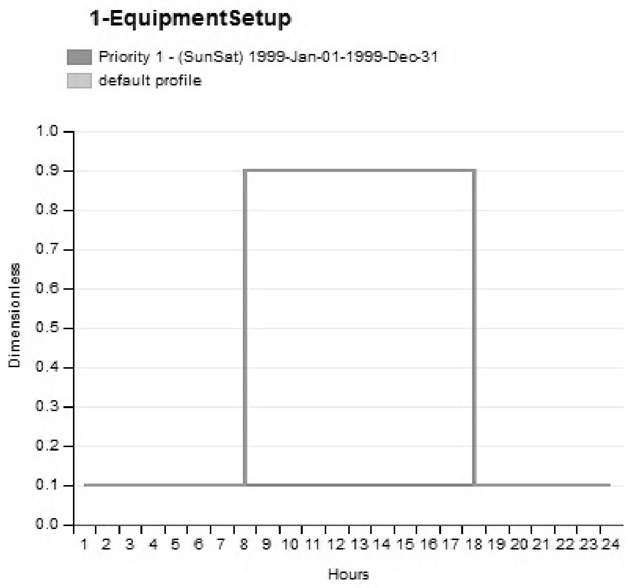
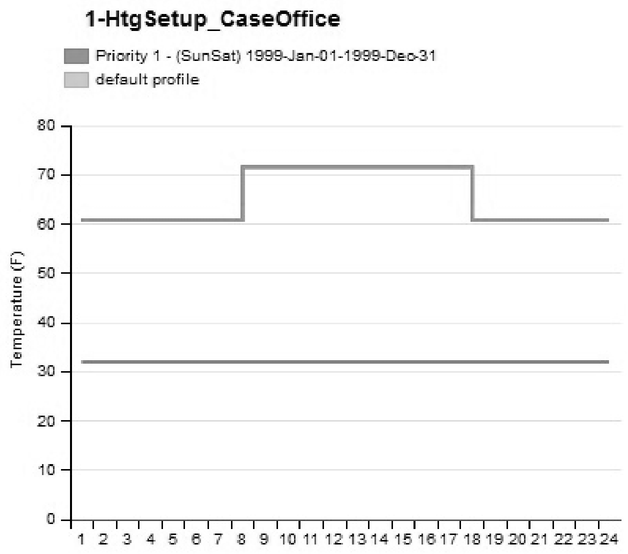

1-ClgSetup_CaseOffice


1-ClgSetup_CaseOthers


1-CLO_winter and summer


1-EquipmentSetup


1-HtgSetup_CaseOffice
Priority 1 - (SunSat) 1999-Jan-01-1999-Dec-31
default profile
Temperature (F)
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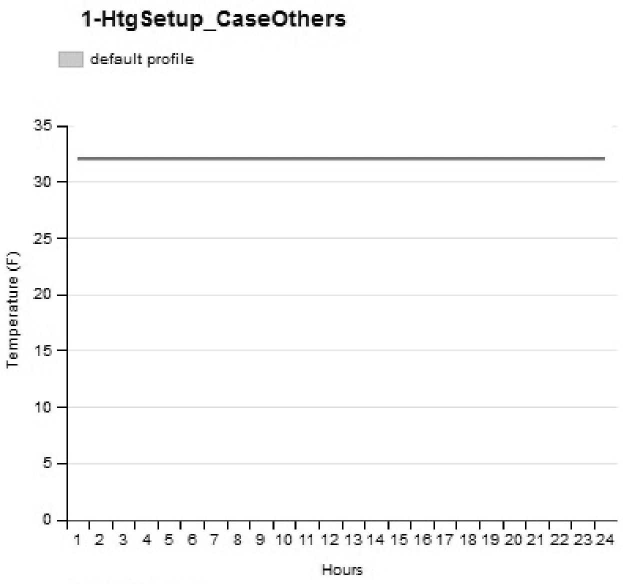
10
20
30
40
50
60
70
80
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24


