Retrofitting to reach climate goals

Energy label specific retrofitting of Dutch office buildings

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Abstract

The built environment is responsible for 40% of the total CO_2 emissions of the European Union (Dekker & Schuur, 2018). The Dutch Cabinet is aiming for a low-carbon building stock in 2050 (TNO, 2019). As incorporated in the Building Decree of 2012: by 2023, all office buildings bigger than 100 m^2 need to have at least energy label C and by 2030 energy label A (RVO 2, 2019). When an office building does not reach this energy label, the building cannot be used as an office anymore. The obligation for an energy label C affects 52% of the current office area and energy label A affects 75% (EIB, 2016). An effective way to improve the energy performance of existing buildings, is retrofitting (Ma et al., 2012). Much research has been carried out to determine the best retrofit options for existing buildings. However, they do not focus on reaching a certain energy performance level, e.g. energy label, after retrofitting. Based on this, the research aim was to build a Decision Support System (DSS) which considers the future mandatory energy labels, following the Dutch Building Decree of 2012, when selecting retrofit measures for office buildings in the Netherlands. The ISSO 75.3 was used as the guideline for the energy label calculation. This publication is widely used in the Dutch building sector. In addition, the DSS enabled the possibility to include the office building owner's preferences regarding costs and sustainability ambitions in the selection of retrofit measures. The DSS was tested on three office buildings and showed that the preferences of the owner highly impacted the proposed retrofit measures. The preferences of the owner could result in more retrofit measures proposed than needed to obtain energy label C or A. Regarding the financial and environmental implications of the retrofit measures, the highest investment costs are coupled to the retrofitting of the heat and cold suppliers. The highest energy use reduction and therefore CO_2 emission reduction is achieved by heat suppliers. When a heat pump is proposed as a suitable retrofit measure, it can be beneficial to wait a few years before installing. Its relatively short lifetime could namely interfere with the energy label A target year in 2030. Lastly, the robustness of the DSS was tested through a sensitivity analysis, which validated the results of this research. This research can be used to build other DSS using the energy requirements from different countries.

Keywords: Office building, Energy label, Retrofitting, Decision Support System (DSS)

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1. Introduction

The effect of CO_2 emissions due to human activities on the Earth's climate and the need to reduce them is widely acknowledged (Boasson & Wettestad, 2016; Schneider & Thompson, 1981; Sellers et al., 1996). A main contributor to the emittance of CO_2 is the built environment. In the European Union (EU), this sector is responsible for around 40% of energy-related CO_2 emissions (UN Environment and International Energy Agency, 2017). Utility buildings are one of the biggest contributors, being 60% more energy intensive than residential buildings (Rousselot, 2018). In the Netherlands, utility buildings account for 18% of the total CO_2 emissions, which equals 460 million m^2 floor area and approximately 380.000 buildings who are responsible for 280 Peta Joule. The largest contributors to the energy use in utility are industrial- and office buildings, 44% and 15% respectively (Dekker & Schuur, 2018).

The Dutch Cabinet is aiming for a low-carbon building stock in 2050 by promoting far-reaching CO_2 reduction measures. The target is set on reducing the emittance of CO_2 emissions by 49% in 2030 and 95% in 2050 compared to the reference year 1990 (TNO, 2019). To reach this goal, the government incorporated the following in the Building Decree of 2012: by the first of January 2023, all office buildings bigger than 100 m^2 need to have energy label C or higher (RVO 2, 2019). When an office building does not reach this energy label, the building cannot be used as an office anymore. By 2030, this target will be stricter and all office buildings bigger than 100 m^2 need to have energy label A or higher. The obligation for an energy label C affects 52% of the current office area. When setting the mandatory energy label A, 75% of the current office area does not comply with these requirements (EIB, 2016). This shows that there is a high need to improve the energy performance of Dutch office buildings in the coming years.

An effective way to improve the energy performance of existing buildings at relatively low cost and high uptake rates, is retrofitting (Ma et al., 2012). A retrofit involves modifications to existing buildings that may improve energy efficiency or decrease energy demand (U.S. Department of Energy, 2019). The effectiveness of retrofitting existing buildings to reduce energy use has been researched extensively. The OFFICE project by the Design and Evaluation Group showed that substantial reductions can be achieved in both thermal- and electrical energy use by using passive and low-energy technologies (Hestnes & Kofoed, 2002). Dascalaki & Santamouris (2002) stated that due to retrofitting, cost-effective energy savings in the order of 20-30% can be achieved. Ardente et al. (2011) showed with multiple case studies that substitution of insulation, lighting and glazing components provided significant reductions in energy use.

In addition, much research has been carried out to determine the best retrofit options for existing buildings. Ma et al. (2012) described a systematic approach to identify the best retrofit options for existing buildings. Chidiac et al. (2011) developed a method to screen office buildings for their current level of energy consumption and potential for retrofit technologies. Their decision for the best retrofit measures was influenced by climate, occupancy, heating and cooling systems, envelope properties and building geometry. Caccavelli & Gugerli (2002) developed a decision-making tool for selecting office building upgrading solutions considering deterioration, functional obsolescence of building services, energy consumption and indoor environmental quality.

What these methods have in common is that they all focus on the characteristics of the existing building and possible retrofit measures. When consulting these methods, the result will be a set of suitable retrofit measures for a specific building. However, they do not focus on reaching a certain energy performance level, e.g. energy label, after retrofitting. To effectively retrofit the Dutch office buildings according to the requirements of the 2012 Building Decree, this needs to be incorporated. In addition, to enable specific planning to reach these future climate goals, the time needed to install the retrofit measures should also be considered.

Based on this, the research aim is to build a Decision Support System (DSS) which considers the future mandatory energy labels, following the Dutch Building Decree of 2012, when selecting retrofit measures for office buildings in the Netherlands. In the selection of the retrofit measures suitable to obtain a better energy label, the cost and sustainability ambitions of the office building owner are incorporated. The DSS aims to advice to the office building owner about the financial and environmental implications of the selected retrofit measures. Therefore, the DSS answers the following research question:

What are the financial and environmental implications of different retrofit measures for office buildings when aiming to reach mandatory energy labels following the Dutch Building Decree of 2012?

To answer this research question and to develop the DSS, the following sub questions are answered first:

1. How are the Dutch energy labels for office buildings determined?

By answering this question, insight is given in the energy label system for office buildings in the Netherlands. The results are used to determine the criteria to obtain a certain energy label. For example, the yearly energy use of the building.

2. What are office building characteristics that determine its energy use?

This question provides insights in the characteristics of office buildings that determine the level of energy use. Examples of these characteristics are the amount of fresh air needed per occupant and heat production by appliances.

3. What are the available retrofit measures and their characteristics for office buildings in the Netherlands?

The result of this question is a list of the available retrofit measures in the Netherlands, which are considered in this research. In addition, the financial and environmental implications and the installation time corresponding to these measures are collected.

4. What are the decision variables for the office building owner when selecting retrofit measures?

The answer to this question describes the decision criteria for a certain set of retrofit measures for a building. These criteria are used in a Multicriteria Decision Analysis (MCDA) to compare the different retrofit measures and to incorporate the preferences of the office building owner.

The answers to the sub questions are used to build the DSS. The DSS is tested on three office buildings and the preferences of their owner. The results of the DSS are two sets of retrofit measures which aim to reach either energy label C in 2023 or energy label A in 2030. These sets are presented with their financial and environmental implications and their installation time. With these results, the research question is answered, and the research aim is reached.

At the moment, no retrofit decision model is available which considers the need to meet mandatory energy labels after retrofitting and shows the time needed to realize the retrofit measures. Since the energy labels of Dutch office buildings will be checked in the near future and specific planning is required to reach these energy labels, the need for such a model is high. With this research, more insights are given in the method to select retrofit measures for office buildings in the Netherlands considering these two variables. In addition, existing methods are compared on their strong and weak points to learn from when building this DSS. Lastly, this research contributes to the Dutch Cabinet's aim to reduce the energy consumption of the built environment.

This research was part of an internship at SPIE Nederland BV. SPIE is a specialist in the installation branch and one of their pillars focuses on energy efficient buildings. SPIE provides energy efficient electrical installations. For example, a unified digital platform, which enables building owners to manage their inside environment from a single interface. They are involved in a project called Road to Paris, in which multiple companies gather their knowledge to tackle the energy improvement challenge of existing office buildings in the Netherlands. With the results of this research, SPIE aspires to change the way in bringing in assignments. Instead of waiting for the client to come with a retrofit project to them, they want to approach possible clients with retrofit possibilities. The DSS aims to fit to this desire of SPIE. Lastly, SPIE hopes to use this DSS in other countries and for different types of buildings in the future. Therefore, the DSS is made in a way so adjustments and additions can easily be made.

The remainder of this research reads as follows. Section 2 describes important concepts in this research. Section 3 describes the methodology for using the DSS and generating the results. Section 4 gives an overview of the operation of the DSS, including screenshots from the model. Next, Section 5 describes the results of the DSS for three different office buildings. Section 6 includes the discussion of the results and of the operation of the DSS. Lastly, the conclusions are given in Section 7.

2. Theory

This chapter describes relevant theory regarding this research. Section 2.1 describes the development of the current and future energy requirements in the Dutch built environment. The concept of retrofitting and the energy flows in a building to be considered when retrofitting are described in Section 2.2. Section 2.3 describes the energy requirements for office buildings and their specific energy use. In addition, the retrofit measures suited for office buildings are specified. Section 2.4 gives an overview of the already existing DSS for retrofitting office buildings and describes the theory used to build the DSS. Lastly, Section 2.5 describes the decision criteria when retrofitting existing buildings.

2.1 The development of current and future energy requirements in the built environment

The development of energy requirements in the built environment started with the 1973 oil crisis (Zeiler, 2013). Due to political motivated oil embargos by the Organization of Arab Petroleum Exporting Countries (OPEC), the price of oil increased with nearly 400% (Francisco, 2004). Since the Netherlands imported most of its oil from the OPEC, this crisis forced the Dutch government to consider alternative sources and strategies for energy use. Before this period, the governmental regulations in the built environment were primarily concerned with the indoor environment and health. After this energy crisis, the focus shifted to saving energy. Between 1973 and 1990, energy efficiency and diversification became key subjects in new governmental energy policies (Zeiler, 2013).

The first Building Decree entered into force in 1992, stating technical building regulations for the entire country. Besides safety, usability and health requirements, also energy efficiency requirements where incorporated. For existing and new residential buildings, these requirements where based on thermal insulation and air permeability (Online bouwbesluit, n.d.). For new non-residential buildings, also an Energy Performance Coefficient (EPC) was introduced. The EPC is a figure expressing the energy performance of a building depending on the energy consumed for space heating and cooling, hot water, lighting, ventilation and humidification (Filippidou, Nieboer & Visscher, 2017). The non-building-related energy use is not considered, also referred to as use-related energy use. Examples are computers, household appliances and machines (NTA 8800, 2019). The EPC is based on an index number and uses the year 1990 as a reference. In 1990, the average energy use of a residential building corresponded to an EPC of 1.0. When a house has an index of 0.6, he uses 60% of the energy he would have used in 1990 (Lepper, 2018). The lower the EPC, the more energy efficient the building should be (Santin, Itard & Visscher, 2010). The aim of the introduction of the EPC was to stimulate energy savings and the use of sustainable energy (Eco-logisch, 2020). In 1995, the EPC was incorporated in the Dutch building code of the 'Sustainable Building Plan: Investing in the Future', making it applicable to new residential buildings as well (Zeiler, 2013). If the EPC were to be calculated in 1995, the EPC for residences would been on average 1.5. The first EPC requirement was therefore set at 1.4 (Maldonado, Wouters, & Papaglastra, 2011). This gave the market time to get used to the new requirements and to adapt the construction method accordingly (Scheffe, 2015). Every couple of years these requirements are tightened. This tightening has gone hand in hand with innovation in construction and installation technology (Valk, 2014).

In the past, a certified EPC calculation for new buildings was enough to demonstrate that a building met EPC requirements (RVO 1, n.d.). Since 2008, a national labelling scheme is added to these requirements (Majcen, Itard & Visscher, 2013). Each building that is being sold, let or newly built, must carry an energy label. These requirements correspond to the 2002 Directive on the Energy Performance of Buildings (EPBD) by the EU (European Commission, 2002) and were incorporated in the Dutch Building Decree of 2012. With the introduction of an energy label, the government aimed at stimulating building owners to retrofit their buildings even more. Making these requirements applicable to all buildings, new and existing. In contrast to the EPC, an energy label includes retrofit possibilities for the corresponding building (RVO 2, n.d.). Moreover, an energy label contains the following: 1) the result of the energy performance calculation, 2) reference values which can be used to compare and assess the energy performance, and 3) recommendations for a cost-optimal or cost-effective improvement in energy performance, unless there is no reasonable potential for such an improvement in relation to the applicable energy performance requirements (Overheid.nl, 2006). The energy labels range from G to A, with A being the most energy efficient.

The energy label for new building is based on the EPC calculation. For existing buildings, another method is introduced, since exact specifications of structures and details (such as thermal bridges) of many existing buildings are not known (RVO 2, n.d.). The energy label for existing buildings is determined using the Energy-Index. The Energy-Index (EI) is described as a figure indicating the energy consumption based on the amount of energy deemed necessary for the different needs (also described as the allowed energy use) related to the standardized use of a building (Artikel 3.1 of Besluit energieprestatie gebouwen, 2019). The EI typically takes values between 0 (extremely good performance) to 4 (extremely bad performance) (Filippidou et al., 2017). In the ISSO 75.1 publication (2013), these values are linked to an energy label, as presented in Table 1.

Table 1: Energy label with corresponding Energy-Index (ISSO 75.1, 2013)

Energy label	**Limits Energy-Index**
A	≤1.05
B	1.06 – 1.15
C	1.16 – 1.30
D	1.31 – 1.45
E	1.46 – 1.60
F	1.61 – 1.75
G	>1.75

Up to 2014, the need of an energy label was not enforced. In most cases the buyer and seller of a building agreed on the absence of an energy label when little benefit was expected from it (Vringer, Van Middelkoop & Hoogervorst, 2016). However, research by Brounen and Kok (2011) has shown that buildings of high energy efficiency were being sold sooner and for a higher price. This resulted in an incentive for sellers to provide such an energy label. Since the beginning of 2015, every homeowner is obliged to register the energy label of his home. However, on October 17, 2018, the Council of State ruled that the enforcement of the energy label system is legally rattling. If the energy label for the property sold is not yet registered as final, the seller risks a fine of € 405. That fine is in the first instance a "penalty payment". This means that the seller is given the option of applying for the energy label in the short term. If this is done, there will be no fine. But the energy label can only be requested by the owner. And so, after passing the deed, the seller of the house can no longer apply for the energy label. He is then no longer the owner (Samen energie besparen, 2018). To overcome this, the Human Environment and Transport Inspectorate (ILT) has announced that as of July 3rd, 2019, it will immediately impose a fine without the possibility of rectifying this afterwards. The fine is € 170 for individuals and € 340 for organizations (Leeuw, 2019). In addition, as of July 1st, 2020, an energy label can only be granted by a professional. Vereniging Eigen Huis (2019) criticizes this measure, because it merely increases the costs. They expect that this will reduce support by building owners.

2.1.1 Future developments building energy requirements

With the rising awareness of climate change, more attention is given to clean energy in addition to energy efficiency. In 2013, more than 40 organisations and the government agreed upon the Energy Agreement (Energieakkoord in Dutch). The aim of this agreement is to secure an affordable and clean energy supply. They also aim to create jobs and exploit economic opportunities for the Netherlands in the clean technology markets. The Energy Agreement covers energy savings, sustainable supply, clean technologies and climate policy (SER 1, n.d.). The regulations are divided into twelve domains, of which one covers the built environment. The following points describe the governmental ambition for the built environment (SER 2, n.d.):

- Energy neutral built environment in 2050
- Up until 2020, annually 300.000 existing dwellings and other buildings at least two steps higher in energy label
- All new construction almost energy neutral from 2020
- Minimum energy label B in 2020 for houses of rent corporations
- 80% energy label C in 2020 for private rental houses
- Energy saving in built environment contributes to an average of 15.000 extra full-time jobs per year
- The built environment (buy, rent and real estate) contributes 53 PJ to the intended energy savings of 100 PJ in 2020

These ambitions resulted in an information obligation for existing buildings, from July 2019 onwards (see Figure 1). Which means that the building owners are obligated to report the energy label of their building (RVO 3, 2019). This obligation is the starting point for the introduction of mandatory energy labels and the control of these labels. The first mandatory energy labels are set for office buildings. Following the Building Decree of 2012, starting the first of January 2023, office buildings must have an energy label C or higher. In 2030, office buildings must at least have an energy label A. When an office building does not reach these energy label targets, its use will be prohibited as of that date (Christ, 2018). The competent authority for the Building Decree - usually the municipality where the office building is located - is responsible for enforcing these energy label obligations. They can take various measures: from giving a warning to imposing an order subject to periodic penalty payments, administrative enforcement or - in the event of repeated violations - an administrative fine. The competent authority will consider for each situation which enforcement measures are necessary and desirable (RVO 5, n.d.). However, there is much uncertainty on how strictly the requirements will be enforced (Christ, 2018). This is of importance since the enforcement of the requirement is a big part of the incentive for office building owners to retrofit. Moreover, real estate markets fear that office owners who wait until 2022 to make their offices more sustainable will face a shortage of construction workers who is able to take retrofit measures (Eerenbeemt, van den, 2018).

Following the energy saving ambitions of the Dutch government in the built environment, the current EPC is no longer adequate. For example, you can place a large glass wall in a building and meet the EPC requirement by compensating these energy losses through the glass with solar panels; the current construction requirement does not take into account the energy loss of the building due to its shape (RVO 3, n.d.). Hence, the current requirement does not promote energy saving as much as possible. For that reason, the Dutch government is working on a new method to calculate the energy performance of new buildings, the NTA 8800. The NTA 8800 follows the European standards and replaces the current EPC with the energy requirement per square meter (kWh/m^2) (NEN, 2020). The energy requirement per square meter will be used to set the Nearly Zero-Energy Buildings (NZEB) requirements. The NZEB requirements are based on the Trias Energetica, which is explained more elaborate in Section 2.2. It is not possible to improve the energy performance by solar panels while the building envelope is not insulated when considering the Trias Energetica. The 3 NZEB requirements differ per type of building and are based on the following parameters (RVO 4, n.d.):

1. the maximum energy requirement in kWh per m^2 of usable area per year;
2. the maximum primary fossil energy consumption, also in kWh per m^2 usable area per year;
3. the minimum of renewable energy in percentages.

The introduction of the NTA 8800 is delayed until the 1st of January 2021 (Tweede Kamer, 2020). The reason for this delay is the yet unavailable calculation software to determine the energy performance of buildings based on this NTA 8800 method. After the introduction for new buildings, it is expected that these requirements will be implemented for existing buildings as well, since one of the ambitions of the Dutch government is an energy neutral built environment in 2050. These developments and the energy label requirements for office buildings as described are presented on a timeline in Figure 1.

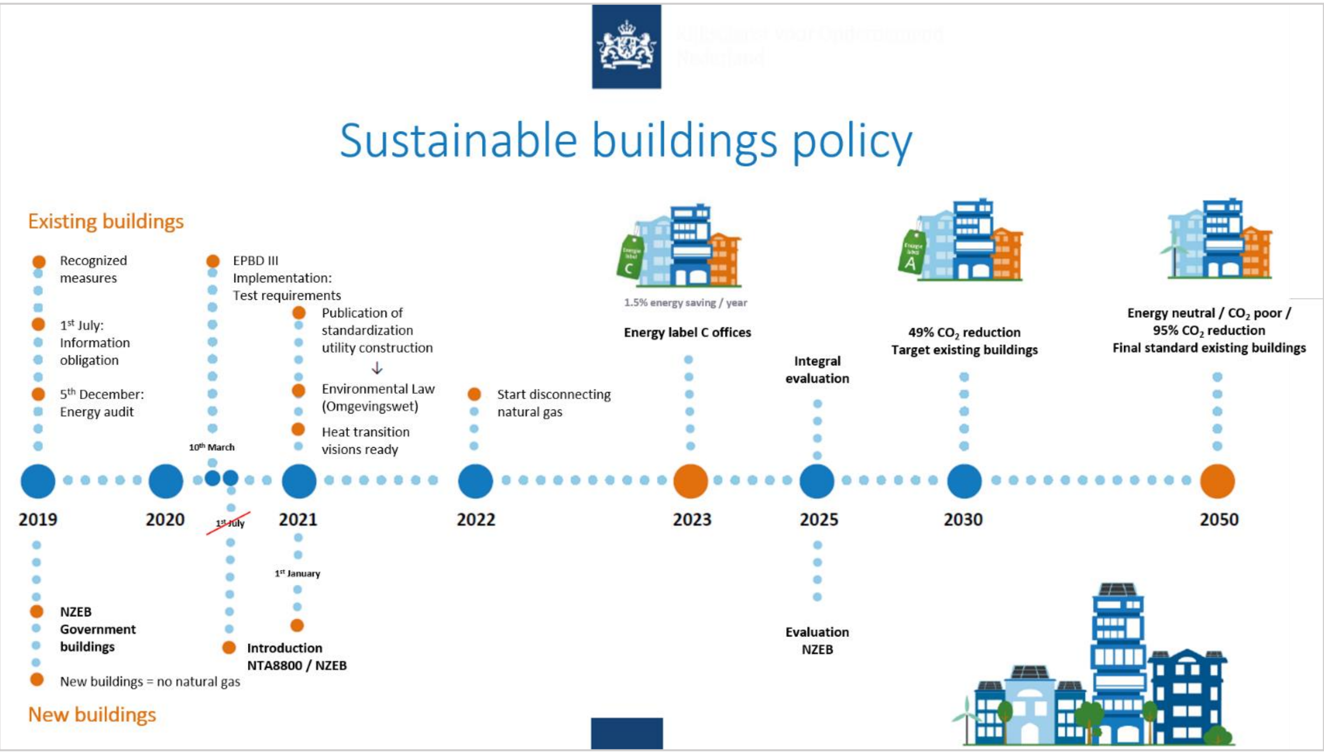

Figure 1: Sustainable building policy timeline (RVO 1, 2019)

2.2 Retrofits based on Trias Energetica

An effective way to improve the energy performance of buildings and to come to the required energy labels, is retrofitting. Retrofitting is described as the directed alteration of the fabric, form or systems that comprise the building to improve energy, water and waste efficiencies (Eames et al., 2014). In this research, the focus lies on the improvement of the energy efficiencies and therefore reduce the energy use. The Trias Energetica is the most used strategy to select energy saving measures (RVO, 2013). The use of a strategy to determine retrofit measures is of importance, because this ensures the optimal result in both costs and energy use reduction. The Trias Energetica states that the energy demand should be reduced first. This results in the best base for the implementation of renewable energy technologies and energy efficient installations (RVO, 2013).

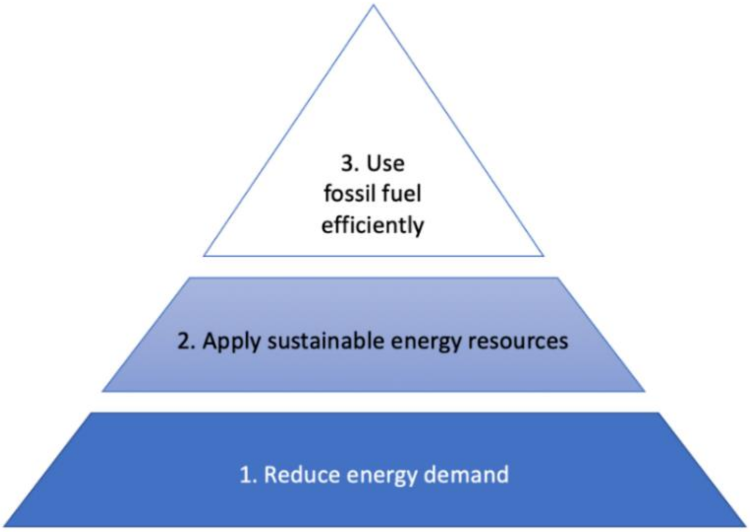

Figure 2: Trias Energetica (RVO, 2013)

Figure 2 presents the three levels of the Trias Energetica, which should be followed in that order. They are explained as follows (Brouwers & Entrop, 2005):

1. Take measures which reduce the energy use of the building, for example insulation and efficient ventilators;
2. Use as much sustainable energy resources as possible to fulfil the energy demand;
3. In case of insufficient supply of energy by sustainable energy resources, it is necessary to use fossil fuel resources. Use this energy supply as efficiently as possible, for example by replacing an old boiler with a more efficient one.

2.2.1 Energy use of a building

To reduce the energy use of a building, it is important to know which elements of a building determine this energy use. Figure 3 describes the energy use of a building through the different energy flows and system boundaries. The energy use of a building is determined by the energy demand for heating, cooling, ventilation, domestic hot water (DHW), lighting and appliances. This is represented as the energy need in the green box in Figure 3. Moreover, the energy demand for heating and cooling is determined by a preferred inside temperature. The inside temperature is influenced by the heat exchange through the building envelope and the solar and internal heat gains. These two factors therefore impact the energy need of the building (Kurnitski et al., 2011). Therefore, the net energy need is the energy need minus these two factors. The net energy need is supplied by the building technical systems (the blue box in Figure 3). Examples of these building technical systems are boilers and air-conditioners. The building technical systems need energy inputs, like electricity or fuels, to deliver the needed output. The energy input is depended on the system losses and energy conversion in some systems (i.e. heat pumps, fuel cells). The energy input for these building technical systems comes from delivered energy to the building or from onsite renewable energy (without fuels). The energy delivered to the building contains electricity from the grid, district heating and cooling and fuels. This makes up the net delivered energy to the building (Kurnitski et al., 2011). To conclude, the energy use of a building depends on the energy need, the solar and internal heat gains, the heat exchange through the building envelope and the system losses of the building technical systems.

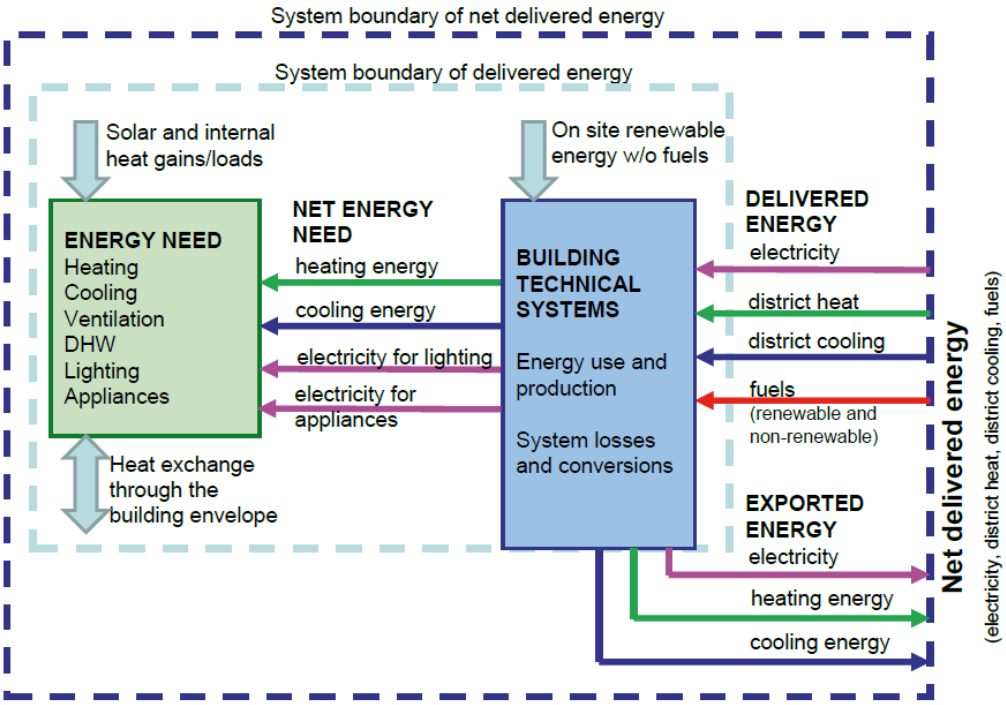

Figure 3: Energy boundaries of a building (Kurnitski et al., 2011)

2.2.2 Heat balance of a building

As discussed in Section 2.2.1 and shown in Figure 3, the heating (and cooling) demand of a building is determined by the heat exchange through the building envelope and by solar and internal heat gains. This heat exchange comes in two forms: sensible heat and latent heat. Sensible heat flow results in a change in temperature, which flows from hot to cold. Latent heat flow results in a change in moisture content (humidity), which flows from areas of greater concentration to areas of lower concentration. These two flows together determine the total heat flow and the inside comfort to occupants (BPAC, n.d.).

Sensible heat flows between two areas in three ways: 1) Conduction, which is described as the heat transfer between substances which are in direct contact with each other, 2) Convection, which is de movement of gases and liquids caused by heat transfer, and 3) Radiation, which occurs by electromagnetic waves (from the sun, for example) (BPAC, n.d.). The rate of heat flow depends on (The Open University, n.d.):

- the temperature difference between the two sides
- the total area available for the flow
- the insulating qualities of the material.

Hence, more heat flows through a large area of wall or window than a small one, and more when there is a bigger difference between preferred inside temperature and the outside temperature. The different heat flows in a building are shown in Figure 4.

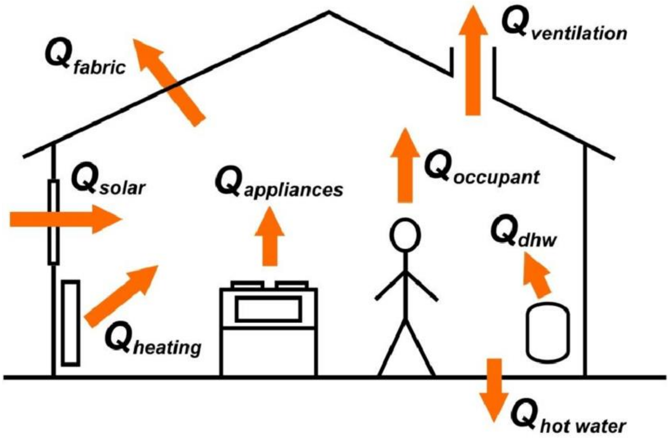

Figure 4: Heat balance of a building (Simon, 2017)

In Figure 4, Q represents the heat flow (Simon, 2017). As can be seen, heat enters the building though solar irradiation, heating generators (e.g. radiators), appliances, occupants and DHW. Heat is loss from the building through fabric, ventilation and hot water. Heat loss through the fabric (e.g. building envelope) depends on the difference in temperature between two side and the characteristics of the building fabric (as described above). The building fabric comprises walls, floors and the roof, as well as windows and doors. To overcome this heat flow, attention should be paid to the insulating qualities of the materials. Moreover, the amount of heat loss through the building envelope depends on the insulation value of the surface. This value is presented by the U-value, also described as the rate of heat flow through the material. This value is measured in W/m^2K. The U-value of a building surface is determined by the thickness of the surface and the thermal conductivity. In addition to the building envelope, much heat is loss through ventilation as well. The heat loss through ventilation is described as the passage of air through the building. This means the controllable air movement through openable windows, extractor fans, or a mechanical ventilation system (The Open University, n.d.).

2.2.3 Building retrofit measures

To improve the energy performance of a building, multiple retrofit measures are available. Ma et al. (2012) described three main categories of building retrofit technologies: demand side management, supply side management and energy consumption patterns. These three categories are linked to the concept of the Trias Energetica: reduce energy demand, apply sustainable energy resources and use fossil fuel effectively, respectively. Hong et al. (2019) divided these three main categories into five subcategories. These are the following: building envelope, equipment system, new/renewable technology, energy conserving behaviour and energy management and control systems. See Table 2 for an overview and corresponding retrofit measures.

Table 2: General building retrofit measures and classification (Ma et al., 2012; Hong et al., 2019)

Trias Energetica	Building Retrofit Classification	Building Retrofit Measures
Reduce energy demand	Building Envelope	– Building fabric insulation (i.e., ceiling, wall, etc.) – Windows retrofits (i.e., multiple glazing, low-E coatings, shading systems, etc.) – Airtightness – Cool roofs and coatings – Floor retrofits, etc.
	Equipment System	– Natural ventilation – Control upgrade – Lighting upgrade – Energy-efficient equipment (HVAC, water heating, lift, etc.) – Thermal storage and heat recovery, etc.
Apply sustainable energy resources	New/Renewable Technology	– Solar PV/PVT systems – Solar thermal systems – Biomass systems – Electric system retrofits – Geothermal systems – Wind power systems, etc.
Use fossil fuel effectively	Energy Management and Control System	– Management and maintenance (i.e., review service systems, energy sourcing, utility rate structure, etc.) – Access to control (i.e., automatic control systems, optimization control strategies, etc.)
	Energy Conserving Behaviours	– Occupancy regimes, schedules and activities – Comfort requirements – Staff training – New management scheme – Monitoring strategies, etc

2.3 Office buildings: requirements and typical energy use

An office building is described as a building, or part of a building, where the use area (in m^2) with an office function is larger than the use area of the individual other building functions in that building. The office function is therefore the main function and not an ancillary function (RVO 5, n.d.). As described in Section 2.1.1, office buildings will be obligated to energy label requirements in the future. However, in some circumstances an exception is made, and the energy label requirements do not apply (Christ, 2018; Online bouwbesluit, n.d.):

- the office building is part of a (larger) building and the total usable area for office functions is less than 50% of the total usable surface area of that building;
- the total usable area for office functions and ancillary functions in the office building or the building in which the office building is a part is less than 100 m^2;

- an office building that is mentioned in Article 2.2 Energy Performance Buildings Decree. Examples are:
    - an office building that is a national monument;
    - an office building that is only used for a maximum of two year

As described in Section 2.1.1, the NZEB requirements will be introduced for new buildings in 2021 by the Dutch government. The NZEB requirements for new office buildings are shown in Table 3 (RVO 4, n.d.). It is expected that these requirements will be introduced for existing buildings as well in the future.

Table 3: NZEB requirements office buildings

	Energy requirement [kWh / m^2.yr]	**Primary fossil energy consumption [kWh / m^2.yr]**	**Share of renewable energy [%]**
Office building	50	25	50

2.3.1 Energy use office building

To successfully retrofit office buildings, it is useful to know their specific energy use. The spread of energy use in a typical office building is presented in Figure 5 (Liu et al., 2011). Heating represents the highest energy consumption in an office building. The second biggest contributor is lighting.

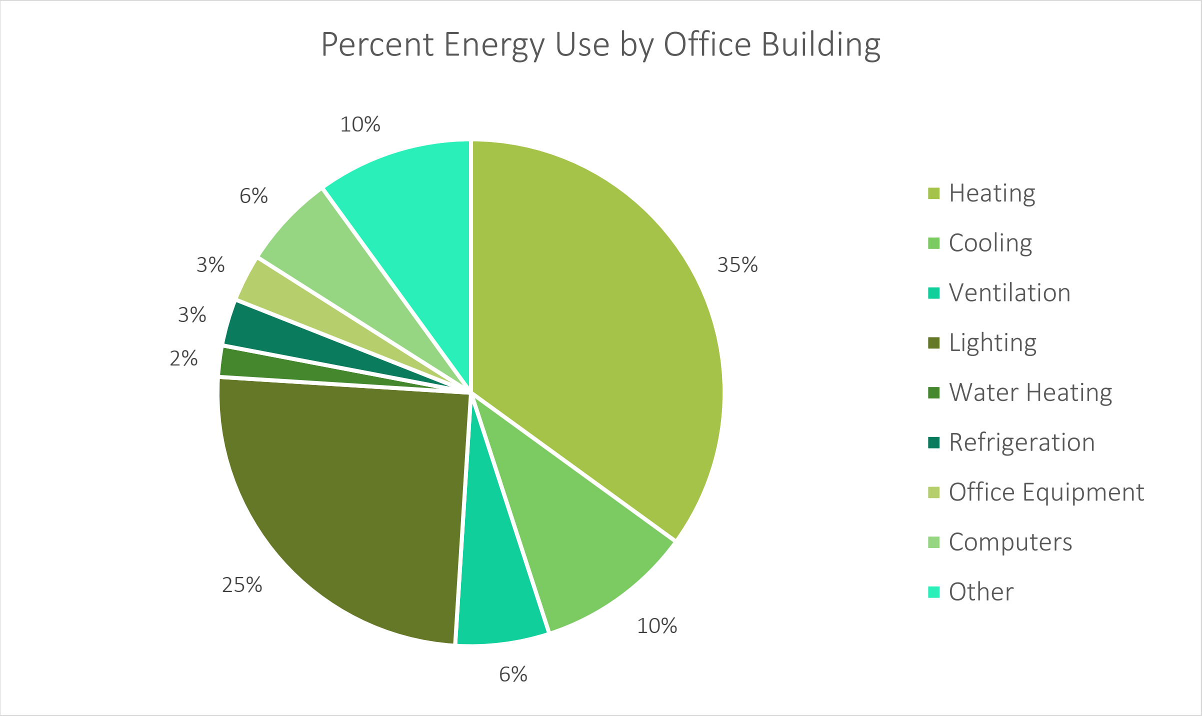

Figure 5: Percent Energy Use by Office Building (Liu et al., 2011)

2.3.2 Retrofit measures suitable for office buildings

This section describes the retrofit measures suitable for office buildings. From the building retrofit classification described in Section 2.2.3, the category Energy Conserving Behaviour is not suitable to reduce the energy use of an office building. Since most of the office buildings are rented and can be rented by other people in the future, the behaviour of occupants can differ per renter. It can therefore not be assumed that the behaviour will stay the same after being changed to improve the energy performance of an office building. In addition, the behaviour of occupants is not part of the energy label calculation (ISSO 75.3, 2011). The energy label can therefore not be improved by changing the behaviour of occupants. The categories Building Envelope, Equipment System, New/Renewable Technology and Energy Management and Control System are suitable for retrofitting office buildings and can be included in the energy label calculation.

Building Envelope

Wall insulation

The insulation of construction parts impacts the energy use of the building as described in Section 2.2.2. This section describes the different insulation materials for walls. In buildings there are commonly two types of walls, cavity walls and solid walls (Isolatie-info.nl, n.d.). If a cavity wall is present, the insulation can be placed within the wall. When this is not the case, the wall can be insulated on the outside of the building or on the inside. The most used insulation materials and their corresponding U-value are shown in Table 4 (Isolatie-info.nl, n.d.; Isolatiemateriaal.nl 1, n.d.; Baveco et al., 2015).

Table 4: Wall insulation materials per installation method

Type of wall	Installation method	Material	U-value [W/m^{2}K]
Cavity wall	Cavity insulation	Glass wool	0.32-0.40
		EPS pearls	0.32-0.36
		PUR	0.23-0.35
Solid	Outside	EPS	0.36
		XPS	0.34-0.36
	Inside	PUR	0.22
		Glass wool	0.30
		Rock wool	0.30

Roof insulation

A roof can be insulated on the inside and on the outside. Outside insulation can be considered, since office buildings can have flat roofs. The most used roof insulation materials are glass wool, rock wool, PUR and PIR (Dakdek-gigant.nl, 2020). See Table 5 for the roof insulation materials corresponding to the installation method (Dakisolatie-advies.nl, n.d.; Isolatie-weetjes, n.d.).

Table 5: Roof insulation per installation method

Installation method	Material	U-value [W/m^{2}K]
Inside	Glass wool	0.32-0.40
	Rock wool	0.32-0.40
	PUR	0.23-0.35
Outside	PIR	0.23-0.26

Floor insulation

For the insulation of the floor, a distinction is made between two types of floors: wood and concrete. The type of insulation material namely depends on the type of floor. A wooden floor can be insulated from below, while a concrete floor can also be insulated on top. The most used materials for floor insulation and their corresponding U-values are shown in Table 6 (Isolatiemateriaal.nl 2, n.d.; Isolatie-info.be 1, n.d.).

Table 6: Floor insulation per installation method

Type of floor	Installation method	Material	U-value [W/m²K]
Wood	Below	Glass wool	0.22
		Rock wool	0.54
Concrete	Below	EPS	0.36
		PIR	0.31
	On top	EPS	0.36
		XPS	0.66
		PIR	0.31
		PUR	0.26

Windows

The next retrofit measure regards the outside windows of the building. They impact the energy use of the building by their U-value and the ZTA-value. The ZTA-value is a characteristic of a glazing type and represents the total amount of solar energy transmitted through the glass. This value lies between 0 and 1. The higher the ZTA-value, the more heat enters (help.vabi.nl, n.d.). There are six types of windows suitable for office buildings, shown in Table 7.

Table 7: Glazing types and corresponding U- and ZTA-value

Glazing type	U-value [W/m²K]	ZTA-value [-]
Single clear glass	5.37	0.73
Double glazing	3.20	0.63
HR glass	2.00	0.59
HR + glass	1.52	0.56
HR ++ glass	1.10	0.52
Triple glazing	0.80	0.45

Awning

Awning is a suitable retrofit measure since it can reduce the energy needed for cooling by blocking incoming solar radiation. The most suitable awning for office buildings are screens. They are weather resistant, let through the light and can be connected to an energy management system (Zonweringgigant.nl 1., n.d.). Screens can reflect up to 90% of the incoming solar radiation, keeping the building cooler at sunny days (Zonweringgigant.nl 2, n.d.). Only automatic awning is considered, since this ensures the use of awning at higher floors.

Equipment system

Heat generators

The ISSO 75.3 (2011) describes multiple heat generators for buildings. The ones suitable for office buildings are CHP (Cogeneration), electric installation, heat delivery by third parties, direct fired air heater, HR-107 boiler and a heat pump. A heat pump can have different types of heat sources. The four most common are soil/outside air, heat from return/exhaust air, ground water and surface water (Warmtepompplein.nl, n.d.). The heat generators impact the energy use of the building through their generation efficiency and impact the operational CO_2 emissions of the building through the fuel needed.

Cold suppliers

The cold suppliers cool down the building on warmer days. The ISSO 75.3 (2011) describes multiple cold suppliers for buildings. These are all suitable for the cooling of office buildings. They are a compression cooling machine, absorption cooling machine on heat supply by third parties, absorption cooling machine on CHP, cold storage and a heat pump in summer operation (in combination with cold storage). The cold suppliers linked to a heat generator, for example the absorption cooling machine on CHP is linked to the CHP, can only be installed when the corresponding heat supplier is also installed.

Lighting

The improvement of lighting ranges from conventional to LED lighting. There are three types of lights who are most used in office buildings according to SPIE. Namely, TL-D, PLC and TL-5 lights. See Figure 6-8 for an example of these lights.

Figure 6: TL-D light

Figure 7: PLC light

Figure 8: TL-5 light

The conventional lights can be replaced by LED versions. This reduces the energy use, since a conventional light of a certain wattage can be replaced by a LED light of a lower wattage. In addition, for conventional lights, the energy use including ballast is higher than the installed wattage because of the energy needed to start the light. Therefore, the energy use of a conventional light is even higher than the installed power. This difference is almost 16%, which is based on calculations made by Eleqtron[1]. The corresponding LED lights are found on Budgetlight.nl (n.d.). The energy use of a LED light is the same as its power since it does not need extra power to be turned on. The type of lights and their corresponding LED versions are shown in Table 10.

Table 8: Lights per W and corresponding LED version

Type of light	Power [W]	Energy use incl. ballast [W]	Power LED [W]	Energy use LED [W]
TL-D	18	21	9	9
	36	42	18	18
	58	68	20	20
PLC	9	11	4.5	4.5
	13	15	4.5	4.5
	18	21	6.5	6.5
	26	30	9.5	9.5
TL-5	14	16	8	8
	21	25	12	12
	28	33	16	16
	42	49	20	20
	56	65	26	26

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[1] *Eleqtron is founder of prefabricated, pluggable installations in the Netherlands.*

Movement detection lights

The energy use of lights can also be reduced by installing movement detection. The ISSO 75.3 (2011) considers a 20% reduction in energy use for lighting when adding movement detection.

Ventilators

Ventilators impact the energy use of a building by the temperature of the incoming air from outside and by losing the heated/cooled air from the inside. The type of supply and extraction is therefore of importance. There are four types of ventilators; 1) only mechanical drain, 2) only mechanical supply, 3) mechanical supply and drain without recirculation or heat recovery and 4) mechanical supply and drain with recirculation or heat recovery (ISSO 75.3, 2013). In addition, flow control can be added to the ventilation system. This results in a more constant flow of air, resulting is a more constant use of the ventilator, which reduces its energy use.

New/Renewable Technology

For the renewable technology systems, solar energy systems are most applicable to office buildings. Other renewable energy systems, like wind or biomass, are used less often since in most cases there is no space around the office building to realize these solutions. For solar energy systems, there are two types: a solar collector used for heating and solar panels used to produce electricity. The two most common solar panels are the ones with amorphous cells and the ones with mono or multi crystalline cells (ISSO 75.3, 2011). Office buildings most of the time have flat roofs, which results in the possibility to place the solar panels in the most preferable orientation. The best way to place the solar energy systems is facing south with an angle of 35°. In practice, in terms of distance, at least 1 panel must fit between each panel, so about 50% of the surface of the flat roof can be covered with solar energy systems (Zonnepaneelprijzen.nl, n.d.).

Energy Management and Control system

A Building Energy Management System (BEMS) can reduce the energy use of the building by controlling and monitoring energy-related building service plants and equipment. For example, lightning or heating, ventilation and air conditioning (HVAC) systems (Sayed & Gabbar, 2018). In addition, Rottondi et al. (2015) showed that the use of a BEMS can optimize the use of solar energy systems. When adding a BEMS, the following reductions can be achieved: 39.5% for lightning (provided LED) and for HVAC between 14.1% and 16.7%. In addition, 10% more solar energy can be used when using the BEMS due to flexibility of the energy use (Lee & Cheng, 2016). A BEMS could also reduce the energy use of the appliances in a building. However, in the energy label calculation as described in Section 2.1, appliances are not considered. Therefore, the impact of a BEMS on the energy use of the appliances is not part of this research.