1-HtgSetup_CaseOthers
default profile
Temperature (F)
0
5
10
15
20
25
30
35
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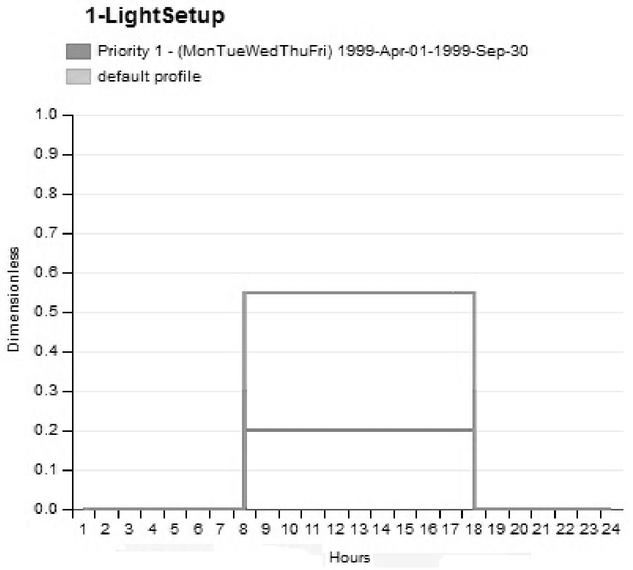
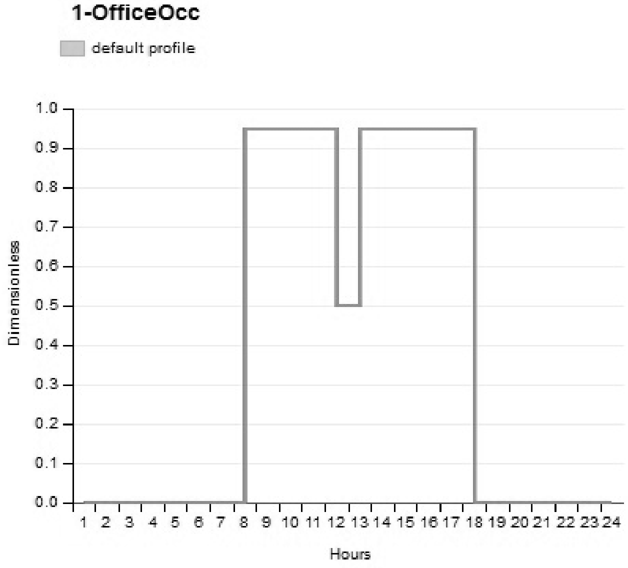
Hours


1-LightSetup
Priority 1 - (MonTueWedThuFri) 1999-Apr-01-1999-Sep-30
default profile
Dimensionless
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hours