2.4 Available DSS for office buildings

The office building retrofitting market has been growing strongly since the life span of office buildings is much shorter than residential buildings. Furthermore, occupants' needs and expectations have increased, demanding working spaces with improved amenities for comfort, infrastructures and services (Balaras et al., 2002). Due to these developments, much research has been done in retrofitting one single office building (Güçyeter & Günaydın, 2012; Wilkinson, 2012; Higgins et al, 2014; Nazi et al., 2017; Hillebrand et al., 2014). However, only a few DSS have been designed to help determine retrofit measures for office buildings. According to Nielsen et al. (2016), which combined research of Wang et al (2009), Ferreira et al. (2013) and Alanne (2004), the ideal retrofit decision process consists of six areas where formal decision-making methods can contribute in retrofit projects. Namely; Goal Setting, Criteria Weighting, Building

Diagnosis, Design Alternatives Generation, Performance Estimation and Design Alternatives Evaluation. See Figure 9. These six areas are used to compare the different DSS specified to retrofitting office buildings.

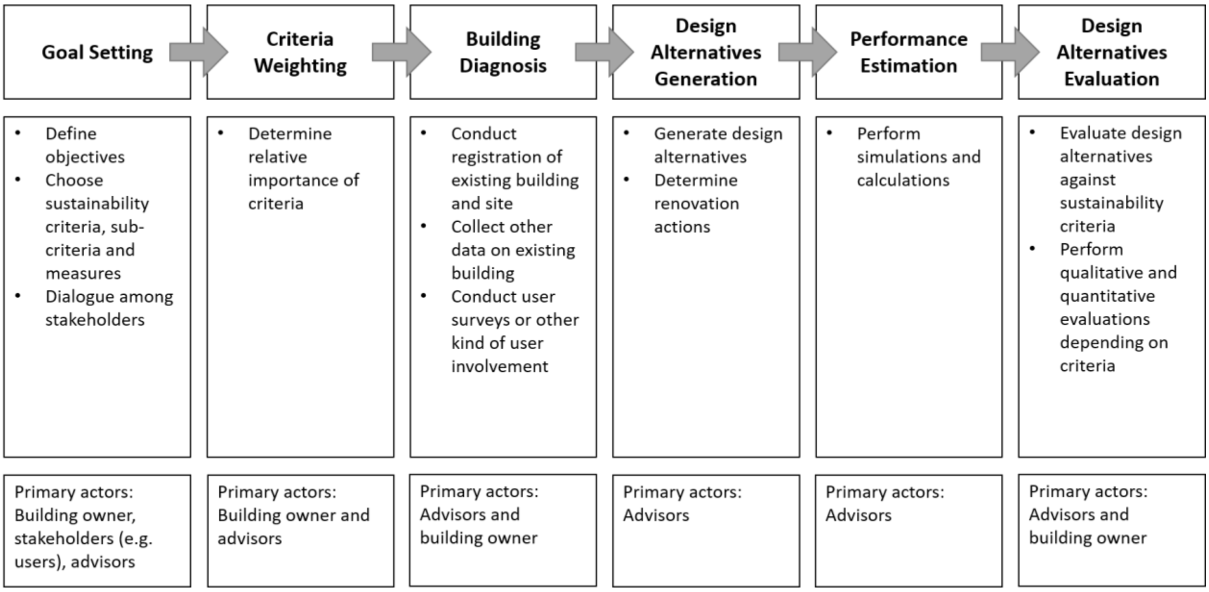


Figure 9: Six areas where formal decision-making methods can contribute in renovation projects (Nielsen et al., 2016)

TOBUS is a DSS specifically made for selecting office building upgrading solutions. The decision-making process of TOBUS starts with the diagnosis of the general state of the office building (Caccavelli & Gugerli, 2002). It therefore skips the first two steps of the Nielsen et al. (2016) method. Next, retrofitting actions are proposed to improve the office building condition, the building energy performance and the indoor environment quality (Caccavelli & Gugerli, 2002). The costs corresponding to these measures is also calculated. The TOBUS model does not evaluate design alternatives. What distinguishes this DSS from others, is that it considers the complex installations of an office building (e.g. central heating, air-conditioning and ventilation, fire protection, low current networks etc.). In addition, the TOBUS model considers the functional obsolescence of building services, so when an installation is dated and in need for renovation it is given the priority in the advised measures (Balaras et al., 2002).

The OFFICE project (Roulet et al., 2002) developed global retrofitting strategies, tools and design guidelines promoting successful and cost-effective implementation of passive solar and energy efficient retrofitting measures to office buildings. The OFFICE project proposed interventions aiming at 1) improving the envelope of the building, 2) reducing the energy use of air conditioning, 3) improving lighting conditions and 4) improving the efficiency of selected building services, like HVAC systems (Santamouris & Dascalaki, 2002). The OFFICE project therefore aims at improving the current conditions. However, it is not possible to set a predefined goal. The methodology allows to rank buildings or retrofit scenarios according to more than one criterion. The OFFICE project therefore includes criteria weighting. Design alternative evaluation is not part of the OFFICE project.

REFLEX developed by Juan et al. (2010) is an integrated DSS for office building retrofits that assesses the current condition of the office building and provides sustainable renovation implementation solutions for decision makers. This study recommends an optimal set of sustainable renovation actions, considering trade-offs between renovation cost, improved building quality, and environmental impacts. The REFLEX model does not include criteria weighting, but the user can set a budget to the project. Furthermore, according to Nielsen et al. (2016) this model does not include design alternative evaluation. However, the model does evaluate the energy performance of the different scenarios and effectiveness of the algorithm (Juan et al., 2010).

Regarding energy label specific retrofitting of office buildings, in the Netherlands, the RVO (2017) published an Energy savings explorer. With this tool, insight is given in the possibilities to improve the energy label of an office building. Investment costs, annual savings in energy use and the Payback Period (PBP) of different retrofit measures are calculated. Also, the reduction in CO_2 emissions is incorporated. However, this model is very simplified in the building characteristics compared to the other models. Examples of these simplifications are 1) that the choice can be made between small, medium or large size and 2) no distinction can be made between area of windows or walls. This model does therefore not contain the building diagnosis. Furthermore, building owners can determine which measures they want to take. No design alternatives are generated. The Energy savings explorer does show the impact of the different retrofit measures on the energy label of the building.

Table 9: Comparison DSS for office building retrofits

			Six areas by Nielsen et al. (2016)						
Type of DSS	**Year**	**Authors/ developers**	**Goal setting**	**Criteria weighting**	**Building diagnosis**	**Design alternatives Generation**	**Performance estimations of retrofit measures**	**Design alternative evaluation**	**Energy labels**
TOBUS	2002	Balaras et al.			✓	✓	✓		
OFFICE project	2002	Roulet et al.		✓	✓	✓	✓		
REFLEX	2010	Juan et al.			✓	✓	✓		
Energy savings explorer	2017	RVO	✓				✓		✓

Table 9 gives an overview of the discussed DSS for office buildings and which of the six areas they included. There is no DSS for office building retrofits available which considers the six areas of retrofitting described by Nielsen et al. (2016). Moreover, there is no DSS for any type of building available that combines all these areas (Nielsen et al., 2016). In addition, the calculation of energy labels into a DSS for retrofitting is missing in most cases. For these reasons and because of the ambition of the Dutch government to reduce the energy demand in office buildings, there is a high need for a model containing all six steps and energy label calculations.

2.5 Criteria for retrofitting

To incorporate the preferences of the office building owner, criteria which enable the comparison of the retrofit measures need to be selected. Lombardi et al. (2017) described a suitable set of criteria for urban energy retrofitting. These criteria are considered in this research and are presented in Table 10 below.

Table 10: Description of the considered criteria (Lombardi et al., 2017)

Aspect	Criteria	Description	Unit
Economic	Investment costs	Investment costs related to the installation of a retrofit technology or adjustment to existing building envelope	Euro
	Payback Period (PBP)	Performance measure used to evaluate the efficiency of an investment	Years
	Maintenance costs	Running fixed and variable costs due to maintenance of the retrofit technology	Euro
Environmental	Reduction of CO_2 emissions	Reduction of the CO_2 pollutant emissions	%
Technical	Reduction of energy requirement	Percentage of reduction in energy demand of the office building due to the retrofit measures applied	%

3. Method

This chapter describes the method to answer the research question and to reach the research aim. The aim was to build a DSS which considers the future mandatory energy labels, following the Dutch Building Decree of 2012. Figure 10 shows the research design that was applied to achieve this aim. First, a literature review regarding laws and regulations of the Dutch energy label system was done which followed in the energy consumption requirements for office buildings (see Section 2.1). The second step consisted of a literature review concerning the energy use in office buildings (see Section 2.3.1). The third step consisted of a literature review regarding the available retrofit measures for office buildings in the Netherlands, including their financial and environmental implications (see Section 2.3.2.). The decision criteria when retrofitting are determined through literature review in step 4 (see Section 2.5). In step 5, the DSS was made. In step 6, data of three office buildings was collected to test the DSS. In this chapter, Section 3.1 explains how the DSS works and describes the data used to build it. In addition, the data used to make the timeline is described. Lastly, Section 3.2 describes the validation of the DSS through a sensitivity analysis, which is represented as the feedback loop in Figure 10.

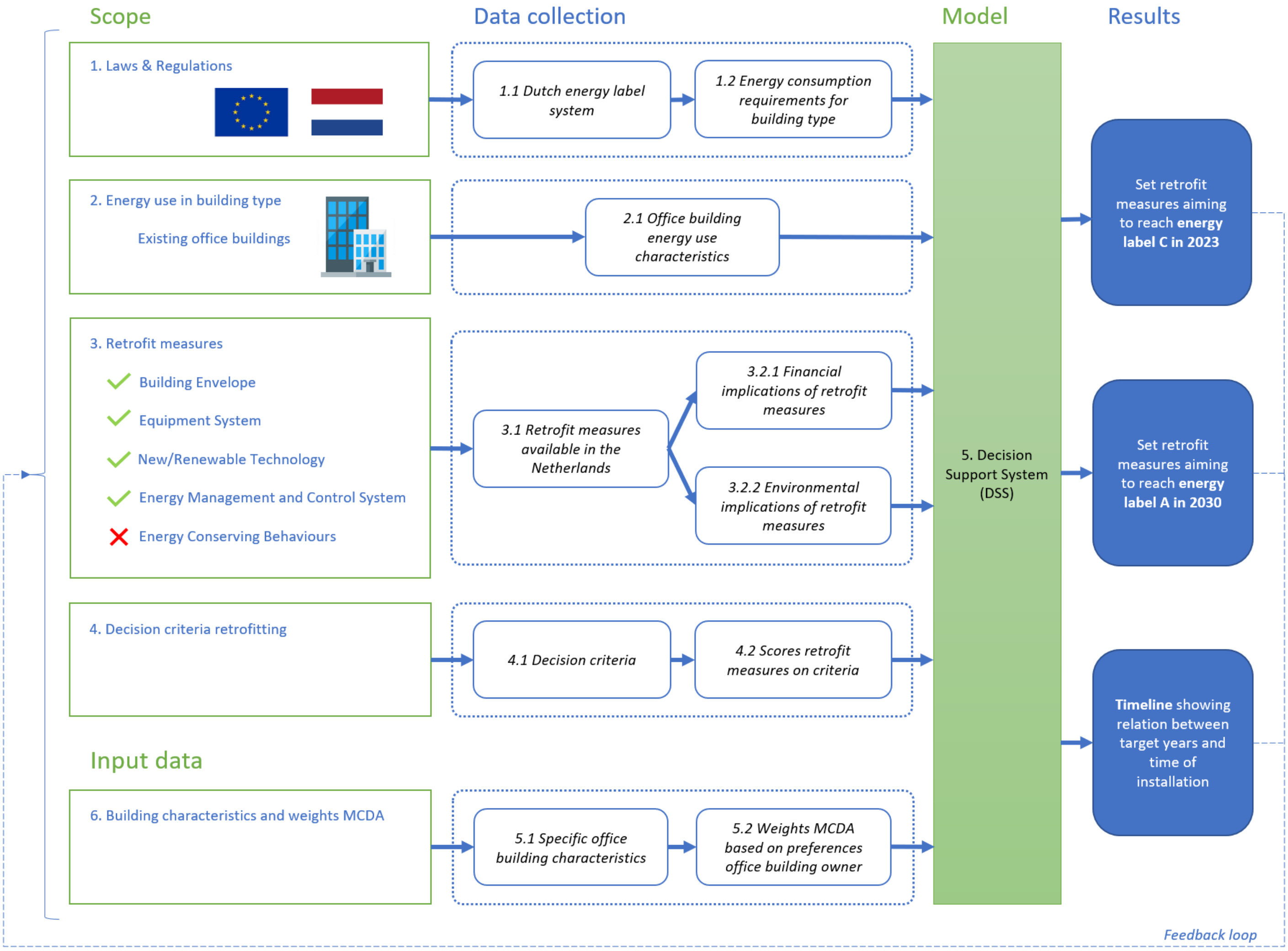


Figure 10: Research design

3.1 The operation of the DSS

This section describes how the DSS works and how it should be used (see Figure 11). First, a questionnaire should be filled in, collecting the input data for the DSS. Section 3.1.1 elaborates upon this questionnaire. Next, Section 3.1.2 explains how the energy label calculation is done (blue box in Figure 11), presenting the current situation and the reduction needed in energy use to achieve either energy label C or A. Next, the retrofit measure impact calculation is done (described in Section 3.1.3). This step consists of determining the impact of the retrofit measures on the energy use and a Multicriteria Decision Analysis. Section 3.1.4 describes how the DSS determines the optimal set of retrofit measures according to the preferences of the office building owner. This is done by combining the previous steps, as presented by the grey box in Figure 11. This results in a set of retrofit measures aiming at achieving energy label C or A and the timeline. Section 3.1.5 describes how the timeline is constructed.

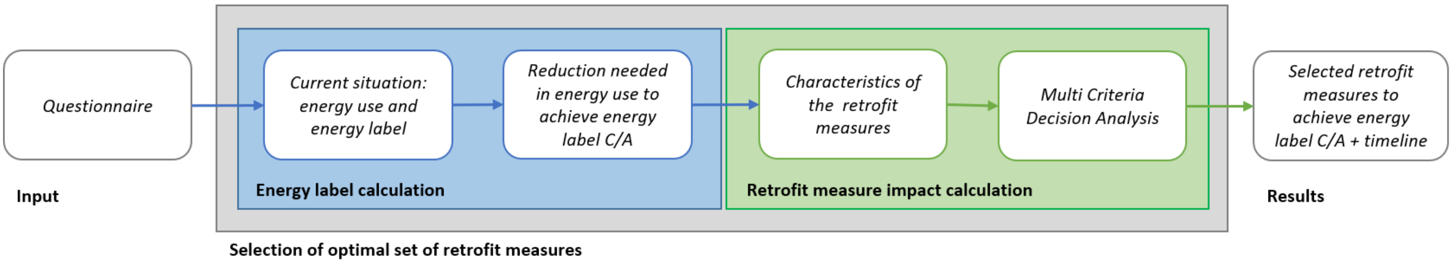


Figure 11: Flow diagram operation of DSS

3.1.1 Questionnaire

The questionnaire collects the input data for the DSS. It is divided into four blocks. The first block collects demographic information, e.g. name of the company, address etc. The second block collects the construction details of the building, e.g. insulation values, glazing type etc. The third block collects information about the installations of the building, e.g. heat supplier, ventilator type etc. Lastly, the preferences of the office building owner are gathered using the questions in the fourth block. These preferences are based on two questions. The first one asks the office building owner to divide 100 points over the decision criteria described in Section 2.5. The criterion with the highest preference should get the most points. In the second question, the office building owner is given the ability to rank the retrofit measures on importance to be a part of the proposed measures. For example, an office building owner is planning to renovate the heat supplier, which should therefore be a part of the set of renovation measures advised. This measure must therefore be included in the ranking. The questionnaire can be found in Appendix A, including the email that was send to the office building owners. The questionnaire was validated by SPIE before sending it to the office building owners. To make sure the DSS can be used when the office building owner does not know the answer to all questions, a database is made of assumptions related to the year of construction. These can be found in Appendix B.

3.1.2 Energy label calculation

The first thing the DSS determines is the current situation; energy label and energy use of an office building. The energy label calculation for existing buildings is based on the Energy-Index (EI) as described in Section 2.1. The EI consists of two parts, the allowable energy use of the building and the actual energy use of the building. The allowable energy use is attributed to the building based on its function of use, area of use, loss area, ventilation and presence of cooling (Sipma, Kremer & Vroom, 2017). In this research, the ISSO 75.3 (2011) method is used to calculate the EI. This version is widely used in the Dutch building sector, making it suitable for the DSS. The formulas for the EI and the allowable energy use can be found in Appendix C. The calculations to determine the actual energy use of the office building are presented in

Appendix D. After inserting these calculations into the DSS, the energy label calculation was validated by calculating the energy label of a building, which already consisted of an energy label. This building and the energy label were provided by SPIE. In addition to the energy label calculation, the energy use in kWh per m^2 is calculated. This energy use in kWh/m^2 does not include the energy generated by solar energy systems. This corresponds to the expected new energy use requirements of the Dutch government, as described in Section 2.1.1.

Next, the reduction in energy use needed to obtain either energy label C or A is calculated. The formula used in the DSS is Formula 1.

$$Q_{prim;reduction} = Q_{prim;building;current} - EI * Q_{prim;allow} \quad [1]$$

In which $Q_{prim;building;current}$ presents the current energy use of the building in GJ, EI the energy index corresponding to energy label C or A and $Q_{prim;allow}$ the allowable energy use of the building. This formula can also be used to determine the energy reduction needed for any other energy label. As described in Section 2.2, the energy use of a building partly depends on the weather. The weather data used in this research is based on the Test Reference Year De Bilt (ISSO 75.3) in the Netherlands. This data is used since De Bilt is the reference point of the Dutch climate. The weather data used is presented in Appendix E.

3.1.3 Retrofit impact calculation

The retrofit measures suitable for office buildings are described in Section 2.2.3. The characteristics of these measures – investment and maintenance costs and lifetime – can be found in Appendix F. These characteristics are based on extensive literature review and in consultation with SPIE. For the characteristic investment costs, it should be noted that this includes both the costs for installation as the costs of purchase. This ensures a complete indication of costs for the office building owner. However, the prices for installation of HVAC systems can differ per installer. Therefore, the assumption was made that the costs for installation of HVAC systems is 50% of the total costs. So, when the purchase of a heat pump costs €5,000, then the total investment costs including installation is €10,000. This assumption is based on the experience of the installers at SPIE. The price data was validated through a check by SPIE. Since they are an established market player, they were able to tell if the values were logical.

In the DSS, a Multicriteria Decision Analysis (MCDA) is performed to incorporate the preferences of the office building owner. A MCDA is a tool to structure decision-making processes and to help decision makers find an optimal balance between conflicting goals (Beinat et al., 1994; Guitouni & Martel, 1998). To find this optimal balance, a MCDA enables the decision maker to prefer certain criteria over others. In the DSS, the criteria are the characteristics of the retrofit measures and the decision maker is the office building owner. The steps of a MCDA are the following (Dodgson et al., 2009): 1) Establish the decision context, 2) Identify the options to be appraised, 3) Identify criteria, 4) Assign scores, 5) Assign weights, 6) Derive overall value and 7) Examine the results. Table 11 shows steps 1 until 3 for this research.

Table 11: Steps 1-3 MCDA

Steps	Description
1. Decision context	Need to retrofit to obtain a better energy label
2. Options to be appraised	Retrofit measures
3. Criteria	• Investment costs • Payback Period • Maintenance costs • Reduction of CO_2 emissions • Reduction of energy requirement

In step 4 of the MCDA, the scores of the different criteria are calculated as follows. First, the values for the different criteria per retrofit measure are determined. For Investment costs and Maintenance costs, these values are shown in Appendix F. The Payback Period (PBP) is determined with Formula 2 (Blok, 2006):

$$PBP = \frac{I}{B - C} \quad [2]$$

Where I represents the initial investment [€], B the annual benefits [€] and C the annual cost [€]. The initial investment are the investment costs. The annual costs are the maintenance costs. The annual benefit is the energy use reduction due to the retrofit measure. To translate this reduction in energy use to monetary terms, the price of gas and electricity in the Netherlands in 2019 were considered. The price for gas for large office buildings in 2019 was 51.99 cents/m^3. For electricity this was 12.72 cents/kWh (RVO 6, n.d.). When the PBP is infinite, meaning that the measure will never pay back itself, the term infinite is given.

The Reduction of the CO_2 emissions due to retrofitting is related to the reduction in operational CO_2 emissions. This is calculated using the CO_2 emission factors of the Dutch electricity and gas grid. The emission factors are shown in Table 12 (Milieubarometer, n.d.). The year 2019 is taken as the reference year. Since the DSS calculates all energy related values in MJ, the following conversion numbers are used to translate the MJ to the corresponding unit of the fuel type: the calorific value of natural gas (=35.17 MJ/m^3) and the primary energy content of electricity (=$3.6/\eta_{el}$ MJ/kWh).

Table 12: Emission factors 2019 (The Netherlands)

Fuel	Unit	kg CO_2/unit
Gas	m^3 gas	1.89
Electricity	kWh	0.649
Heat	GJ	36.0

The Reduction of energy requirement per retrofit measures differs per office building. For example, an office building with more windows can reduce its energy use more with installing a better type of glass than an office building with fewer windows. To ensure that the impact per office building can differ, the reduction of energy use per retrofit measure is inserted in the DSS as a formula and not as a given number. One parameter in changed in the energy label calculation, for example the U-value of glass, and the energy use of the building is calculated again. The difference in energy use between the real situation and the situation with the changed parameter is the energy reduction that can be achieved from this retrofit measure.

As described in Table 10 in Section 2.5, the criteria for retrofitting have different units. To fairly compare the different criteria, the scores are standardized using a maximum standardization. This means that each score is translated to a value between 0 and 1. To do so, each score at a certain criterion is recalculated as (X - min X)/(max X - min X), where X represents the score of the criterion in the original data set. This method allows scores to have differing means and standard deviations but equal ranges. In this case, there is at least one observed value at the 0 and 1 endpoints (Biomedware, n.d.). For the criterion PBP, the max X is set at 10 years since this is considered a reasonable PBP. All values longer than 10 years get the score of 0. Next, the weights are set by the preferences of the office building owner in step 5 of the MCDA. These weights are collected through the questionnaire, as described in Section 3.1.1. These are scaled between 0 and 1. The sum of the weights of all criteria should add up to 1. The weight times the standardized score determines the overall value of the retrofit measure, step 6. The higher the overall value, the higher the change that this retrofit measure is selected in the proposed set of retrofit measures.

3.1.4 Selection of the optimal set of retrofit measures

Determining which retrofit measures should be selected in order to achieve energy label C or A, can be described as a binary 'knapsack problem' (Alanne, 2004). The binary knapsack problem is a problem in combinatorial optimization: given a set of items (in this case the retrofit measures), each with a weight and a value, it determines which item should be included in a collection so that the total value is as large as possible (Shahpasand & Golpayegani, 2014). The Excel Solver was used to solve this problem, because of its ability to find optimal solutions in decision problems. The binary knapsack problem as used in this research is mathematically described as follows.

- Decision variables (the considered retrofit measures) $a_1, a_2, \dots a_n$
- a_i is a binary value, if retrofit measure a_i is proposed $a_i = 1$, else $a_i = 0$

The objective function is to maximise the sum of overall values:

$$MAX \sum_{i=1}^{n} a_i * (S_i + P_i) \quad [3]$$

Where S_i is the overall value achieved by selecting the retrofit measure a_i and P_i describes the points following from the ranking. The index number i relates to the different retrofit measures. The overall value for an arbitrary retrofit action is then:

$$S_i = w_1 s_{1,i} + w_2 s_{2,i} + \cdots + w_n s_{n,i} \quad [4]$$

Where w_n is the weight set by the office building owner (between 0 and 1) for criterion n and $s_{n,i}$ is the standardized score number for the retrofit measure i in respect to the score value for criterion n. To incorporate the ranking of the retrofit measures, points are added to the overall value of the retrofit measure. The retrofit measures are characterized in the following 7 types: glazing, insulation, heat supplier, cold supplier, ventilators, lightning and solar energy systems. These types can be ranked in order of preference. When only one retrofit measure is highlighted in the ranking list, the overall value for this retrofit measure is increased with 7 points. When two retrofit measures are listed, the first one gets 7/3*2= 4.67 points and the second 7/3*1=2.33 points. When three retrofit measures are listed, the first one gets 7/6*3=3.5 points, the second 7/6*2=2.33 points and the last 7/6*1=1.17 points. The formula used to divide these points is Formula 5. In which P_i represents the points for retrofit measure i, y is the number of retrofit measures listed and $place$ the place in the ranking.

$$P_i = \frac{7}{y(y+1)/_2} * (y + 1 - place) \quad [5]$$

The aim of this DSS is to maximise the highest sum of overall values in combination with obtaining the required energy label. This latter is inserted as a constraint. Namely, the new energy use of the office building should be equal or lower than the energy use required to obtain either energy label C or A. Therefore, one of the two formulas below apply:

$$E_{use,new} \leq E_C \quad [6]$$

$$E_{use,new} \leq E_A \quad [7]$$

In which $E_{use,new}$ represents the energy use after retrofitting in MJ. E_C represents the maximum energy use to obtain energy label C in MJ. The maximum energy use to obtain energy label A in MJ is presented by E_A. Since this model is based on a linear problem, the interaction between the retrofit measures is not considered. As described in Section 3.1.3, the impact of a retrofit measure on the energy use of the building is calculated by changing one variable in the energy label calculation. The result therefore does not show the mutual impact of different retrofit measures on their energy use reduction capabilities. For example, imagine improving the insulation value of the walls. Less energy is needed to heat the building. Therefore, the energy reduction that can be achieved by replacing the heat supplier decreases. In a linear model, this counter interaction cannot be considered. To make sure that the energy use of the building cannot reduce below zero, which technically isn’t possible, the following constraint is added.

$$E_{red} \leq E_{use,current} \quad [8]$$

In which E_{red} represents the energy reduction achieved by the proposed retrofit measures in MJ and $E_{use,current}$ represents the current energy use before retrofitting in MJ.

This problem also consists of other constraints. For several retrofit measures, only one type can be selected. For example, usually only one glazing type is selected when retrofitting. Therefore, the sum of a_i representing glazing types should be 0 or 1. This is expressed by the constraint equation 9. This constraint also applies to floor, roof and wall insulation, solar energy systems, ventilators, cold suppliers and heat suppliers.

$$\sum_{i=1}^{glazing\ types} a_i \leq 1 \quad [9]$$

For floor and wall insulation, only the insulation material types corresponding to the right type of floor and wall can be installed. So, when a cavity wall is present, the cavity wall insulation materials can be selected as well. In addition, the DSS is given the ability to select the option “No change” for energy type of retrofit measure. This corresponds to doing nothing for that construction part or installation in the building. The score for this option is calculated considering no investment and maintenance costs, a payback period of 0, and no energy or CO_2 emission reduction. Lastly, a budget constraint is added.

$$\sum_{i=1}^{n} a_i C_i \leq C_{MAX} \quad [10]$$

Where C_i represents the investment costs of retrofit measure a_i and C_{MAX} is the budget of the office building owner.

3.1.5 Construction of timeline

After the DSS selected the optimal set of retrofit measures for an office building, the timeline corresponding to the time needed to realise this set of measures was made. The total process of the preparation of a tender to the completion of the project is considered. Regarding the installation time of the retrofit measures, these include both the demolition of the current construction parts as the installation of the new construction parts. The durations are based on the experience of SPIE and are presented in Table 13. When a calculation is made to come to the duration of a specific part in the process, this is explained in the third column in Table 13. In addition, the assumption is made that a working day consists of 8 hours and a year consists of 180 working days (Vereniging Eigen Huis, n.d.). Lastly, the assumption is made that on average 10 people (supervisors/planners/installers) are working on the retrofits per day (based on experience of SPIE).

Table 13: Time per part of retrofitting process

Part	Time	Explanation
Quotation	0.02 minute per euro of total investment	The costs to prepare a quotation are set at 2% for the total investment costs. The labour costs of a supervisor are around €60 per hour, €1 per minute. Taking 2% of the labour costs, results in 0.02 minute per euro quotation.
Preparation and planning	0.10 minute per euro of total investment	The costs for the preparation and planning is 7% of total investment costs. The labour costs of a planner are around €40 per hour, €0.67 per minute. Taking 7% of the labour costs, results in 0.10 minute per euro.
Retrofit measures		
Insulation	60 min/m^2 wall/roof/floor	Experience of SPIE
Windows	60 min/m^2 window	Experience of SPIE
Heat supplier	Demolish: 10 min/m^2 Install: 20 min/m^2	Based on brochure by Arcadis (2016).
Cold supplier	Demolish: 10 min/m^2 Install: 20 min/m^2	Based on brochure by Arcadis (2016).
Ventilators	600 min	Experience of SPIE
Lighting	Demolish: 15 min/light Install: 36 min/light	Experience of SPIE
Solar energy systems	0.4 min per Watt/peak	Experience of SPIE
BEMS	0.6 min/m^2	Experience of SPIE
Completion of the project	0.05 minute per euro of total investment	The costs for the completion of the project is 5% of total investment costs. The labour costs of a project leader are around €60 per hour, €1 per minute. Taking 5% of the labour costs, results in 0.05 minute per euro.

3.2 Sensitivity analysis

A sensitivity analysis is conducted to validate the results and the operation of the DSS. The characteristics of one office building, equal distribution of weights per criterion and no ranking is set as the base scenario. The impact of changes in input data on this base scenario is reviewed in this sensitivity analysis. The assumptions regarding the price developments of gas and electricity and the CO_2 emission factor of the electricity grid are changed 10% up and down, since these values might change in the future, due to for example more renewables in the electricity mix. Also, the investment costs of the retrofit measures, the weights set by the office building owner and the ranking of the different retrofit measures are changed to see their impact on the results. The investment costs are changed with 20%. This range is larger compared to the other assumptions, since these values are most uncertain. In addition, it is expected that the investment costs could change in the future due to innovation. Changing this price data can give an idea of what this could do to the proposed sets of retrofit measures. Regarding the weights for the criteria, each criterion is given the preference once by setting its weight on 0.5 and the others on 0.125 each. Lastly, each type of retrofit measure is ranked once by assigning 7 points to this measure. These two types of input data are changed to see the impact of the preferences of the office building owner on the proposed set of retrofit measures. See Table 14 for an overview of the sensitivity limits.

Table 14: Limits sensitivity analysis

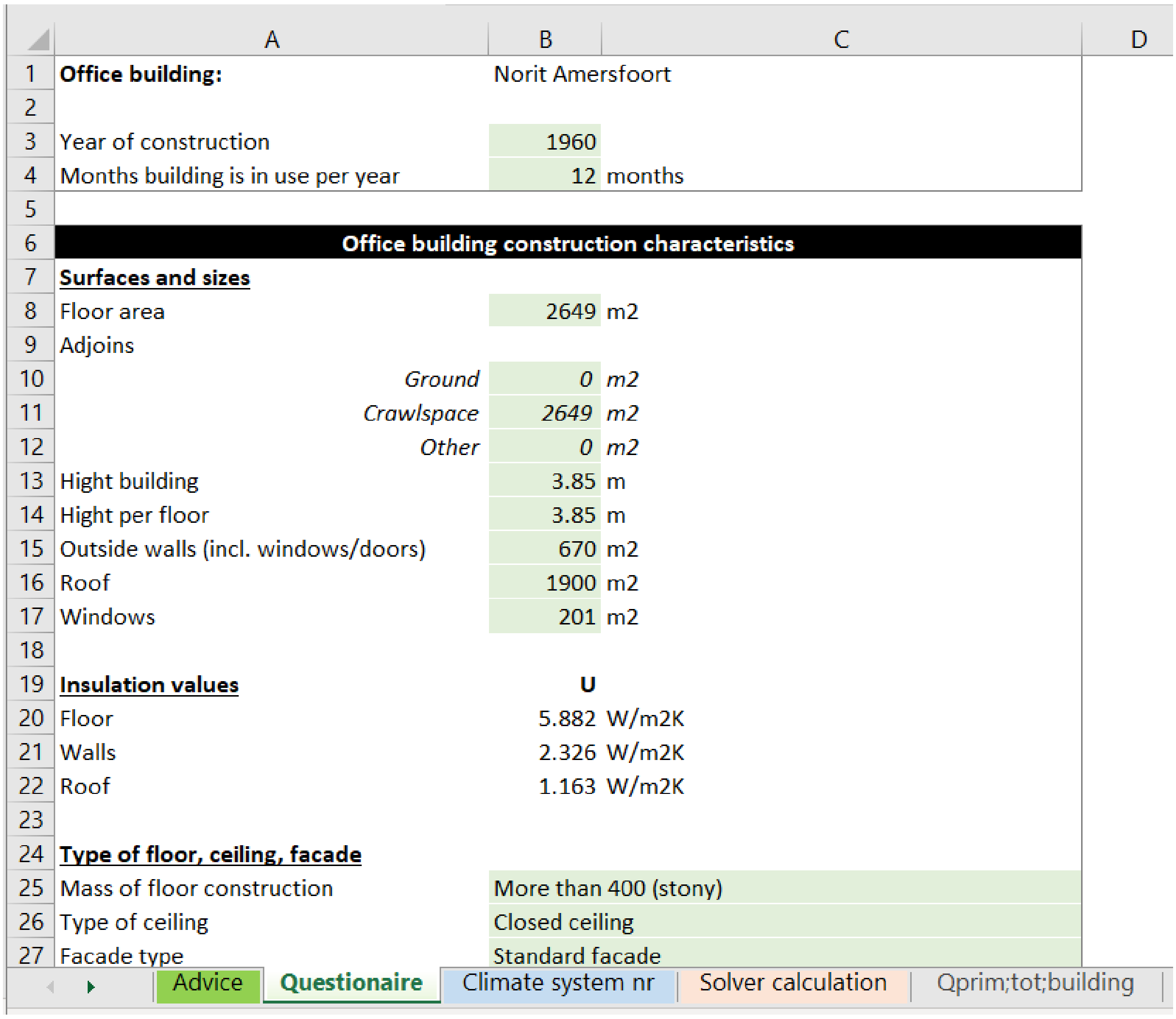
Assumption	**Lower limit**	**Higher limit**
Gas price	-10%	+10%
Electricity price	-10%	+10%
CO_2 emission factors	-10%	+10%
Investment costs retrofit measures	-20%	+20%
	Preferred criterion	**Others**
Weights determined by the owner	0.5	0.125
	Ranked measure	**Others**
Ranking	7	0

4. Operation of the DSS

This chapter describes the operation of the DSS using screenshots of the Excel model. First, where the building characteristics need to be inserted is explained in Section 4.1. Next, Section 4.2 describes how the energy reduction needed to obtain either energy label C or A is determined. Furthermore, the Excel Solver set up and how the generated scores for the different retrofit measures per criterion are presented is described in Section 4.3. This includes an example on how the DSS selects the proposed set of retrofit measures. Lastly, Section 4.4 describes how the DSS presents the results.

4.1 Input data

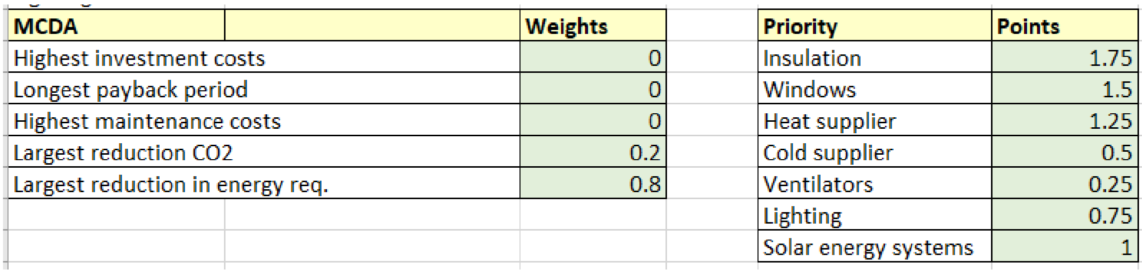
First, the green fields of the questionnaire should be filled in at the tap “Questionnaire”. This list of values corresponds to the questionnaire presented in Appendix A. It includes information divided in four categories: demographic information, construction details of the building, installations of the building and the preferences of the office building owner. Figure 12 shows a screenshot of the “Questionnaire” tap of the DSS. By filling in these values, the current energy label is calculated and presented in the tab “Advice”.



	A	B	C	D
1	**Office building:**	Norit Amersfoort		
2				
3	Year of construction	1960		
4	Months building is in use per year	12	months	
5				
6	**Office building construction characteristics**			
7	**Surfaces and sizes**			
8	Floor area	2649	m2	
9	Adjoins			
10	*Ground*	*0*	*m2*	
11	*Crawlspace*	*2649*	*m2*	
12	*Other*	*0*	*m2*	
13	Hight building	3.85	m	
14	Hight per floor	3.85	m	
15	Outside walls (incl. windows/doors)	670	m2	
16	Roof	1900	m2	
17	Windows	201	m2	
18				
19	**Insulation values**	**U**		
20	Floor	5.882	W/m2K	
21	Walls	2.326	W/m2K	
22	Roof	1.163	W/m2K	
23				
24	**Type of floor, ceiling, facade**			
25	Mass of floor construction	More than 400 (stony)		
26	Type of ceiling	Closed ceiling		
27	Facade type	Standard facade		

Figure 12: DSS Questionnaire tab

After filling in the necessary input data in the “Questionnaire”, the scores for the MCDA and ranking are added in the tab “Solver calculation”. These scores represent the preferences of the office building owner. Figure 13 shows a screenshot of the corresponding tables. The user should insert its preferences regarding the MCDA criteria and the ranking in the green cells.



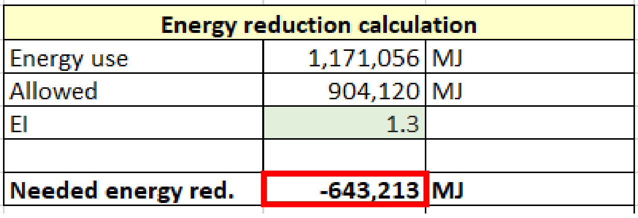
MCDA	Weights
Highest investment costs	0
Longest payback period	0
Highest maintenance costs	0
Largest reduction CO2	0.2
Largest reduction in energy req.	0.8

Priority	Points
Insulation	1.75
Windows	1.5
Heat supplier	1.25
Cold supplier	0.5
Ventilators	0.25
Lighting	0.75
Solar energy systems	1

Figure 13: DSS MCDA and ranking tables

4.1 Energy use reduction estimation

The reduction needed in energy use of the office building to obtain either energy label C or A is determined next. Formula 1, as described in Section 3.1.2, is used to calculate the needed reduction in energy use. The cell showing the EI value (green cell) should be set to the EI value corresponding to the energy label aimed for. For energy label C, this must be 1.3 and for energy label A 1.05. The cell marked red than shows the reduction in energy use needed (negative sign means reduction).

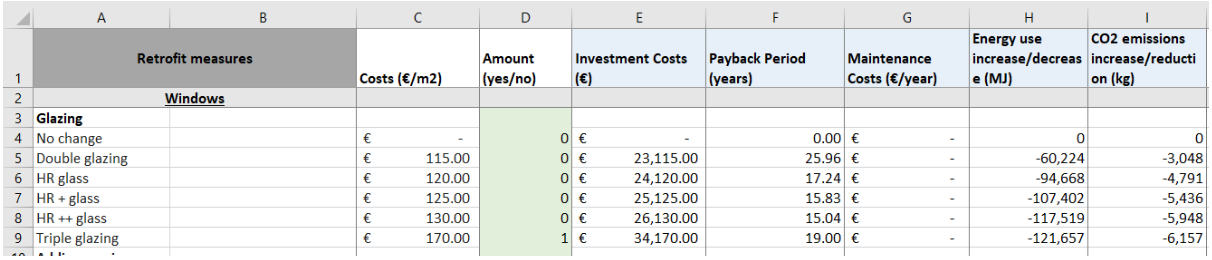


Energy reduction calculation		
Energy use	1,171,056	MJ
Allowed	904,120	MJ
EI	1.3	
Needed energy red.	**-643,213**	**MJ**

Figure 14: DSS Goal seek table

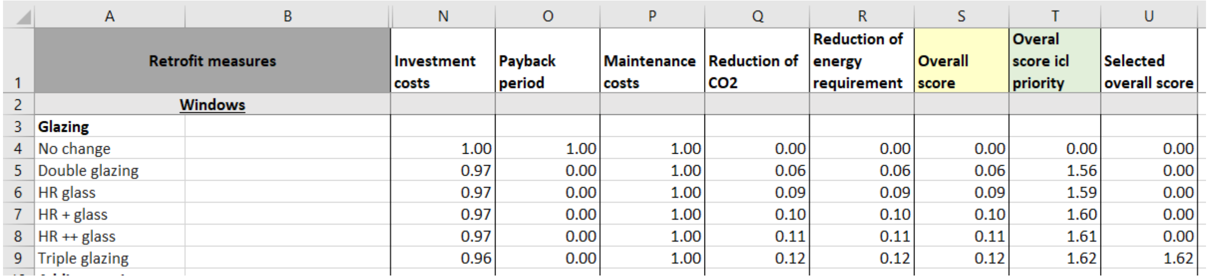
4.1 Optimisation process

To find the optimal set of retrofit measures, the values for the different criteria per retrofit measure are gathered. See Figure 15, columns E until I. These values are copied from other sheets and do not have to be inserted by the user. These values are used to calculate the scores for the different criteria, see Figure 16 columns N until R. Column S shows the overall score including the weights set by the office building owner. Column T shows the overall score including the priority points set by the owner.



	A	B	C	D	E	F	G	H	I
1	**Retrofit measures**		**Costs (€/m2)**	**Amount (yes/no)**	**Investment Costs (€)**	**Payback Period (years)**	**Maintenance Costs (€/year)**	**Energy use increase/decrease (MJ)**	**CO2 emissions increase/reduction (kg)**
2	**Windows**								
3	**Glazing**								
4	No change		€ -	0	€ -	0.00	€ -	0	0
5	Double glazing		€ 115.00	0	€ 23,115.00	25.96	€ -	-60,224	-3,048
6	HR glass		€ 120.00	0	€ 24,120.00	17.24	€ -	-94,668	-4,791
7	HR + glass		€ 125.00	0	€ 25,125.00	15.83	€ -	-107,402	-5,436
8	HR ++ glass		€ 130.00	0	€ 26,130.00	15.04	€ -	-117,519	-5,948
9	Triple glazing		€ 170.00	1	€ 34,170.00	19.00	€ -	-121,657	-6,157

Figure 15: DSS Values per criterion per type of glazing



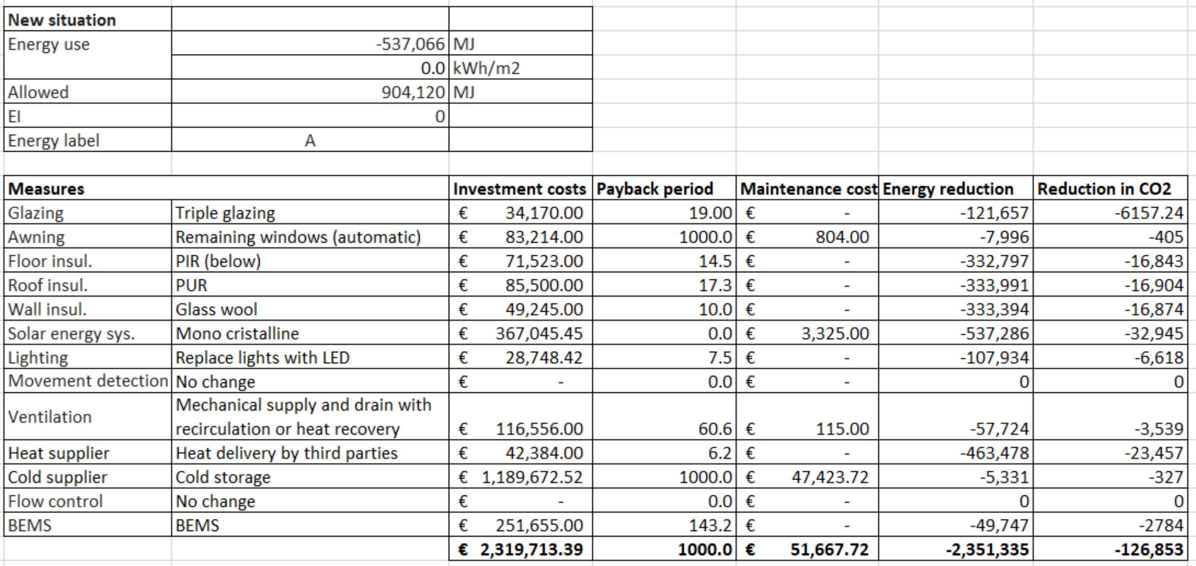
	A	B	N	O	P	Q	R	S	T	U
1	**Retrofit measures**		**Investment costs**	**Payback period**	**Maintenance costs**	**Reduction of CO2**	**Reduction of energy requirement**	**Overall score**	**Overal score icl priority**	**Selected overall score**
2	**Windows**									
3	**Glazing**									
4	No change		1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00
5	Double glazing		0.97	0.00	1.00	0.06	0.06	0.06	1.56	0.00
6	HR glass		0.97	0.00	1.00	0.09	0.09	0.09	1.59	0.00
7	HR + glass		0.97	0.00	1.00	0.10	0.10	0.10	1.60	0.00
8	HR ++ glass		0.97	0.00	1.00	0.11	0.11	0.11	1.61	0.00
9	Triple glazing		0.96	0.00	1.00	0.12	0.12	0.12	1.62	1.62

Figure 16: DSS Scores per criterion per type of glazing

In order to exemplify how the optimization process works, an example of glazing renovation is shown. However, the DSS contains different options for insulation, solar energy systems, lighting, ventilation, cold suppliers, heat suppliers and BEMS. In the first column, the different options for glazing are presented including the option “No change”. The green column in Figure 15 represents the yes/no decision, which is determined by the Excel Solver using the Knapsack model as described in Section 3.1.4. As can be seen, the triple glazing is given the number 1. As described in Section 3.1.4, this means that this measure is selected. This selection is based on the scores for the different criteria of the MCDA. Figure 16 shows that the retrofit measure triple glazing got the highest overall score including priority. This measure was therefore selected by the Excel Solver. For all types of retrofit measures, these scores are calculated, and the Excel Solver determines which is best to select. It is possible that the Excel Solver doesn’t pick the highest score for a certain retrofit measure, since it must comply with the constraints of reaching the energy reduction corresponding to the required energy label. For example, when an office building owner assigns all the weights to the criterion Investment costs, the option of no change always gets the hights score. However, when the building does not have the right energy label yet, some retrofit measures with a lower score should be selected.