1-OfficeOcc
default profile
Dimensionless
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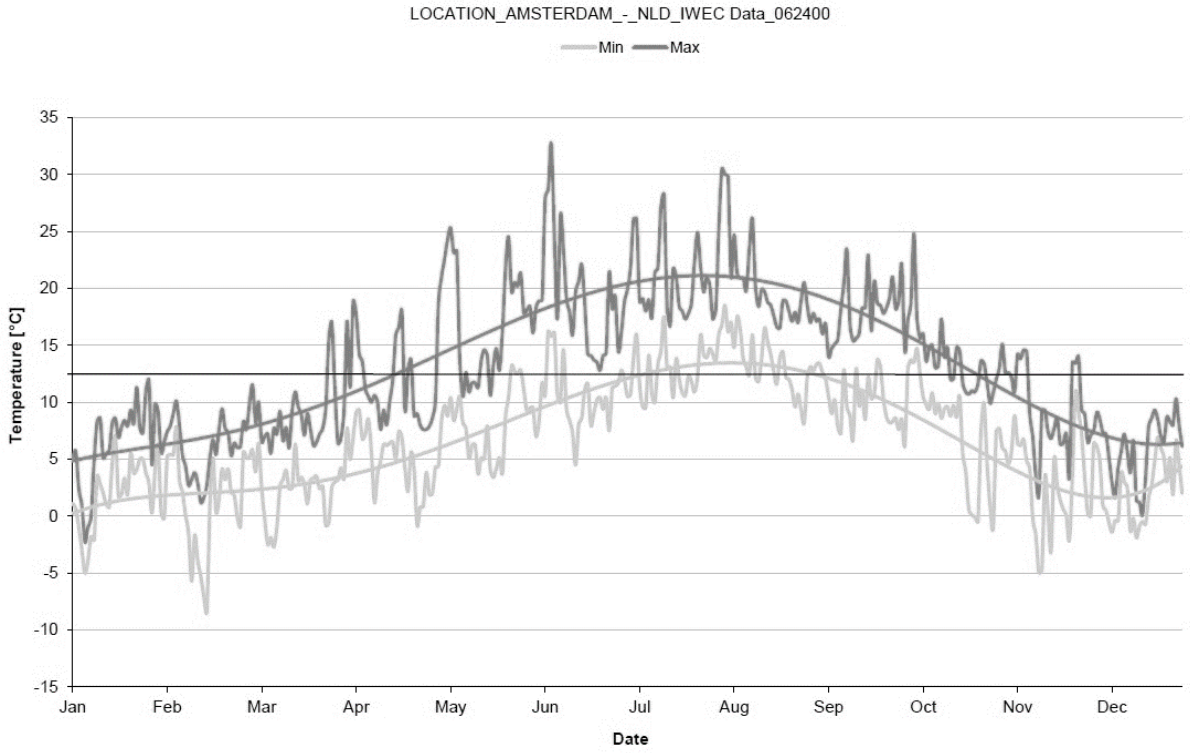
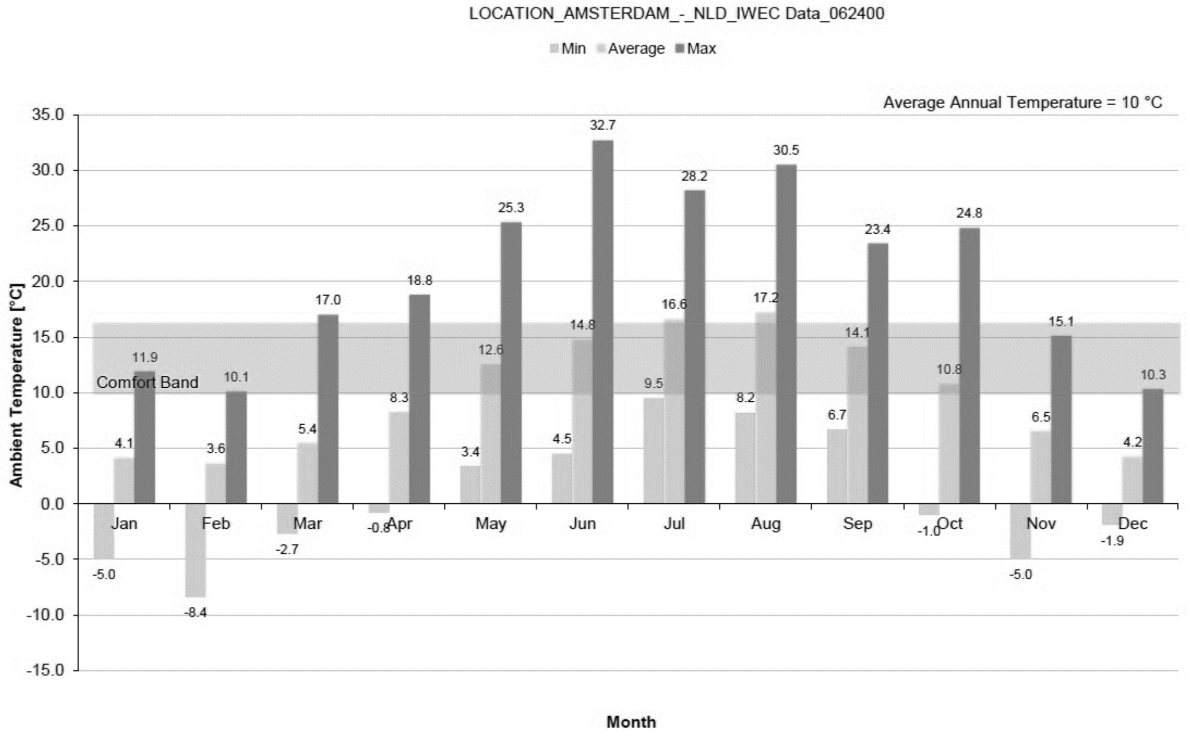
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hours