4.2 Results DSS

The Excel Solver generates the optimal set of retrofit measures, corresponding to the preferences of the office building owner and the energy label target. The “results” screen is shown in Figures 17 and 18. The first table in Figure 18 shows the “New situation”, which is the state of the building after applying the proposed retrofit measures. The energy use in MJ and kWh/m^2 is presented, as well as the EI and corresponding energy label. The second table in Figure 18 presents the proposed retrofit measures by the Excel Solver. The name of the retrofit measure is shown, including the values for the different criteria. The last row represents the totals. The value 1000 in the PBP column corresponds to an infinite PBP.



New situation		
Energy use	-537,066	MJ
	0.0	kWh/m2
Allowed	904,120	MJ
EI	0	
Energy label	A	

Measures		Investment costs	Payback period	Maintenance cost	Energy reduction	Reduction in CO2
Glazing	Triple glazing	€ 34,170.00	19.00	€ -	-121,657	-6157.24
Awning	Remaining windows (automatic)	€ 83,214.00	1000.0	€ 804.00	-7,996	-405
Floor insul.	PIR (below)	€ 71,523.00	14.5	€ -	-332,797	-16,843
Roof insul.	PUR	€ 85,500.00	17.3	€ -	-333,991	-16,904
Wall insul.	Glass wool	€ 49,245.00	10.0	€ -	-333,394	-16,874
Solar energy sys.	Mono cristalline	€ 367,045.45	0.0	€ 3,325.00	-537,286	-32,945
Lighting	Replace lights with LED	€ 28,748.42	7.5	€ -	-107,934	-6,618
Movement detection	No change	€ -	0.0	€ -	0	0
Ventilation	Mechanical supply and drain with recirculation or heat recovery	€ 116,556.00	60.6	€ 115.00	-57,724	-3,539
Heat supplier	Heat delivery by third parties	€ 42,384.00	6.2	€ -	-463,478	-23,457
Cold supplier	Cold storage	€ 1,189,672.52	1000.0	€ 47,423.72	-5,331	-327
Flow control	No change	€ -	0.0	€ -	0	0
BEMS	BEMS	€ 251,655.00	143.2	€ -	-49,747	-2784
		€ 2,319,713.39	**1000.0**	**€ 51,667.72**	**-2,351,335**	**-126,853**

Figure 17: DSS Results new situation and proposed measures

Table 18 represents the times needed to realize certain parts of the retrofit process. In the second column, the times as described in Section 3.1.5 are presented. In the column "This project", the times per part considering the proposed measures by the DSS are presented. The last two rows represent the time total in days and in years.

Part	Times		This project	
Quotation	0.02	min/euro investment	46,907	min
Preparation and	0.1	min/euro investment	234,533	min
Insulation	60	min/m2	301,080	min
Windows	60	min/m2	12,060	min
Heat supplier	30	min/m2	79,470	min
Cold supplier	30	min/m2	79,470	min
Ventilators	600	min	600	min
Lighting	51	min/light	0	min
Solar energy systems	0.4	min/watt.peak	45,600	min
BEMS	0.6	min/m2	1,589	min
Completion of the	0.05	min/euro investment	117,266	min
			191	**days**
			1.06	**year**

Figure 18: DSS Results installation times

5. Results

This chapter describes the results from the DSS for three office buildings and the sensitivity analysis. Section 5.1 describes the results for Norit Amersfoort, a client of SPIE who is (at the time of writing this thesis) in the process of retrofitting its building. Section 5.2 describes the results for the Utrecht University Freudenthal building, this building will be undergoing several scheduled maintenance activities at the end of 2020 or in the beginning of 2021. Section 5.3 shows the results for the SPIE Utrecht office building, a new office building of SPIE which needs a retrofit. First, the office building is described, followed by the current energy label. Next, the measures proposed by the DSS to either reach energy label C or A are presented. The timeline shows whether the measures can be achieved on time. Lastly, Section 5.4 presents the sensitivity analysis to validate the results and test the robustness of the DSS.

5.1 Norit Amersfoort

Norit Amersfoort is a client of SPIE, who wants to retrofit its office building. At the time of writing this thesis, SPIE was in negotiations about the retrofit measures suitable for this building. The office building was built in 1960 and currently not in use. The office building owner therefore wants everything to be updated. This shows in the priority points (see Table 16), since every type of retrofit measure is included in the ranking. In addition, the weights for the criteria in Table 15 show that the office building owner doesn't find the costs and PBP relevant, which shows that the office building owner is willing to pay more when it reduces the energy use of the building even more. The filled in questionnaire can be found in Appendix G.

Table 15: Weights Norit Amersfoort

Criteria	Weights office owner
Lowest investment costs	0
Fastest Payback Period in years	0
Lowest maintenance costs	0
Reduction of CO_2 emissions	20
Reduction of energy requirement	80

Table 16: Priority points Norit Amersfoort

Priority	Points office owner
Insulation	1.75
Windows	1.5
Heat supplier	1.25
Cold supplier	0.5
Ventilators	0.25
Lighting	0.75
Solar energy systems	1

Current situation

The current energy label of this building is G, with an energy index of 2.02. This energy index is based on the energy consumption allowed, which is 904 GJ per year for this building according to the calculations of the ISSO 75.3. The total operational CO_2 emissions related to the energy use of the building are 95 ton per year. The results can be found in Table 17.

Table 17: Current situation Norit Amersfoort

Current situation		
Energy label	**G**	
EI	2.02	
Energy use per year		
Building	1,822	GJ
	191	kWh/m^2
Allowed	904	GJ
CO$_2$ emissions		
Total	95	tonne

Energy label C

To reach energy label C, the building should reduce its yearly energy use by 643 GJ. The proposed measures when aiming at an energy label C are described in Table 18.

Table 18: Measures energy label C Norit Amersfoort

Measures		**Investment costs**		**Payback period (years)**	**Maintenance costs (per year)**		**Energy reduction (GJ)**	**Reduction in CO$_2$ (tonne)**
Glazing	Triple glazing	€	34,170	19.00	€	-	122	6
Awning	Remaining windows (automatic)	€	83,214	infinite	€	804	8	0.4
Floor insul.	PIR (below)	€	71,523	14.5	€	-	333	16.8
Roof insul.	PUR	€	85,500	17.3	€	-	334	16.9
Wall insul.	Glass wool	€	49,245	10.0	€	-	333	16.9
Solar energy sys.	Mono cristalline	€	367,045	0.0	€	3,325	537	32.9
Lighting	Replace lights with LED	€	28,748	7.5	€	-	108	6.6
Movement detection	No change	€	-	0.0	€	-	0	0
Ventilation	Mechanical supply and drain with recirculation or heat recovery	€	116,556	60.6	€	115	58	3.5
Heat supplier	Heat delivery by third parties	€	42,384	6.2	€	-	463	23.5
Cold supplier	Cold storage	€	1,189,673	infinite	€	47,424	5	0.3
Flow control	No change	€	-	0.0	€	-	0	0
BEMS	BEMS	€	251,655	143.2	€	-	50	2.8
		€	**2,319,713**	**infinite**	**€**	**51,668**	**2,351**	**126.9**

With the retrofit measures advised in Table 18, the new yearly energy use of the building will be -537 GJ. The energy use has become negative since the proposed measures reduce the energy use until zero and the addition of solar panels who generate electricity pushes that energy use below zero. It should be noted that the building is still using energy for its heating and cooling demand. The energy use following from the model is zero, since the DSS uses a linear model as described in Section 3.1.4. This means that the impact of certain measures on the energy reduction of other measures is not included. For example, when insulating the walls which results in an energy reduction, the impact of placing triple glazing is lower than when only doing that measure. This causes the energy use to be able to drop to zero. In this case, the energy index will be equal to 0 which corresponds to an energy label A. So, when aiming for energy label C, the most suitable set results in an energy label A. The energy use per m^2 comes at 0.0 kWh. However, when aiming for an energy label C, a combination between solar panels and replacing lights with LED is enough to reduce the energy use by 643 GJ. What stands out in Table 18, is that replacing the lights with LED reduces more CO_2 emissions than the measure triple glazing, while triple glazing reduces more energy. This can be explained by the fact that the conversion factor from MJ electricity to CO_2 emissions is larger than that of MJ gas to CO_2 emissions. Since the triple glazing impacts the heat demand, and the current heating installation uses gas, the emission factor of gas is used here.

Energy label A

Considering the preferences of the office building owner, the set of retrofit measures aiming for energy label C resulted in an energy label A. Therefore, the same measures can be advised when aiming for energy label A. However, the proposed measures reduce the energy use more than needed to obtain energy label A. An energy reduction of 873 GJ compared to the current situation is needed to obtain energy label A. Therefore, the combination of solar panels and heat delivery by third parties or insulating the whole building is enough to reach energy label A.

Timeline

Figure 19 shows the timeline for the proposed set of retrofit measures presented in Table 18. The time needed to realize these retrofit measures, is 191 days. This corresponds to 1 year and 1 months. The lifetime of the different retrofit measures is 15 years or longer (see Appendix F). When realizing the retrofit measures today, their lifetime will not have to be extended before 2030, the target year of energy label A. Therefore, all measures could be realized today to reach both energy label targets.

Figure 19: Timeline retrofits Norit Amersfoort

5.2 Freudenthal UU

The Freudenthal building is an office building from the Utrecht University (UU). It was built in 1970 and it has not been renovated since. The filled in questionnaire can be found in Appendix H. The box about the preferences of the office building owner is filled in by two people, one financial manager and one technical maintenance manager. Their weights are presented in Table 19. They both give the most preference to the lowest maintenance costs. This can be explained by the inconvenience of doing maintenance activities in a building which is constant in use for education. However, the distribution of the weights differs between the two managers. Regarding the ranking, the technical maintenance manager is more focused on the installations, while the financial manager also includes the structure of the building. The priority points are given in Table 20.

Table 19: Weights criteria Freudenthal UU

Criteria	Weights financial manager	Weights technical maintenance manager
Lowest investment costs	20	0
Fastest Payback Period in years	0	30
Lowest maintenance costs	50	40
Reduction of CO_2 emissions	10	20
Reduction of energy requirement	20	10

Table 20: Priority points Freudenthal UU

Priority	Points financial manager	Points technical maintenance manager
Insulation	1.17	0
Windows	1.17	0
Heat supplier	2.3	2.8
Cold supplier	2.3	1.4
Ventilators	0	0
Lighting	0	2.1
Solar energy systems	0	0.7

Current situation

The current energy label of this building is E, with an energy index of 1.53. This energy index is based on the energy consumption allowed, which is 1,407 GJ per year for this building according to the calculations of the ISSO 75.3. The total operational CO_2 emissions related to the energy use of the building are 164 ton per year. The results can be found in Table 21.

Table 21: Current situation Freudenthal UU

Current situation		
Energy label	**E**	
EI	1.53	
Energy use per year		
Building	2,151	GJ
	130	kWh/m^2
Allowed	1,407	GJ
CO_2 emissions		
Total	164	tonne

Energy label C

To reach energy label C, the building should reduce its yearly energy use by 326 GJ. The proposed measures when aiming at an energy label C with the preference of the financial manager are described in Table 22.

Table 22: Measures energy label C Freudenthal (financial manager)

Measures		**Investment costs**	**Payback period (years)**	**Maintenance costs (per year)**	**Energy reduction (GJ)**	**CO_2 emission reduction (tonne)**
Glazing	Triple glazing	€ 218,960	64.5	€ -	230	11.6
Awning	No change	€ -	0.0	€ -	0	0
Floor insul.	Glass wool	€ 11,823	19.1	€ -	42	2.1
Roof insul.	Glass wool	€ 15,483	25.6	€ -	41	2.1
Wall insul.	Glass wool	€ 22,540	37.3	€ -	41	2.1
Solar energy sys.	Mono crystalline	€ 108,955	0.1	€ 987	159	9.8
Lighting	Replace lights with LED	€ 55,854	7.1	€ -	223	13.7
Movement detection	Add movement detection	€ 44,269	50.5	€ -	25	1.5
Ventilation	Mechanical supply and drain with recirculation or heat recovery	€ 201,432	27.7	€ 115	209	12.8
Heat supplier	Heat pump: Heat from return / exhaust air - Gas	€ 250,600	26.0	€ 150	661	33.5
Cold supplier	Cold storage	€ 1,869,083	Infinite	€ 74,507	28	1.7
Flow control	Flow control	€ 13,734	5.0	€ -	77	12.1
BEMS	No change	€ -	0.0	€ -	0	0
		€ 2,716,942	**Infinite**	**€ 75,759**	**1,736**	**103.0**

After completing the retrofit measures advised in Table 22, the new yearly energy use of the building will be 415 GJ. The energy index will be equal to 0.29 which corresponds to an energy label A. So, when aiming for energy label C, the most suitable set results in an energy label A. The energy use per m^2 comes at 34.8 kWh. When only aiming for an energy label C, replacing the heat supplier is enough. Or a combination of placing solar panels and replacing the lights with LED. What stands out in Table 22 is the high investment costs, maintenance costs and therefore the infinite PBP of the cold storage. The financial manager ranked the cold supplier at the first place in the ranking, which resulted the inclusion of this measure in the proposed set. However, without the cold storage, energy label C can be reached as well. When removing the cold storage from the set of proposed measures, the PBP becomes 64.5 years (based on the measure triple glazing).

The results considering the preferences of the technical maintenance manager are shown in Table 23.

Table 23: Measures energy label C Freudenthal (technical maintenance manager)

Measures		**Investment costs**	**Payback period (years)**	**Maintenance costs (per year)**	**Energy reduction (GJ)**	**CO_2 emission reduction (tonne)**
Glazing	No change	€ -	0.0	€ -	0	0
Awning	No change	€ -	0.0	€ -	0	0
Floor insul.	No change	€ -	0.0	€ -	0	0
Roof insul.	No change	€ -	0.0	€ -	0	0
Wall insul.	No change	€ -	0.0	€ -	0	0
Solar energy sys.	Mono crystalline	€ 108,955	0.1	€ 987	159	9.8
Lighting	Replace lights with LED	€ 55,854	7.1	€ -	223	13.7
Movement detection	Add movement detection	€ 44,269	50.5	€ -	25	1.5
Ventilation	No change	€ -	0.0	€ -	0	0
Heat supplier	Heat pump: Heat from return / exhaust air - Gas	€ 250,600	26.0	€ 150	661	33.5
Cold supplier	Cold storage	€ 1,869,083	Infinite	€ 74,507	28	1.7
Flow control	No change	€ -	0.0	€ -	0	0
BEMS	No change	€ -	0.0	€ -	0	0
		€ 2,328,760	**Infinite**	**€ 75,758.95**	**1,096**	**60.1**

After completing the retrofit measures advised in Table 23, the new yearly energy use of the building will be 1,054 GJ. The energy index will be equal to 0.75 which corresponds to an energy label A. So, when aiming for energy label C, the most suitable set results in an energy label A. The energy use per m^2 comes at 73.7 kWh. Again, when only aiming for an energy label C, replacing the heat supplier is enough. Or a combination of installing solar panels and replacing the lights with LED. The proposed set of measures considering the preferences of the technical maintenance manager is very different from the set considering the preferences of the financial manager. The main difference is the selection of insulation measures. The technical maintenance manager did not include insulation in their ranking, which resulted in selecting "No change" for these measures. What both proposed sets of retrofit measures included but was not included in both rankings by the different managers, were the replacing of lights with LED and the installation of solar panels. These measures are therefore suitable regardless of the preference of the owner.

Energy label A

For the preferences of both the financial manager and the technical maintenance manager, the proposed set of retrofit measures aiming for energy label C resulted in an energy label A. Therefore, the same measures can be advised when aiming for energy label A. However, only a reduction of 583 GJ is needed to obtain energy label A. This can be achieved by installing the heat pump or a combination of solar panels, LED lights and triple glazing.

Timeline

Figure 20 shows the timeline for the two different set of retrofit measures, as presented in Tables 22 and 23. The installation time corresponding to the proposed set of retrofit measures considering the preferences of the financial manager, is 212 days (1 year and 2 months). The time needed to realize the retrofit measures considering the preferences of the technical maintenance manager is 148 days (10 months). The lifetime of the heat pump proposed in both sets is 10-15 years. Since the energy label A target year is in 10 years, it could be preferable to realize this measure in a few years, to ensure that it is still active when reaching 2030. The lifetime of the other retrofit measures in both sets is 15 years or longer (see Appendix F). When realizing the retrofit measures today, their lifetime will not have to be extended before 2030, the target year of energy label A. It could therefore be preferable to use these measures to reach energy label C, and install the heat pump when reaching the target year for energy label A.

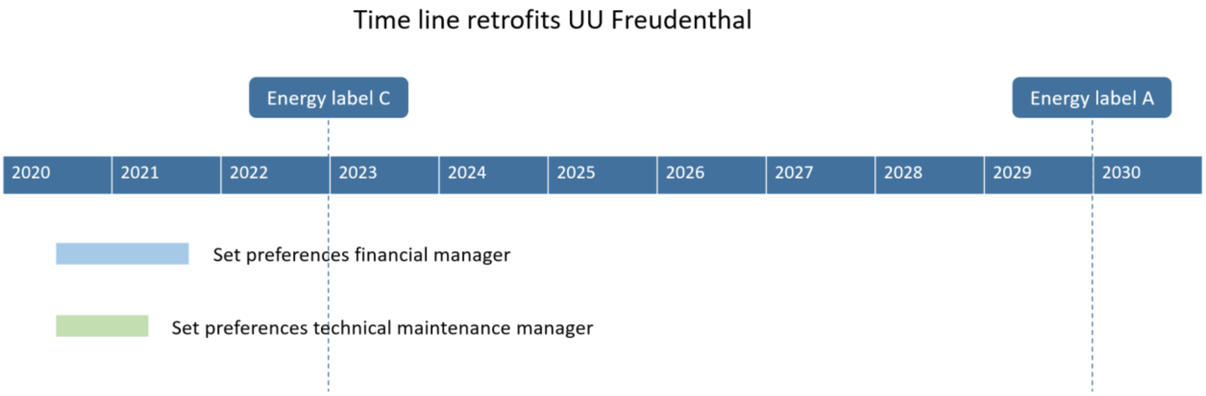


Figure 20: Timeline retrofits UU Freudenthal

5.3 Office SPIE

The SPIE office building is a new property of SPIE in Utrecht. The office building is still empty and that is why SPIE is considering retrofitting before the employees are moving into this building. The preferences are set by the facility manager of SPIE. The weights and priority points are presented in Tables 24 and 25, respectively. Most preference is given to low investment costs. However, the facility manager aims at improving all components of the building. Therefore, the focus will lie on the cheapest retrofit measure resulting in an energy reduction rather than changing nothing. The filled in questionnaire can be found in Appendix I.

Table 24: Weights criteria Office SPIE

Criteria	Weights office owner
Lowest investment costs	30
Fastest Payback Period in years	20
Lowest maintenance costs	20
Reduction of CO_2 emissions	10
Reduction of energy requirement	20

Table 25: Priority points Office SPIE

Priority	Points office owner
Insulation	0.25
Windows	1.75
Heat supplier	0.75
Cold supplier	1
Ventilators	0.5
Lighting	1.5
Solar energy systems	1.25

Current situation

The current energy label of this building is D, with an energy index of 1.32. This energy index is based on the energy consumption allowed, which is 1,422 GJ per year for this building according to the calculations of the ISSO 75.3. The total operational CO_2 emissions related to the energy use of the building are 101 ton per year. The results can be found in Table 26.

Table 26: Current situation Office SPIE

Current situation		
Energy label	**D**	
EI	1.32	
Energy use per year		
Building	1,877	GJ
	119	kWh/m^2
Allowed	1,422	GJ
CO_2 emissions		
Total	101	tonne

Energy label C

To reach energy label C, the building should reduce its yearly energy use by 27 GJ. The proposed measures when aiming at an energy label C are described in Table 27.

Table 27: Measures energy label C Office SPIE

Measures		**Investment costs**	**Payback period (years)**	**Maintenance costs (per year)**	**Energy reduction (GJ)**	**Reduction in CO_2 (tonne)**
Glazing	HR ++ glass	€ 63,180	13.89	€ -	129	7.9
Awning	No change	€ -	0.0	€ -	0	0
Floor insul.	Glass wool	€ 61,635	36.5	€ -	48	2.9
Roof insul.	PIR	€ 32,760	22.6	€ -	41	2.5
Wall insul.	PUR	€ 36,713	36.2	€ -	29	1.8
Solar energy sys.	Mono crystalline	€ 121,705	0.1	€ 1,103	178	10.9
Lighting	Replace lights with LED	€ 4,508	0.8	€ -	154	9.4
Movement detection	No change	€ -	0.0	€ -	0	0
Ventilation	Mechanical supply and drain with recirculation or heat recovery	€ 192,588	17.9	€ 115	307	18.9
Heat supplier	Heat delivery by third parties	€ 70,032	4.4	€ -	447	27.4
Cold supplier	Cold storage	€ 1,659,375	Infinite	€ 66,147	24	1.5
Flow control	Flow control	€ 13,131	5.0	€ -	74	11.6
BEMS	No change	€ -	0.0	€ -	0	0
		€ 2,255,627	**Infinite**	**€ 67,365**	**1,431**	**94.8**

With the retrofit measures advised in Table 27, the new yearly energy use of the building will be 446 GJ. The energy index will be equal to 0.31 which corresponds to an energy label A. So, when aiming for energy label C, the most suitable set results in an energy label A. The energy use per m^2 comes at 39.6 kWh. To only reach energy label C, insulating the walls, roof or floor is enough. What stands out in Table 27 is again the high investment and maintenance costs and infinite PBP of the cold storage. The same explanation applies as for the other buildings that the inclusion of the cold supplier into the ranking resulted in the addition of the cold storage is the set of proposed measures. Again, this measure isn't needed to achieve energy label C. Without the cold storage, the PBP of the proposed set of retrofit measures becomes 36.5 years (based on the floor insulation measure).

Energy label A

Considering the preferences of the office building owner, the proposed set of retrofit measures aiming for energy label C resulted in an energy label A. Therefore, the same measures can be advised when aiming for energy label A. However, to reach energy label A, a reduction of 383 GJ in energy use is enough. This corresponds to the change in heat supplier.

Timeline

Figure 21 shows the timeline for the realization of the proposed retrofit measures. The installation time corresponding to the proposed set of measures presented in Table 27, is 209 days. This corresponds to 1 year and 2 months. The lifetime of the different retrofit measures is 15 years or longer (see Appendix F). When realizing the retrofit measures today, their lifetime will not have to be extended before 2030, the target year of energy label A. Therefore, all measures could be realized today to reach both energy label targets.

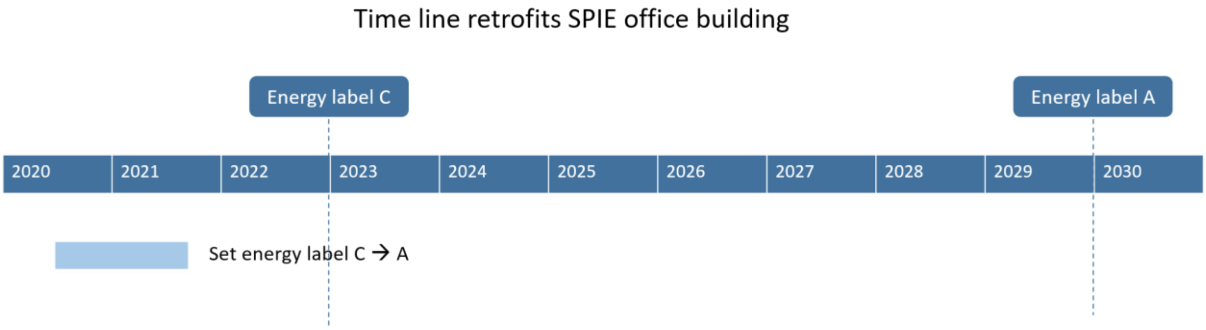


Figure 21: Timeline retrofits SPIE office building

5.4 Sensitivity analysis

This section describes the sensitivity analysis to validate the operation of the DSS. The input data to be able to run the DSS, is based on the characteristics of the Freudenthal UU building. Every other building could be used to conduct the sensitivity analysis. The preferences of the office building owner are not considered in this case to fairly see the impact of the changes in variables on the results. Therefore, the weights are divided equally, and no ranking is made. The energy reduction aimed for corresponds with the energy label C. Table 28 shows the results of the DSS for the Freudenthal UU building without the preferences of the office building owner. With this set of measures, energy label A is reached. The impact of the change in variables on this set of measures is researched in this sensitivity analysis.

Table 28: Base scenario sensitivity analysis results

Measures		**Investment costs**	**Payback period (years)**	**Maintenance costs (per year)**	**Energy reduction (GJ)**	**Reduction in CO_2 (tonne)**
Glazing	No change	€ -	0.0	€ -	0	0
Awning	No change	€ -	0.0	€ -	0	0
Floor insul.	No change	€ -	0.0	€ -	0	0
Roof insul.	No change	€ -	0.0	€ -	0	0
Wall insul.	No change	€ -	0.0	€ -	0	0
Solar energy sys.	Mono crystalline	€ 108,954	0.1	€ 987	159	9.8
Lighting	No change	€ -	0.0	€ -	0	0
Movement detection	No change	€ -	0.0	€ -	0	0
Ventilation	No change	€ -	0.0	€ -	0	0
Heat supplier	Heat pump: Heat from return / exhaust air - Gas	€ 250,600	26.0	€ 150	661	33.5
Cold supplier	No change	€ -	0.0	€ -	0	0
Flow control	No change	€ -	0.0	€ -	0	0
BEMS	No change	€ -	0.0	€ -	0	0
		€ 359,554	**26.0**	**€ 1,137**	**820**	**43.2**

5.4.1 Gas price

In this section, the gas price is changed 10% up and down. Table 29 shows the results of the DSS with a changed gas price. From the results, only the PBP of gas using installations is influenced. The PBP is decreased when the gas price is increased, since this results in higher benefits from decreasing the energy demand and therefore decreasing the gas use. The set of retrofit measures is not impacted by the change is gas price, making the results robust for these fluctuations.

Table 29: Gas price changes Freudenthal

	Gas price -10%	Proposed	Gas price +10%
Investment costs	€ 359,554	€ 359,554	€ 359,554
PBP (years)	29.0	26.0	23.6
Maintenance costs	€ 1,137	€ 1,137	€ 1,137
Reduction in energy use (GJ)	820	820	820
Reduction in CO_2 emissions (tonne)	43.2	43.2	43.2
Energy label	A	A	A
Set of retrofit measures	Stayed the same		Stayed the same

5.4.2 Electricity price

The electricity price is changed 10% up and down in this section. Table 30 shows that the set of proposed retrofit measures does not change when decreasing the electricity price with 10%. When increasing the electricity price with 10%, replacing lights with LED is added as a retrofit measure. This can be explained by the fact that the overall score of replacing lights with LED and “No change” are close together, namely 0.60 and 0.77 respectively. When the electricity price increases, the measure replacing lights gets more points for the criterion PBP. Due to this increase, replacing lights with LED becomes the preferred measure instead of “No change”. The addition of this retrofit measure results in higher investment costs, larger reduction in energy use and in CO_2 emissions. In other words, the PBP from electricity using installations changes when changing the electricity price. The overall PBP does not change, since the largest PBP is based on the installment of a heat pump. This measure impacts the heating demand, making the PBP depended on the gas price.

Table 30: Electricity price changes Freudenthal

	Electricity price -10%	Proposed	Electricity price +10%
Investment costs	€ 359,554	€ 359,554	€ 415,408
PBP (years)	26.0	26.0	26.0
Maintenance costs	€ 1,137	€ 1,137	€ 1,137
Reduction in energy use (GJ)	820	820	1,044
Reduction in CO_2 emissions (tonne)	43.2	43.2	56.9
Energy label	A	A	A
Set of retrofit measures	Stayed the same		Measure added: lights are replaced by LED

5.4.3 CO_2 emission factor Dutch electricity grid

In this section, the CO_2 emission factor from the Dutch electricity grid is changed. Table 31 shows that a lower emission factor does not change the proposed measures. However, increasing the emission factor results in the addition of LED lights. This, again, can be explained by the fact that the overall score of replacing lights with LED and "No change" are close together. When the CO_2 emission factor increases, the measure replacing lights with LED gets more points for the criterion Reduction in CO_2 emission. Due to this increase, replacing lights with LED becomes the preferred measure instead of "No change". This added measure results in higher overall investment costs, larger reduction in energy use and in CO_2 emissions.

Table 31: CO_2 emission factor change Freudenthal

	CO_2 emission factor -10%	**Proposed**	**CO_2 emission factor +10%**
Investment costs	€ 359,554	€ 359,554	€ 415,408
PBP (years)	26.0	26.0	26.0
Maintenance costs	€ 1,137	€ 1,137	€ 1,137
Reduction in energy use (GJ)	820	820	1,044
Reduction in CO_2 emissions (tonne)	43.2	43.2	56.9
Energy label	A	A	A
Set of retrofit measures	Stayed the same		Measure added: lights are replaced by LED

5.4.4 Investment cost

The next step of the sensitivity analysis consists of changing the investment costs of the different retrofit measures. They are changed 20% up and down individually. When increasing the investment costs of the different measures, no change occurred in the proposed set of retrofit measures. Even when the price of solar energy system or the heat suppliers (which are incorporated in the base set) are increased, the proposed retrofit measures stay the same. This can be explained by the high overall score of the solar energy systems and the heat supplier. These scores are high due to their large impact on the energy use, which is not changed when increasing the investment costs. The corresponding PBP does increase. With higher investment costs, the PBP is longer. When decreasing the investment costs of the different measures, in most of the cases no change occurred in the proposed set of retrofit measures. However, when decreasing the investment costs of replacing lights with LED, this measure was included in the proposed set. As described before, this can be explained by the small difference between the scores in the options changing the lights with LED and "No change".

5.4.5 Weights MCDA

The weights for the criteria from the MCDA are changed in this section. When giving the preference to the criterion Investment costs, no solar panels were installed. This is to be expected since the solar panels score lower on the criterion Investment costs than the option "No change". The score for Reduction of energy requirement or Reduction of CO_2 emissions is not high enough to raise the overall score of the solar panels above the option "No change". The disappearance of the solar panels in the set of proposed retrofit measures, resulted in an energy reduction corresponding to an energy label B instead of A. When giving the preference to the PBP and the Maintenance costs, no change occurred in the proposed set of retrofit measures. When preferring the criterion Reduction of energy requirement and Reduction of CO_2 emissions, the set of retrofit measures changed. Namely, the retrofit measures triple glazing, replace lights with LED, ventilation with mechanical supply and drain with recirculation and flow control were added. This can be explained by the fact that retrofitting becomes more interesting than doing nothing when preferring these two criteria, since retrofitting reduces the energy use and CO_2 emissions of the building.

5.4.6 Ranking of retrofit measures

The points for the ranking of the retrofit measures are changed last in the sensitivity analysis. Each type of retrofit measure is included in the ranking once individually. When including a retrofit measure in the ranking, it was included into the set of proposed measures. For example, when ranking windows, triple glazing was added to the set of measures. This is explained by the fact that the scores of the corresponding retrofit measures are increased, while the score of the option “No change” is not. This sensitivity analysis therefore showed that when including a measure in the ranking, it is certain that this measure is including in the set of proposed retrofit measures.

6. Discussion

This chapter describes the discussion of the research. First, the results of the DSS are discussed in Section 6.1. Section 6.2 discusses the operation of the DSS. Next, the theory used to build the DSS is discussed in Section 6.3. Section 6.4 describes the use of the DSS in practice and what should be noted when consulting this DSS. Lastly, Section 6.5 describes the limitations and suggestions for further research.

6.1 Findings

The results of the DSS for the three office buildings showed that most energy reduction can be achieved by retrofitting the heat supplier and replacing the conventional lights with LED. This corresponds to the expectations described in Section 2.3.1, which showed that heating and lighting make up most of the energy demand of an office building. Another measure that can reduce the energy demand of an office building effectively is the installment of solar panels. Solar panels are specifically suitable for office buildings, since office buildings require most energy during the day which matches the energy production of solar panels when the sun shines.

What stands out from the results of the DSS is the overall high PBP. A reason for this overall high PBP could be that the investment costs of the retrofit measures is too high, or the energy reduction achieved is too low. This latter could be explained by the fact that when changing from double glass to HR+ glass, for example, the effect on the energy reduction is marginal. This results in a longer PBP since the price remains the same, but the energy reduction is lower than when changing from single glass to HR+ glass for example. The sensitivity analysis showed that a decrease in investment costs could lead to the addition of a retrofit measure. Therefore, the user of this DSS should be aware that when the investment costs decrease, the proposed set of measures can change. In addition, the DSS currently considers every retrofit measure, even when it will not be able to payback itself. A constraint could be added to exclude these measures from the proposed set, to ensure the cost-effectiveness of the proposed set of retrofit measures.

The results of the DSS showed that when aiming for energy label C and considering the preferences of the office building owner, it is possible that the measures proposed could reduce the energy use as much as to an energy label A. This can be explained by the fact that a retrofit measure can get a higher point on the MCDA compared to the “No change” option. For example, when the office building owner prioritizes the criterion Reduction of energy requirement, a retrofit measure will get a higher score for this criterion than the “No change” option since this doesn’t reduce the energy demand. The sensitivity analysis confirmed that the results are highly depended on the preferences of the office building owner. Especially when ranking a type of retrofit measure to be included in the set of proposed measures, it is certain that it will be selected. The results of the DSS therefore provides an advice to the office building owner, considering its preferences. However, it could be that the office building owner does not want to retrofit more than necessary. The results of the DSS should therefore be interpreted as an advice and not as the way to go.

In addition, this ranking method can be used to operate according to the principle of the Trias Energetica. When prioritizing the insulation, it is certain that these measures will be selected first. The ranking method can also be used to include the functional obsolescence of building services. On the other hand, the weights for the criteria can be used to select the most cost-effective retrofit measures to obtain energy label C or A by assigning all the points to the criterion Investment costs. In this case, the proposed set of retrofit measures includes the minimum of retrofit measures needed to reach the selected energy label, since the option of “No change” always scores higher on the criterion Investment costs than a retrofit measure.

6.2 Operation of the DSS

The DSS is made to select retrofit measures to reduce the energy use of the building to a certain energy use level. To do so, the Knapsack problem (described in Section 3.1.4) is used in this research. It should be noted that the addition of the possibility to not change a building characteristic was added to this problem. When this option of “No change” is not added, only retrofit measures can be selected by the Excel Solver. In some cases, retrofitting is not preferred, for example when the improvement of a construction part does not result in a significant energy reduction. In addition, when renovating to aim for a better energy label, it is possible that only improving the insulation is enough. The model should therefore be able to select “No change” on the other types of renovation measures. For that reason, the addition of a “No change” decision variable is crucial when using the Knapsack problem to renovate a building to a certain energy label.

Moreover, the DSS considered the Dutch energy label requirements. Since the energy label is based on the net energy use per year, it is possible to obtain a better energy label by only placing solar panels. The net energy use is namely described by the actual energy demand of the building minus the energy generated by for example solar energy systems. When improving the energy label by installing solar panels, the net energy use is lowered, but the actual energy demand isn’t. Which is strange, because when the solar panels do not generate electricity, for example with cloudy weather, the energy use is the same as with the old energy label. As described in Section 2.3, the energy use requirements are therefore changing in the future to NZEB requirements. These requirements focus more on the Trias Energetica, resulting in a maximum energy use per m^2. This makes it impossible to obtain a good energy label by only placing solar panels at the roof and not improving the insulation for example. The DSS is made is such a way that the energy use per m^2 can be set as a constraint instead of the energy use in MJ. In addition, as explained in Section 5.1, the ranking can also be used to incorporate the Trias Energetica principle with the current energy label system. This together makes sure that the DSS will stay valuable even when the energy requirements are changed by the Dutch government.

6.3 Theory

The theory of Nielsen et al. (2016) was used to build the DSS (see Section 2.4). The six steps of the ideal retrofit decision process are implemented as follows: 1) Goal setting is covered with the aim to reach either energy label C or A, 2) Criteria weighting is specified by the preferences of the office building owner, who divides 100 points over the six criteria, 3) the characteristics of the building are described in the questionnaire, therefore covering the step Building Diagnosis, 4) the DSS generates the ideal set of retrofit measures (Design Alternatives Generation) and 5) the results of the DSS describe the performance of these measures (Performance Estimation). Lastly, step 6 includes the Design Alternatives Evaluation which is partly done through a sensitivity analysis of the results. What is lacking is the evaluation of the sustainability of the proposed retrofit measures. This research showed the impact on the operational CO_2 emissions but did not consider the embedded CO_2 emissions for example.

The criteria used in the MCDA were based on research by Lombardi et al. (2017), as described in Section 2.5. These criteria are described as suitable for retrofitting. However, some of the criteria partly overlap. For example, the criterion PBP is based on the criteria Investment costs, Maintenance costs and Reduction of energy requirement. When preferring the PBP, indirectly the others are preferred as well because low investment costs, low maintenance costs and high energy reduction result in a short PBP. In addition, the criterion Reduction in CO_2 emissions is depended on the criterion Reduction of energy requirement. Due to this interdependence of the different criteria, criteria could get more priority without the user of the

DSS knowing. Therefore, the user should be aware of this interdependency and he/she should communicate this with the office building owner who needs to provide its preferences.

6.4 Practical application

In practice, the DSS will be useful to advice which set of retrofit measures should be realized to achieve a certain energy label. It gives the office building owner the possibility to manage its property and plan its renovation. However, during this research, the collection of the characteristics of the building was more difficult than expected. Most of the office building owners were not aware of the conditions of their building. As described in Section 2.1, up until 2014 the energy label was not enforced by the Dutch government. This resulted in the seller and buyer of a building to agree upon the absence of the energy label. In other words, the building characteristics determining the energy use of the building were unknown. This could be an explanation for the lack of knowledge of this empirical data by office building owners. Therefore, when using this DSS, enough time (couple of weeks) should be reserved to be able do a complete energy audit of the building (Krarti, 2016).

6.5 Limitations and suggestions for further research

The first limitation of this research was the exclusion of the energy use by appliances in the office building. This energy use is not considered in the energy label calculation by the ISSO 75.3 (2011) and therefore not considered in this research. However, this energy use accounts for 3% of the total energy use in an office building as described in Section 2.3.1. It is expected that the new NTA 8800 (described in Section 2.1.1) will include the energy use of appliances. When this calculation method is available, it should be added to the DSS.

The second limitation of this research was that the DSS did not allow for the solar panels to be scalable. In some cases, it would be preferable to only install a few solar panels and not use all the available space at the roof of the building. For example, using the total available space could lead to an overproduction of electricity. When the office building is not able to store this electricity and use it later, this energy is sent back to the grid. When the netting arrangement ("salderingsregeling") currently active in the Netherlands is removed, this energy is loss. Therefore, it could be financially more attractive to place fewer solar panels who generate just enough electricity to cover the demand of the building. The Excel Solver used in this DSS was not able to include this scalability, since this resulted in a non-linear problem. Other programs could therefore be tested to build this DSS which could handle a non-linear problem. Another limitation of the DSS, which could probably be solved with a non-linear model, is the mutual impact of the retrofit measures. As described in Section 3.1.4, the DSS was not able to include this interaction between the retrofit measures and their energy reduction capability.

This research did not consider a discount rate or the price development of the retrofit measures. It could be possible that the price of for example heat pumps will decrease in the coming years. Since the target year of energy label A is still 10 years away, it could be beneficial to invest in a heat pump in a later year than today. A study considering the experience curve of the considered retrofit measures in this research is suggested. In addition, these expected investment cost decreases (or increases) could be added to the DSS to determine the right moment to make the investment.

Lastly, this research was missing the sustainability impact of the retrofit measures in the last step of the ideal DSS as described by Nielsen et al. (2016). Examples of this sustainability impact are the embedded CO_2 emissions or the waste generation when retrofitting. These sustainability criteria could be added to the MCDA, giving the office building owner the ability to include these in their decision as well.

7. Conclusion

The aim of this research was to build a Decision Support System (DSS) which considers the future mandatory energy labels, following the Dutch Building Decree of 2012, when selecting retrofit measures for office buildings in the Netherlands. To build the DSS, first the following sub questions were answered.

1. How are the Dutch energy labels for office buildings determined?

In the Netherlands, the energy labels are based on the Energy Index (EI). In the Dutch building sector, the ISSO 75.3 (2011) is widely used to determine the EI of a building. This method was therefore used in the DSS to determine the energy use of an office building and subsequently its energy label. In the future, the energy label requirements are going to change to the NZEB requirements, which are given in kWh/m^2. Therefore, this aspect was included in the DSS, keeping it valuable when the energy requirements change.

2. What are office building characteristics that determine its energy use?

As found through a literature review (see Section 2.3.1), the heating demand and lighting of an office building highly determine its energy use. Moreover, the heating demand is impacted by the insulation values of the construction parts and the efficiency of the heat suppliers.

3. What are the available retrofit measures and their characteristics for office buildings in the Netherlands?

The retrofit measures suitable for office buildings were selected based on the theory by Ma et al. (2012) and Hong et al. (2019). From this theory, the category Energy Conserving Behaviour was not considered suitable to reduce the energy use of an office building. For the other four categories, retrofit measures were collected including their financial implications (see Section 2.3.2 and Appendix F).

4. What are the decision variables for the office building owner when selecting retrofit measures?

The decision criteria for selecting retrofit measures by the owner of the building are Investment costs, Payback period, Maintenance costs, Reduction of energy requirement and Reduction of CO_2 emissions (see Section 2.5). These criteria are based on research by Lombardi et al. (2017). When using these criteria in the DSS, it should be noted that they are interdependent.

With the answers to the above sub questions, the DSS was build. The sensitivity analysis in Section 5.5 showed that the operation of the DSS was robust for fluctuations in input data. However, when the overall score of two retrofit measures are close to each other, a slight change in input data could result in another proposed measure. The results of the DDS where highly dependent on the preferences of the office building owner. Including a type of retrofit measure in the ranking ensured its inclusion in the proposed measures. In addition, the test results of the DSS showed that the preferences of the office building owner can result in more retrofit measures proposed than needed to obtain a certain energy label. The DSS is based on the energy label calculation and therefore doesn't include the principle of the Trias Energetica. However, the ranking of retrofit measures can be used to ensure the inclusion of insulating measures and energy efficient installations.

The DSS was able to answer the main research question, namely:

What are the financial and environmental implications of different retrofit measures for office buildings when aiming to reach mandatory energy labels following the Dutch Building Decree of 2012?

The financial and environmental implications of the different retrofit measures for the three tested office buildings are presented in Section 5. Overall, the highest investment costs are coupled to the retrofitting of the heat and cold suppliers. The highest energy use reduction and therefore CO_2 emission reduction is achieved by heat suppliers. In addition, the installation of solar panels and the replacement of lights with LED are financially attractive retrofit options for office buildings. However, it should be noted with the changing energy requirements, that only installing solar panels isn’t enough to comply with this new regulation. The timeline of the three test buildings showed that the total set of proposed measures takes around a year to be realized. This ensures that the office buildings can reach the two energy label target years in time, when retrofitting is started today. When a heat pump is proposed in the set of retrofit measures, it can be beneficial to wait a few years before installing it, due to its relatively short lifetime. This ensure its use in 2030 when energy label A needs to be reached. In that case, other measures can be used to obtain energy label C.

With this research, a tool is presented to support the decision regarding retrofits for office buildings in the Netherlands. SPIE will be able to use the DSS to provide quick indications of the measures needed to improve the energy use of an office building. This will help them to support the governmental ambition to reduce the Dutch CO_2 emissions linked to the built environment. In addition, this research can be used to build other DSS using the energy requirements from different countries. What is needed to do so is a clear calculation of the energy requirements valid in that country.

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Appendix A - *Questionnaire*

This section presents the questionnaire and the email that has been send to the office building owners in this research. Since Dutch building owners where part of this research, also a Dutch version is added.

A.1 English email and questionnaire

Dear [office building owner],

My name is Pam Engwirda and I am currently writing my graduation thesis (Utrecht University) on the retrofitting of Dutch office buildings. As you might know, the energy requirements for office buildings are changing in the near future. As of January 1st, 2023, every office building in the Netherlands should carry an energy label C. In 2030, this requirement is even set at an energy label A. To improve the energy label of your building, multiple retrofit options are possible. The aim of my research is to select the best suited retrofit options for a specific office building. In this case your office building. To do so, I made a decision support system in collaboration with SPIE Nederland BV. I would like to test this model using the characteristics of your office building.

What's in it for you? The result will be two sets of retrofit measures specified to your office building. One set aiming to achieve energy label C and one set aiming to achieve energy label A. The results will show the expected costs (investment and maintenance), payback period, reduction in CO_2 emissions and a timeline showing the time needed to install these measures.