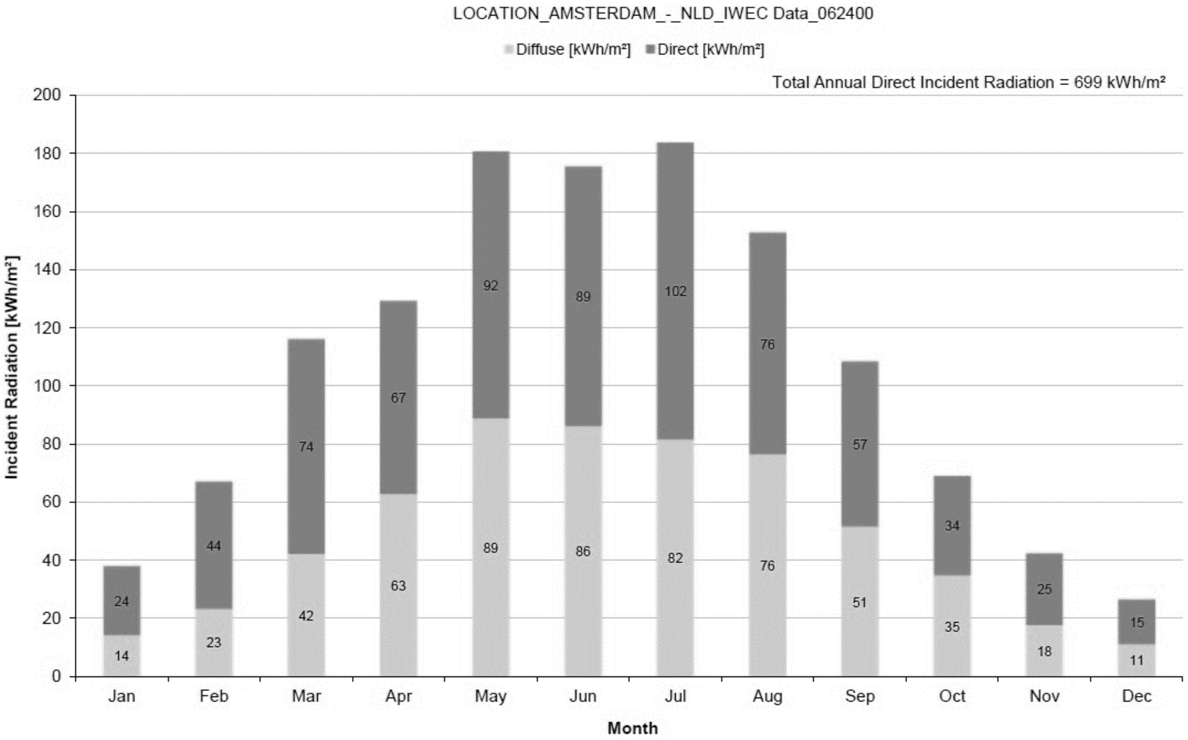
Weather data for the Netherlands



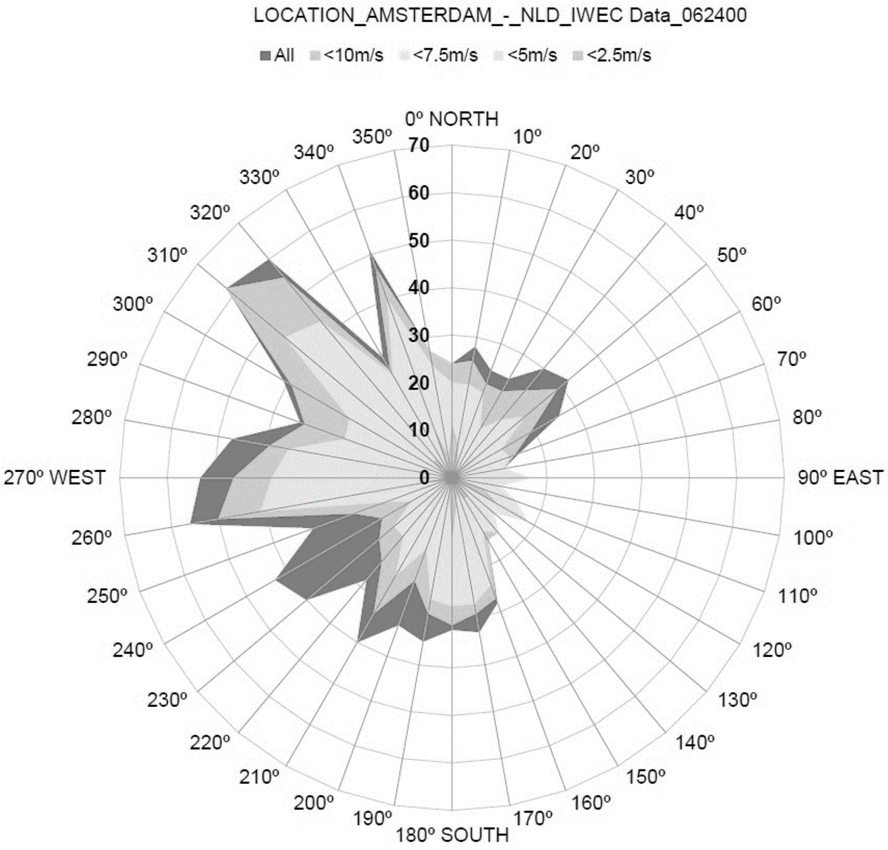
Appendix B Annual min. and max. temperature (ASHRAE, 2016)



Appendix B Monthly ambient air temperature (ASHRAE, 2016)



Appendix B Monthly incident radiation (ASHRAE, 2016)



Appendix B Wind direction and speed frequency in Amsterdam, the Netherlands (ASHRAE, 2016)

Appendix C – Supplementary data for retrofitting measures

Appendix C - Fenestration properties for proposed measures and the present state

Type	Build in mm and inert gas filling	normalized U_w in W/m^{2}K	T_{vis}	g-value	light reflexion
Present state	3	5.34	90%	84%	8%
Double, air	4-16L-4	1.35	82%	64%	12%
Double, argon	4-16AR-4	1.13	82%	64%	12%
Triple, argon	4-12AR-4-12AR-4	0.85	71%	51%	17%
Triple, krypton	4-12KR-4-12KR-4	0.71	71%	51%	17%
Triple, krypton, sun protective	4-12KR-4-12KR-4	0.64	57%	35%	29%

Appendix C - Heat pump systems

Heat pump type	Heat source	COP		Performance	
		Heating	Cooling	Heating	Cooling
Ambient air with heat exchanger	Air	4.5	3.2	200	130
Ambient air	Air	4	2.6	200	130
Ground	Ground	4.5	3	200	130
Groundwater	Groundwater	4.5	7	200	130

Appendix C - Small scale vertical and horizontal wind turbine systems (Agentschap NL, 2010b).

Type	Description	Power in kW	Rotor surface in m^2
DONQI	Horizontal turbine	1.75	1.8
Tulio	Horizontal turbine	2.5	19.6
Turby	Vertical turbine	2.8	5.8
Energyball v200	Vertical turbine	0.7	3.8