What I need from you is to answer the added questionnaire to the best of your abilities. If something is unclear or you could not answer the question, please make a note. I will use this to optimise the questionnaire.

Would you be willing to help me?

Thank you in advance!

Kind regards,

Pam Engwirda

Questionnaire

Demographic information		
Name office building		
Address		
Year of construction		
Months building is in use per year		months

Office building construction characteristics		
Surfaces and sizes		
Total floor area office building		m^2
Floor area 1st floor		m^2
Crawlspace present?	☐ Yes	☐ No

Hight building		m
Hight per floor		m
Area outside walls (incl. windows/doors)		m^2
Area roof		m^2
Area windows (all outside windows, including glass doors)		m^2

Insulation values	**U (based on year of construction)**	**If known, fill in here**	
Floor	5.882		W/m^{2}K
Walls	2.326		W/m^{2}K
Roof	1.163		W/m^{2}K
If applicable, year of renovation			

Type of floor, ceiling, facade	
Mass of floor construction (kg/m^2)	
Type of ceiling	
Facade type	

Windows		
Type of glazing		
Outdoor blinds present?	☐ Yes	☐ No
If yes, type of blinds		

Office building installations

Climate system nr		See tab Climate system nr

Heating and cooling system		
Type of heat generator		
Individual control heating	☐ Yes	☐ No
Cold supplier		
Area of cooled zones		m^2
CHP		
Present?	☐ Yes	☐ No
Electric power		kW
Thermal power		kW
Type of distribution		

More detailed information heating system

Heat pump

Source

Type of fuel

Demanded temperature level

Boiler

Type of boiler

Temperature level heat supply

One or more central heating appliances that supply heat for an use area of

Steam boiler

Economizer

Air preheater

Hot water boiler with 150 °C water

Flue gas condenser

Ventilators

Type of ventilation system	
Provision in ventilation system	
Type of arrangement	
Heat recovery system	
Ventilation facility with cooling requirement	

Humidification

Type of humidification installation	
Moisture recovery	

Hot tap water

Type of generator	
Distribution system	

Solar energy systems

Solar panels

Present	☐ Yes	☐ No
Type of pv-system		
Peak power (Other pv system)		W/m^2
Surface area		m^2
Orientation		
Slope angle		

Solar collector

Present	☐ Yes	☐ No
Surface area		m^2

Lighting (see box below)

Total installed power of lighting		
Conventional	0.00	kW
LED		kW
Luminaire type		
Type of control/switch		
Movement detection		

Preferences retrofit

I would like to ask you to divide 100 points over the next criteria. The one who is of most importance to you, should get the most points. The second most important a little less and so on.

	Points	***Example***
Lowest investment costs		*50*
Fastest Payback Period in years		*20*
Lowest maintenance costs		*0*
Reduction of CO_2 emissions		*10*
Reduction of energy requirement		*20*
	0	

Lastly, I would like you to rank the retrofit measures in order of preference. At number 1, place the building characteristic that is in the highest need of renovation. At number 7, place the building characteristic that has your least preference of being renovated. For example, a year ago you improved the insulation of your building so you would want to do other renovations first.

1	
2	
3	
4	
5	
6	
7	

Notes

Lighting

	Power (W)	Amount
TLD	18	
	36	
	58	
	72	

Fill in the amount of lights per type. If not known which type of lights are installed or other lights are installed, fill in the green box below.

Installed conventional lights (kW)

	116	
PLC	9	
	13	
	18	
	26	
	36	
TL5	14	
	21	
	28	
	42	
	56	

Climate System number
Different calculations in the energy label calculation depend on the climate system present in the building. Especcially the transport of heat and cold within these systems. The tabel below shows the relation between the distribution systems and the system number. Dual duct (twee kanalen) system is only considered for totally air based climate systems.

Heat transport through	**Cold transport through**	**Dual duct**	**System nr**
Water or water and air	n.a.	n.a.	1
	Water	n.a.	2
	Air	n.a.	3
	Water and air	n.a.	4
	Locally	n.a.	9
Air	n.a.	n.a.	5
	Water	n.a.	6
	Air	Yes	13
		No	7
	Water and air	n.a.	8
	Locally	n.a.	10
Locally	n.a.	n.a.	11
	Locally	n.a.	12

A.2 Dutch email and questionnaire

Beste [kantoorpand eigenaar],

Mijn naam is Pam Engwirda en momenteel schrijf ik mijn afstudeer opdracht (Universiteit Utrecht) over de verduurzaming van kantoorpanden in Nederland. Zoals u wellicht weet worden de eisen voor het energie gebruik van kantoorpanden aangescherpt. Per 1 januari 2023 dienen alle kantoorpanden in Nederland een energie label C te dragen. In 2030, dit wordt nog verder aangescherpt tot een energie label A. Er zijn verschillende renovatie mogelijkheden mogelijk om het energie label van uw pand te verbeteren. Het doel van mijn onderzoek is om de meest geschikte renovatie mogelijkheden te selecteren voor een specifiek kantoorpand. In dit geval dat van u. Om dit te doen, heb ik in samen werking met SPIE Nederland BV een model opgesteld. Graag zou ik dit model willen testen aan de hand van de karakteristieken van uw kantoorpand.

Het resultaat van het onderzoek zijn twee sets van renovatie mogelijkheden voor uw kantoorpand. Een met het doel om energie label C te behalen en de ander met energie label A als doel. De resultaten laten de te verwachten kosten (investering en onderhoud), terug verdientijd, reductie in CO_2 uitstoot en een tijdlijn die aangeeft hoelang de renovatie verwacht te duren.

Wat ik daarvoor van u wil vragen is om bijgevoegde vragen lijst in te vullen. Mochten er dingen niet duidelijk zijn, of heeft u bepaalde informatie niet paraat? Maak hier een notitie van, dit zal ik gebruiken om de vragenlijst de verbeteren.

Zou u mij willen helpen?

Alvast bedankt!

Met vriendelijke groet,

Pam Engwirda

Vragenlijst

Demografische informatie		
Naam kantoorpand		
Adres		
Bouwjaar		
Aantal maanden pand is in gebruik		maanden

Kantoorpand constructie eigenschappen		
Oppervlakten en maten		
Totale vloeroppervlakte		m^2
Vloeroppervlakte begane grond		m^2
Kruipruimte aanwezig?	☐ Ja	☐ Nee
Hoogte kantoorpand		m
Hoogte per verdieping		m
Oppervlakte buiten muren (incl. ramen/deuren)		m^2
Oppervlakte dak		m^2

Oppervlakte ramen grenzend aan buiten		m^2	
Issolatie waarden	**U**	**Indien bekend, vul hier in**	
Vloer	5.882		W/m^{2}K
Muren	2.326		W/m^{2}K
Dak	1.163		W/m^{2}K
Eventueel renovatie jaar			
Type vloer, plafond en gevel			
Massa van vloerconstructie [kg/m^2]			
Type plafond			
Gevel type			
Ramen			
Type beglazing			
Zonwering aanwezig (aan de buitenkant)?	☐ Ja	☐ Nee	
Zo ja, type zonwering			

Kantoorpand installaties

Klimaat systeem nr		Zie tab Climate system nr	
Warmte en koude voorziening			
Type verwarmingsinstallatie			
Individuele regeling verwarming	☐ Ja	☐ Nee	
Koude leverancier			
Oppervlakte van gekoelde zones		m^2	
WKK			
Aanwezig?	☐ Ja	☐ Nee	
Elektrisch vermogen		kW	
Thermisch vermogen		kW	
Soort distributie			
Gedetailleerde informatie warmte voorziening			
Warmtepomp			
Bron			
Brandstof			
Temperatuur niveau warmteaanvoer			
Ketel			
Type ketel			
Temperatuur niveau warmteaanvoer			
Een of meer centrale verwarmingstoestellen die warmte leveren voor een oppervlakte van			
Stoomketel			
Economizer			

Luchtvoorverwarmer

Heetwaterketel

Rookgascondensor

Ventilatoren

Type ventilatie systeem	
Provision in ventilation system	
Regeling	
Systeem type warmte terugwinning	
Ventilatie voorziening voor koelbehoefte	

Bevochtiging

Type bevochtigingsinstallatie	
Vochtterugwinning	

Warm tap water

Type toestel	
Distributie systeem	

Zonne-energie systemen

Zonnepanelen

Aanwezig	☐ Ja	☐ Nee
Type zonnepaneel		
Indien anders, piekvermogen		W/m^2
Oppervlakte paneel		m^2
Orientatie		
Hellingshoek		

Zonne collector

Aanwezig	☐ Ja	☐ Nee
Oppervlakte paneel		m^2

Verlichting (zie box rechts)

Totaal geinstalleerd vermogen verlichting		
Conventioneel	0.00	kW
LED		kW
Armatuurtype		
Type regeling/schakeling		
Bewegingsmelders		

Voorkeuren renovatie

Verdeel 100 punten over de onderstaande criteria. Diegene die voor u het belangrijkste is, vul daar de meeste punten in. De tweede belangrijkste iets minder en zo verder.

	Punten	Voorbeeld
Laagste inversteringskosten		*50*
Snelste terug verdientijd		*20*
Laagste onderhoudskosten		*0*
Reductie van CO_2 uitstoot		*10*
Reductie van energie gebruik		*20*
	0	

Als laatste wil ik u vragen de verschillende renovatie mogelijkheden te rangschikken op prioriteit. Zet op nummer 1 dat gene neer wat u het liefst aangepakt ziet worden. Op nummer 7 diegene die het laatste gedaan moet worden. Bijvoorbeeld als u net de isolatie heeft vervangen, heeft dit minder prioriteit.

1	
2	
3	
4	
5	
6	
7	

Notities

Verlichting

	Vermogen (W)	Aantal
TLD	18	
	36	
	58	
	72	
	116	
PLC	9	

Vul het aantal lampen per type in. Als dit niet bekend is, vul dan hieronder het totale vermogen van de conventionele verlichting in.

Totaal geïnstalleerd conventioneel vermogen (kW)	

	13	
	18	
	26	
	36	
TL5	14	
	21	
	28	
	42	
	56	

Klimaat Systeem nummer
Diverse berekeningen in de rekenkern hangen af van het type klimaatsysteem dat aanwezig is, in het bijzonder hoe het warmte- en koudetransport plaatsvindt. De tabel hieronder geeft de relatie tussen de typen distributiesystemen en het systeemnummer aan. Een dual duct (tweekanalen) systeem kan alleen voorkomen bij volledige lucht systemen.

Warmtetransport door	**Koudetransport door**	**Dual duct**	**Systeem nr**
Water of water en lucht	n.v.t. (geen koeling	n.v.t.	1
	Water	n.v.t.	2
	Lucht	n.v.t.	3
	Water en lucht	n.v.t.	4
	Lokaal	n.v.t.	9
Lucht	n.v.t. (geen koeling	n.v.t.	5
	Water	n.v.t.	6
	Lucht	Ja	13
		Nee	7
	Water en lucht	n.v.t.	8
	Lokaal	n.v.t.	10
Lokaal	n.v.t. (geen koeling	n.v.t.	11
	Lokaal	n.v.t.	12

Appendix B - *Assumptions linked to year of construction*

This section describes the assumptions linked to the year of construction. Table 32 describes the different U-values for the facades, the floor and the roof. These values are received from the ISSO 75.3.

Table 32: Insulation values linked to year of construction

Insulation values				
Building period		U-value (W/m2K)		
		Facade	Floor	Roof
1965	1975	2.326	5.882	1.163
1975	1983	0.769	1.923	0.769
1983	1988	0.769	0.769	0.769
1988	1992	0.500	0.769	0.500
1992	2013	0.395	0.395	0.395
2013		0.286	0.286	0.286

Appendix C - *Calculations for energy labels in the Netherlands*

This section presents the formulas of the energy label calculation. An energy label can be calculated for different types of buildings. Since this research focussed on the energy label of an office building, only the formulas and variables corresponding to this building type are described. First, the link between the energy labels and the Energy-Index is described. Next, the formula to calculate the Energy-Index is presented. Specific values for the variables in the Energy-Index formula specified on office buildings are presented. Lastly, the calculations needed to incorporate the NZEB requirements in the DSS are presented.

C.1 Energy labels through the Energy-Index

As described in Section 2.1, in the Netherlands, the energy label of a building is determined based on the Energy-Index. In the ISSO 75.1 publication, these values are linked to an energy label, as presented in Table 33. As can be seen, an energy label C or lower is reached when the Energy-Index is lower or equal to 1.30.

Table 33: Energy label with corresponding Energy-Index (ISSO 75.1, 2013)

Energy label	Limits Energy-Index
A	≤1.05
B	1.06 – 1.15
C	1.16 – 1.30
D	1.31 – 1.45
E	1.46 – 1.60
F	1.61 – 1.75
G	>1.75

The calculation of the EI is based on formulas presented in the ISSO 75.1 and the ISSO 75.3 publications. The EI is calculated with Formula A1.

$$EI = \frac{Q_{prim;tot,building}}{Q_{prim;allow}} \quad [A1]$$

In which:

$Q_{prim;tot,building}$ = total primary energy use of the building [MJ]

$Q_{prim;allow}$ = total allowable primary energy use of the building [MJ]

The calculation of the total primary energy use of the building is described in Appendix D. The calculation for the total allowable primary energy use of the building is presented below. In these calculations, some variables are specific to an office building.

The total allowable energy use of the building ($Q_{prim;allow}$) is calculated with Formula A2.

$$Q_{prim;allow} = \sum_{sc} \left(\begin{array}{c} \left(\frac{1}{f_{cool}}\right) * c_{g;allow} * A_{g;sc} * EPC_{req;sc} * c_{EPC;sc} * c_{EPA;sc} + \\ y_V * c_V * \frac{1}{h} * f_{use;sc} * u_{v;min;sc} * A_{g;sc} * f_{occupied\ area} \end{array} \right) + c_{loss;allow} * y_{loss} * A_{loss} \quad [A2]$$

In which:

$Q_{prim;allow;sc}$ = total allowable primary energy use of space category in the building [MJ]

$c_{loss;allow}$ = measure for transmission losses (= 65) [MJ/m^2]

y_{loss} = correction factor from Building decree 2006 (= 1.2) [-]

A_{loss} = loss area of the energy sector [m^2]

f_{cool} = weighting factor that provides partial compensation for the presence of cooling [-]

$c_{g;allow}$ = reference energy use (= 330) [MJ]

$A_{g;sc}$ = surface area of space category sc [m^2]

$EPC_{req;sc}$ = EPC requirement of space category sc in 2003 [-]

$c_{EPC;sc}$ = correction factor for the EPC requirement of the space category sc [-]

$c_{EPA;sc}$ = correction factor for space category sc (= 1) [-]

y_V = correction factor from Building decree 2006 (= 1.25) [-]

c_V = factor from Building decree 2006 for energy use deemed acceptable for ventilation (= 135) [MJ·s/dm^3]

h = conversion factor from dm^3/s to m^3/h (= 3.6) [-]

$f_{use;sc}$ = usefactor: surface area weighted time fraction of which the ventilation is in operation for the space category sc [-]

$u_{v;min;uf}$ = minimum ventilation rate of air coming directly from outside for use function [dm^3/s·m^2]

$f_{occupied\ area}$ = correction factor for surface of occupied area (= 0.8) [-]

Most of the values in the formula above are standardized for all types of buildings. If so, they are mentioned behind the corresponding variable in brackets. However, for two variables, another formula is needed to calculate these. In the ISSO 75.3 publication these formulas are explained.

The weighting factor that provides partial compensation for the presence of cooling (f_{cool}) is calculated with Formula A3.

$$f_{cool} = \frac{c_{cool} * y_{cool}}{c_{cool} * y_{cool} + \frac{A_{g;cool}}{A_{tot}}} \quad [A3]$$

In which:

c_{cool} = coefficient for cooling from building decree (= 4)

y_{cool} = coefficient for cooling from building decree (= 3)

$A_{g;cool}$ = surface area of cooled zones in the building [m^2]

A_{tot} = total surface area of the building [m^2]

The loss area of the energy sector (A_{loss}) is calculated with Formula A4.

$$A_{loss} = \sum_{k} d_k * A_k \quad \text{[A4]}$$

In which:

d_k = weighting factor [-]

A_k = surface area of shell part k [m^2]

The weighting factor (d_k) for the surface of an element from the separation structure of a building depends on the space on the other side of the element, $\text{type}_{\text{border;k}}$. See Table 34.

Table 34: Weighting factor d

Construction adjoins ($\boldsymbol{type_{border;k}}$)	**$\boldsymbol{d_k}$ [-]**
Ground	0.7
Crawlspace	0.7
Other	1

Lastly, in Formula A1, some variables are specific to the building type. Regarding office buildings, they are presented in Table 35. As can be seen in Table 35, the EPC requirements are becoming stricter in time. The EPC requirement set in 2015 is used in further calculations.

Table 35: Variables Energy-Index specific for office buildings

Variable	**Amount**	**Unit**
$EPC_{req;sc}$	1.5 (2003), 1.1 (2009), 0.8 (2015)	-
$c_{EPC;sc}$	0.96	-
$f_{use;sc}$	0.3	-
$u_{v;min;sc}$	1.3	dm^3/s·m^2

To conclude, the following variables need to be determined by the office building characteristics to calculate the total allowable primary energy use of the office building:

- $A_{g;cool}$ = surface area of cooled zones in the building [m^2]

- A_{tot} = total surface area of the building [m^2]
- A_k = surface area of shell part [m^2]

C.2 NZEB requirements

As described in Section 2.1.1., the energy label system will change in the near future. Namely, to the Nearly-Zero Energy Building (NZEB) requirements. To ensure the usability of the DSS in the future, these requirements are incorporated as well. These requirements are based on the energy requirement per square meter (kWh/m^2). Filippidou et al. (2017) linked a mean theoretical primary energy consumption to the different energy labels, expressed in kWh/m^2/year. This link is presented in Table 36.

Table 36: Energy label with corresponding mean energy consumption (Filippidou et al., 2017)

Energy label	**Limits Energy-Index**	**Mean theoretical primary energy consumption (kWh/m^2/year)**
A	≤1.05	96.8
B	1.06 – 1.15	132.5
C	1.16 – 1.30	161.6
D	1.31 – 1.45	207.8
E	1.46 – 1.60	265.0
F	1.61 – 1.75	328.0
G	>1.75	426.9

As it can be seen, the NZEB requirements described in Section 2.3 are stricter than the energy label requirements. To incorporate the NZEB requirements, the primary energy consumption in kWh/m^2/year is calculated as well. This is done by Formula A5.

$$Q_{prim;tot,building}\left[\frac{kWh}{m^2 * year}\right] = \frac{Q_{prim;tot,building}\left[\frac{MJ}{year}\right]}{h * A_u} \qquad [A5]$$

In which:

$Q_{prim;tot,building}$ = total primary energy use of the building [MJ]

h = conversion factor from MJ to kWh (= 3.6)

A_u = use area of building [m^2]

Appendix D - *Calculation energy demand office building*

This section describes the calculations needed to determine the energy use of an office building. These calculations are presented in the ISSO 75.1 and the ISSO 75.3. The generation efficiencies for electricity used are η_{el} = 0.39 and $\eta_{el,marg}$ = 0.39. These follow from ISSO 75.3 and since this method is widely used in the building sector, these values are used in this research.

D.1 Calculation of total energy use office building

The total net energy use of the building is equal to the sum of the total energy use, minus the contributions of solar energy and cogeneration. This is described in Formula A6.

$$Q_{prim;tot,building} = Q_{prim;tot;use} - Q_{prim;CHP} - Q_{prim;pv} \quad \text{[A6]}$$

In which:

$Q_{prim;tot,building}$ = total net primary energy use of the building [MJ]

$Q_{prim;tot;use}$ = total primary energy use [MJ]

$Q_{prim;CHP}$ = total primary energy contribution of cogeneration [MJ]

$Q_{prim;pv}$ = total primary energy contribution of solar panels [MJ]

In Formula A6, the energy contribution of solar panels depends on the type of panel. An amorfe cell has a peak power of 45 W/m^2, while a mono- or multi crystalline cell has a peak power of 120 W/m^2. The energy contribution by cogeneration depends on the primary energy contribution of a CHP and thermal and electric conversion numbers.

The total primary energy use of an office building is calculated with Formula A7.

$$Q_{prim;tot;use} = Q_{prim;sh} + Q_{prim;vent} + Q_{prim;light} + Q_{prim;pumps} + Q_{prim;cooling} + Q_{prim;hum} + Q_{prim;tap} \quad \text{[A7]}$$

In which:

$Q_{prim;tot;use}$ = total primary energy use [MJ]

$Q_{prim;sh}$ = total primary energy use for space heating [MJ]

$Q_{prim;vent}$ = total primary energy use for ventilation [MJ]

$Q_{prim;light}$ = total primary energy use for lightning [MJ]

$Q_{prim;pumps}$ = total primary energy use for pumps [MJ]

$Q_{prim;cooling}$ = total primary energy use for cooling [MJ]

$Q_{prim;hum}$ = total primary energy use for humidification [MJ]

$Q_{prim;tap}$ = total primary energy use for preparation of hot tap water [MJ]

D.2 Energy use for space heating

The primary energy use for space heating can be described with Formula A8:

$$Q_{prim;sh} = Q_{sh} \quad [A8]$$

In which:

$Q_{prim;sh}$ = total primary energy use for space heating [MJ]

Q_{sh} = energy use for space heating [MJ]

The energy use for space heating of the total period is equal to the sum of the energy use per month, Formula A9. The energy use per month is calculated with Formula A10.

$$Q_{sh} = \sum_{i=1}^{n_{month;period}} Q_{sh;i} \quad [A9]$$

$$Q_{sh;i} = \frac{Q_{sh;dem;i} * f_{use}}{\eta_{gen;sh;i} * \eta_{sys;sh}} \quad [A10]$$

In which:

Q_{sh} = energy use for space heating in total period [MJ]

$Q_{sh;i}$ = energy use for space heating in month i [MJ]

$Q_{sh;dem;i}$ = heat demand in month i [MJ]

f_{use} = use factor the building is in use [-]

$\eta_{gen;sh;i}$ = efficiency for heat generation in month i [-]

$\eta_{sys;sh}$ = yearly average system efficiency for space heating [-]

D.2.1 Heat demand

The heat demand per month of a building is determined as followed:

If the temperature demand inside is higher than the outside temperature ($T_i > T_{o;i}$) and $\gamma \leq 2.5$ then:

$$Q_{sh;dem;i} = Q_{tr;i} + Q_{vent;i} - \eta_{u;sh;i} * \left(Q_{intern;hp;i} + Q_{sun;t;i} + Q_{sun;es;i}\right) \quad [A11]$$

Otherwise:

$$Q_{sh;dem;i} = 0 \quad [A12]$$

In which:

$Q_{tr;i}$ = heat loss through transmission in month i [MJ]

$Q_{vent;i}$ = heat loss through ventilation in month i [MJ]

$Q_{intern;hp;i}$ = heat gain through internal heat production in month i [MJ]

$Q_{sun;t;i}$ = sun heat gain through transparent construction parts in month i [MJ]

$Q_{sun;es;i}$ = sun heat gain through solar energy systems in month i [MJ]

$\eta_{u;sh;i}$ = utilization factor for heat gain in month i [-]

γ = gain/loss ratio in month i [-]

D.2.2 Heat loss through transmission

The transmission loss per month can be calculated with Formulas A13 and A14:

$$Q_{tr;i} = H_{tr} * \left(T_{in} - T_{o;i}\right) * t \quad [A13]$$

$$H_{tr} = \sum_{k} (a_k * A_k * (U_k + U_{tb})) \quad [A14]$$

In which:

$Q_{tr;i}$ = heat loss through transmission in month i [MJ]

H_{tr} = specific heat loss through transmission [W/K]

T_{in} = inside temperature [°C] → *is 19 ℃ for office buildings*

$T_{o;i}$ = monthly average outside temperature in month i [°C]

t = time in a month (= 2.63) [Ms]

a_k = the weighting factor to be assigned to the partition construction k [-]

A_k = area of the projection of partition construction k [m^2]

U_k = heat transfer coefficient of partition construction k [W/(m^{2}K)]

U_{tb} = surcharge for thermal bridges (= 0.1) [W/(m^{2}K)]

In this research, the outside temperature corresponds to the monthly average temperatures measured in De Bilt in 2019. They are presented in Appendix E.

The summation of k describes all constructions adjacent to outside air, ground, water, unheated spaces or strong ventilated spaces. The transmission loss cannot be smaller than 0. If $Q_{tr;i} < 0$ then: $Q_{tr;i} = 0$.

U value

The U-value for a closed construction is calculated with Formula A15.

$$U = \frac{1}{R_a} \quad [A15]$$

In which:

R_a = air-to-air heat resistance of a structure [m^{2}K/W]

U = heat transfer coefficient of a structure [W/m^{2}K]

The air-to-air heat resistance consists of the construction resistance R_c, the resistance of the air layer inside the construction R_i and the resistance of the air layer outside the construction R_e. See Formula A16.

$$R_a = R_i + R_c + R_e \quad [A16]$$

In which:

R_a = air-to-air heat resistance [m^{2}K/W]

R_c = heat resistance of construction [m^{2}K/W]

R_i = heat resistance of air layer inside the construction (= 0.13) [m^{2}K/W]

R_e = heat resistance of air layer outside the construction [m^{2}K/W] (see Table 37)

Table 37: The values for R_e when heat flows from inside out

Construction type	Construction adjoints to	R_e [m^{2}K/W]
Facade, panel, window, door	Outside air or water	0.04
	Highly ventilated, non-lockable space	0.13
	Unheated adjacent space	0.13
	Ground	0.13
Roof	Outside	0.04
	Ground	0.13
	Unheated upper room	0.13
Floor	Outside air or water	0.04
	Highly ventilated, non-lockable space	0.13
	Unheated lower room	0.13
	Crawlspace	0.13
	Ground	0.13

An additional calculation applies to floors, to consider the resistance of the floor package:

$$U_k = \frac{1}{{}^{1}/_{U_{floor}} + 5} \quad [A17]$$

In which:

U_k = U-value to be charged for the floor including the ground package

U_{floor} = U-value of the floor conform Formula A15

Weighting factor of partition construction

The weighting factor to be assigned to the partition construction k depends on the space on the other side of the element, $type_{border;k}$. See Table 38.

Table 38: Weighting factor a

Construction adjoins ($\boldsymbol{type_{border;k}}$)	$\boldsymbol{a_k}$ [-]
Outside air or water	1
Strong ventilated space	1
Unheated adjacent space	1/(1+U_k/10)
Unheated upper floor	1/(1+U_k/3)
Ground	1/(1+U_k)
Crawl space	1/(1+U_k)

In this research, the assumption is made that the outside walls only adjoin outside air, that the floor adjoins either ground or crawlspace and the roof adjoins outside air. This to simplify the calculations, which is needed due to time constraints.

D.2.3 Heat loss through ventilation

The monthly heat loss through ventilation (as a result of infiltration, natural and mechanical ventilation and flushing) is calculated with Formulas A18 and A19:

$$Q_{vent;i} = H_{vent} * \left(T_{in} - T_{o;i}\right) * t \quad [A18]$$

$$H_{vent} = \rho * c_l * \frac{1}{h} * \left(v_{v;inf} + v_{v;nat} + (1 - \eta_{hre}) * v_{v;mech}\right) * V_{sector} \quad [A19]$$

In which:

H_{vent} = specific heat loss through ventilation [W/K]

$\rho * c_l$ = heat capacity of air (=1.2) [J/dm^{3}K]

h = conversion factor from dm^3/s to m^3/h (= 3.6) [-]

$v_{v;inf}$ = ventilation rate of to be heated fresh air coming directly from outside through infiltration [1/h]

$v_{v;nat}$ = ventilation rate of to be heated fresh air coming directly from outside through natural ventilation [1/h]

η_{hrs} = efficiency of the heat recovery system [-]

$v_{v;mech}$ = ventilation rate of to be heated fresh air coming directly from outside through mechanical ventilation [1/h]

V_{sector} = net volume of the energy sector [m^3]

The ventilation loss cannot be smaller than 0. If $Q_{vent;i} < 0$ than $Q_{vent;i} = 0$.

<u>Ventilation rate through infiltration</u>

$$v_{v;inf} = f_{wind} * f_{inf} * q_{v10;spec} * h * \frac{A_{u;sector}}{V_{sector}} \quad [A20]$$

In which:

f_{wind} = building height dependent correction factor wind pressure introduced infiltration [-]

f_{inf} = correction factor due to ventilation system [-]

$q_{v10;spec}$ = specific infiltration [-]

h = conversion factor from dm^3/s to m^3/h (= 3.6) [-]

$A_{u;sector}$ = area of use from energy sector [m^2]

V_{sector} = net volume of the energy sector [m^3]

The factor f_{wind} corresponds to the sector height, presented in Table 39.

Table 39: Correction factor f_{wind}

Sector height	f_{wind} **[-]**
Lower than 13 m	1.00
Between 13 and 70 m	0.425*hbuild$^{0.333}$
Higher than 70 m	1.75

The factor f_{inf} describes the correlation between the infiltration and type of ventilation system, see Table 40.

Table 40: Correction factor f_{inf}

Ventilation system	**Description**	f_{inf}
A	Systems with natural supply and drain	0.080
B	Systems with mechanical supply and natural drain	0.085
C	Systems with natural supply and mechanical drain	0.100
D	Systems with mechanical supply and drain; balance ventilation	0.115

$$q_{v10;spec} = f_{type} * f_{year} * q_{v10;spec;cal} \quad [A21]$$

In which:

f_{type} = coefficient for building type [-]

f_{year} = coefficient for year of construction [-]

$q_{v10;spec;cal}$ = calculation value for $q_{v10;spec}$ [dm^3/s.m^2]

Table 41: Relation between A_{wind}/V_{build}, building shape class and f_{type}

A_{wind}/V_{build} **(1/m)**	**Building shape class**	f_{type}
> 0.15	1	2.2
0.15 ≥ A/V > 0.10	2	2.4
0.10 ≥ A/V > 0.08	3	2.8
0.08 ≥ A/V > 0.05	4	3.4

0.05 ≥ A/V	5	4.6

The building shape class is determined by the ratio between the wind-blown building area (A_{wind}) and the building volume (V_{build}). In which A_{wind} is defined as the building circumference multiplied with the building height. The ratio can be calculated with the following formula:

$$\frac{A_{wind}}{V_{build}} = 2 * \sqrt{\frac{h_{wind;build}}{h_{floor} * A_{u;tot}}} \quad [A22]$$

In which:

$h_{wind;build}$ = height above ground level from highest usage layer [m]

h_{floor} = representative floor height = 3.5 m [m]

$A_{u;tot}$ = use surface [m^2]

Table 42: $q_{v10;spec;cal}$ as function of façade type

Façade type	$q_{v10;spec;cal}$
Standard façade	0.25
Cover or climate façade air technical open	0.23
Cover or climate façade air technical closed	0.22

Table 43: Year of construction f_{year}

Year of construction	f_{year}
Before 1975	1
Between 1975 and 2005	1.0 – 0.02*(year of construction – 1975)
After 2005	0.4

Ventilation rate through natural ventilation

$$v_{v;nat} = f_{use} * v_{v;nat;u} \quad [A23]$$

In which:

f_{use} = usefactor: use area weighted average time fraction of operation of ventilation (=0.3 for office)

$v_{v;nat;u}$ = ventilation rate through natural ventilation during usage time [1/h]

$$v_{v;nat;u} = f_{use\ area} * u_{v;min} * h * \frac{A_{u;sector}}{V_{sector}} \quad [A24]$$

In which:

$f_{use\ area}$ = correction factor for surface of use area (=0.8) [-]

$u_{v;min}$ = minimal air volume flow due to natural ventilation [dm^3/s.m^2] (=1.3 office)

Ventilation rate through mechanical ventilation

$$v_{v;mech} = f_{use} * v_{v;mech;u} \quad [A25]$$

In which:

$v_{v;mech;u}$ = ventilation rate through mechanical ventilation during usage time [1/h]

$$v_{v;mech;u} = u_{v;m} * h * \frac{A_{u;sector}}{V_{sector}} \quad [A26]$$

For mechanical supply, mechanical extraction and balanced ventilations, the following applies:

If $f_{use\ area} * u_{v;min} \leq f_{reg;vent} * u_{v;m;max} \quad [A27]$

Then $u_{v;m} = f_{reg;vent} * u_{v;m;max} \quad [A28]$

Otherwise $u_{v;m} = f_{use\ area} * u_{v;min} \quad [A29]$

For natural ventilation, the following applies:

$u_{v;m} = 0 \quad [A30]$

In which:

$u_{v;min}$ = minimal air volume flow [dm^3/s.m^2]

$f_{reg;vent}$ = weighting factor for provisions for back control of outside air supply [-]

$u_{v;m}$ = air volume flow by mechanical ventilation [dm^3/s.m^2]

$u_{v;m;max}$ = maximum air volume flow by mechanical ventilation [dm^3/s.m^2]

Table 44: Reduction factor for the provision in ventilation

Provision in ventilation system $type_{reg;vent}$	$f_{reg;vent}$
Recirculation	0.6
Flow regulation	0.6
Recirculation and flow regulation	0.6
No recirculation or flow regulation	1

Table 45: Efficiency of heat recovery

Heat recovery system type $type_{hrs}$	η_{hrs}
No heat recovery system	0
Plate or tube heat exchanger	0.65

Two elements system (twin-coil)	0.60
Cold drawers with air handling units	0.40
Slow rotating or intermittent heat exchangers	0.70

D.2.4 Heat gain through internal heat production

$$Q_{intern;hd;i} = \left(Q_{i;pers;i} + Q_{i;app;i} + Q_{i;vent;i} + Q_{i;light;i}\right) * a_{hd} \quad [A31]$$

$$Q_{intern;cd;i} = \left(Q_{i;pers;i} + Q_{i;app;i} + Q_{i;vent;i} + Q_{i;light;i}\right) * a_{cd} \quad [A32]$$

In which:

$Q_{intern;hd;i}$ = heat gain through internal heat production in month i, used for the heat demand calculation [MJ]

$Q_{intern;cd;i}$ = heat gain through internal heat production in month i, used for the cooling demand calculation [MJ]

$Q_{i;pers;i}$ = internal heat production through persons in month i [MJ]

$Q_{i;app;i}$ = internal heat production through appliances in month i [MJ]

$Q_{i;vent;i}$ = internal heat production through ventilators in month i [MJ]

$Q_{i;light;i}$ = internal heat production through lightning in month i [MJ]

a_{hd} = auxiliary factor = 0.8

a_{cd} = auxiliary factor = 1

$$Q_{i;pers;i} = f_{use} * q_{i;pers} * A_u * t \quad [A33]$$

In which:

f_{use} = usefactor: use area weighted average time fraction of operation of ventilation (=0.3 for office) [-]

$q_{i;pers}$ = specific internal heat load by persons (=3 for office) [W/m^2]

A_u = use surface of energy sector [m^2]

t = time in a month (=2.63) [Ms]

$$Q_{i;app;i} = q_{i;app} * A_u * t \quad [A34]$$

In which:

$q_{i;app}$ = specific heat production by appliances (=3 for office) [W/m^2]

$$Q_{i;vent;i} = f_{i;vent} * Q_{prim;vent;i} * \eta_{el} \quad [A35]$$

In which:

$f_{i;vent}$ = reduction factor regarding internal heat load of ventilators [-]

$Q_{prim;vent;i}$ = primary energy use by ventilators in month i [MJ]

η_{el} = efficiency of electricity supply [-]

Table 46: Reduction factor for the internal heat load by ventilators

Ventilator type $\boldsymbol{type_{vent}}$	$\boldsymbol{f_{i;vent}}$
Only mechanical extraction	0
Only mechanical supply	0.3
Mechanical supply and drain without recirculation or heat recovery	0.6
Mechanical supply and drain with recirculation or heat recovery	0.8

$$Q_{i;light;i} = \eta_{el} * \sum_{z} f_{light;z} * Q_{light;z;i} \quad [A36]$$

In which:

$f_{light;z}$ = reduction factor for lightning in lightning zone z [-]

$Q_{light;z;i}$ = primary energy use by lightning in lightning zone z in month i [MJ]

Table 47: Reduction factor for lighting

Luminaire type $\boldsymbol{type_{lum}}$	$\boldsymbol{f_{light}}$
Lightning luminaires are being suctioned	0.5
Other cases	1

D.2.5 Solar heat gain through transparent construction components

$$Q_{sun;t;i} = \sum_{n} (q_{sun,i} * z_{sun,n} * r_{n;i} * f_{sun;n;i} * ZTA_n * A_n * k) \quad [A37]$$

In which:

$q_{sun,i}$ = amount of solar energy which falls on a horizontal plane per m^2 at the respective climate in month i [MJ]

$z_{sun,n}$ = orientation factor [-]

$r_{n;i}$ = shading reduction factor of the daylight opening in month i [-]

$f_{sun;n;i}$ = reduction factor of adjustable blinds in month i [-]

ZTA_n = sun entry factor of the relevant daylight opening [-]

A_n = area of window including frame [m^2]

k = frame factor (=0.75) [-]

Table 48: Shading reduction factor of daylight opening (r)

	Period i	
Situation	**r heating season (oct. until apr.)**	**r summer (may until sept.)**
No awning	1	1
Awning 1	0.9	0.75
Awning 2	0.75	0.6

Type of awning are described as follows:

No awning if $\frac{c-h_1}{h_2} \leq \frac{1}{5}$

Awning 1 if $\frac{1}{5} < \frac{c-h_1}{h_2} < \frac{1}{3}$

Awning 2 if $\frac{c-h_1}{h_2} \geq \frac{1}{3}$

In which:

c = width cantilever [m]

h_1 = vertical distance between cantilever and window [m]

h_2 = height window [m]

Table 49: Reduction factor for adjustable blinds

	Period i	
Sun protection system $Type_{sunprotection}$	**$f_{sun;n;i}$ heating season (oct. until apr.)**	**$f_{sun;n;i}$ summer (may until sept.)**
Manual outdoor blinds	0.5	0.5
Automatic outdoor blinds	0.5	0.35
All other cases	1	1

D.2.6 Solar heat gain through solar collectors for space heating

$$Q_{sun;ze;i} = \eta_{ze} * q_{sun} * A_{ze} \quad [A38]$$

In which:

η_{ze} = the average collector efficiency (=0.5) [-]

q_{sun} = the amount of solar energy that falls on a horizontal surface in month i [MJ/m^2]

A_{ze} = area of the smallest surface that connects the collector edges [m^2]

D.2.7 Utilization factor for heat gain

The usability of the heat gain depends on the profit / loss ratio. As the profit / loss ratio becomes smaller, the usability of the heat gain increases.

$$\eta_{u;sh;i} = \frac{(1-\gamma_i^a)}{(1-\gamma_i^{a+1})}, when\, \gamma \neq 1 \quad [A39]$$

$$\eta_{u;sh;i} = \frac{a}{(1+a)}, when\, \gamma = 1 \quad [A40]$$

In which:

$\eta_{u;sh;i}$ = utilization factor for heat gain in month i [-]

γ_i = profit / loss ratio in month i [-]

a = auxiliary variable [-]

The profit / loss ratio follows from the following formulas.

$$\gamma_i = \frac{Q_{profit;i}}{Q_{loss;i}} \quad [A41]$$

$$Q_{profit;i} = Q_{intern;i} + Q_{sun;t;i} + Q_{sun;ze;i} \quad [A42]$$

$$Q_{loss;i} = Q_{tr;i} + Q_{vent;i} \quad [A43]$$

In which:

γ_i = profit / loss ratio in month i [-]

$Q_{profit;i}$ = heat gain through solar and internal heat production in month i [MJ]

$Q_{loss;i}$ = heat loss through transmission and ventilation in month i [MJ]

$Q_{intern;i}$ = heat gain through internal heat production in month i [MJ]

$Q_{sun;t;i}$ = solar heat gain through transparent construction parts in month i [MJ]

$Q_{sun;ze;i}$ = solar heat gain through solar collectors for space heating in month i [MJ]

$Q_{tr;i}$ = heat loss through transmission in month i [MJ]

$Q_{vent;i}$ = heat loss through ventilation in month i [MJ]

The value for the auxiliary variable follows from Formula A44:

$$a = c_1 + \frac{1}{c_2} * \frac{D * A_u}{H_{tr} + H_{vent}} \quad [A44]$$

In which:

c_1 = constant (=0.81 for office buildings) [-]

c_2 = constant (=76.9 for office buildings) [-]

D = specific effective thermal capacity per m^2 of use area [Wh/(m^{2}K)]

A_u = use area [m^2]

H_{tr} = specific heat loss through transmission [W/K]

H_{vent} = specific heat loss through ventilation [W/K]

The specific effective thermal capacity D depends on the mass of the floor construction per m^2 use area and the presence or absence of an open ceiling. See Table 50.

Table 50: Specific effective thermal capacity D

	D [Wh/(m²K)]	
	Ceiling type	
Mass of floor construction per m² use area [kg/m²]	Closed ceiling	No or open ceiling
Less than 100 (woody)	15	15
Between 100 and 400 (floating screed)	30	50
More than 400 (stony)	50	100

A suspended ceiling is a closed type ceiling. With no false ceiling or with ceiling islands (mini-times 15% of the surface of the ceiling is open) can be selected for open / no ceiling type. Not applying a suspended ceiling is beneficial for it use of the building mass. Without a suspended ceiling, the slowly heat / cool the building mass (concrete floors) store heat / cold and then release it to its environment. The disadvantage of no suspended ceiling is, however, that the extraction of the lighting fixtures can no longer go through the suspended ceiling to be realized (Tima, 2015).

D.2.8 Efficiency of heat generation

When only one generating device is present or a combination of several generating devices with the same efficiency, the following applies:

$$\eta_{gen;sh;i} = \eta_{gen;sh} \quad [A45]$$

In which:

$\eta_{gen;sh;i}$ = efficiency for heat generation in month i [-]

$\eta_{gen;sh}$ = efficiency of generating device [-]

In the other cases, Formula A46 applies:

$$\eta_{gen;sh;i} = \frac{1}{\frac{f_{pref;i}}{\eta_{gen;sh;pref}} + \frac{(1 - f_{pref;i})}{\eta_{gen;sh;npref}}} \quad [A46]$$

In which:

$\eta_{gen;sh;i}$ = efficiency for heat generation in month i [-]

$f_{pref;i}$ = monthly average fraction of the total heat supply that is supplied by the preferentially switched appliance [-]

$\eta_{gen;sh;pref}$ = efficiency of the preferentially switched appliances [-]

$\eta_{gen;sh;npref}$ = efficiency of the other generating devices [-]

Table 51: Fraction of the total heat supply by the preferred appliance

	$f_{pref;i}$ **[-]**	
	Type of preferred appliance	
Month i	**CHP**	**Other**
January	0.418	0.79
February	0.668	0.79
March	0.911	0.79
April	0.947	0.79
May	0.947	0.79
June	0.947	0.79
July	0.947	0.79
August	0.947	0.79
September	0.947	0.79
October	0.947	0.79
November	0.947	0.79
December	0.781	0.79

The generation efficiency of a heat pump depends on the source which the heat pump uses to extract heat, the type of fuel and the temperature demand. The different efficiencies are presented in Table 52. Regarding other heat generators, the efficiency depends on the type of generator, the use area (A_u) for which the generator is used to produce heat and the temperature demand. The use area (A_u) is described as: "the area measured at floor level, between the ascending partition constructions, which enclose the relevant space or group of spaces." These efficiencies are shown in Table 53 and 54.

Table 52: Generation efficiencies heat pumps

Heat pump	**Generation efficiency**					
Sources	**Demanded temperature level**					
	< 35 ˚C		35 – 45 ˚C		45 – 55 ˚C	
	Type of fuel					
	Electricity	Gas	Electricity	Gas	Electricity	Gas
Soil / outside air	$3.4 * \eta_{el}$	1.6	$3.1 * \eta_{el}$	1.5	$2.8 * \eta_{el}$	1.4
Heat from return / exhaust air	$6.1 * \eta_{el}$	2.6	$5.1 * \eta_{el}$	2.2	$4.4 * \eta_{el}$	2.0
Ground water	$4.7 * \eta_{el}$	2.1	$4.2 * \eta_{el}$	1.9	$3.6 * \eta_{el}$	1.8
Surface water	$4.1 * \eta_{el}$	1.9	$3.7 * \eta_{el}$	1.8	$3.3 * \eta_{el}$	1.7

Table 53: Generation efficiencies for heating other than heat pumps

Heating installation	**Generation efficiency**		**Type of fuel**
Electric installation	η_{el}		Electricity
Local gas heating of oil heating	0.65		Gas
Cogeneration	$\varepsilon_{CHP;th}$		Gas
Heat delivery by third parties	η_{th}		Heat
Steam boiler	$\eta_{steam} * f_{loss;st}$		Gas
Hot water boiler	$\eta_{steam} * f_{loss;hw}$		Gas
Direct fired air heater	0.80		Gas
Temperature level heat supply	**≤ 55 ˚C**	**> 55 ˚C**	
One or more central heating appliances (hot water) that supply heat for a use area of less than 500 m2			
Conventional boiler	0.75	0.75	Gas
VR-boiler	0.80	0.80	Gas
HR-100 boiler	0.925	0.90	Gas
HR-104 boiler	0.95	0.925	Gas
HR-107 boiler	0.975	0.95	Gas
One or more central heating appliances (hot water) that supply heat for a use area of 500 m2 or bigger			
Conventional boiler	0.70	0.70	Gas
VR-boiler	0.75	0.75	Gas
HR-100 boiler	0.875	0.85	Gas
HR-104 boiler	0.90	0.875	Gas
HR-107 boiler	0.925	0.90	Gas

Table 54: Efficiencies of steam boilers and hot water boilers

Type of boiler	**Economizer**	**Air preheater**	**Flue gas condenser**	η_{steam}
Steam boiler	With	Without	n.a.	0.94
	Without	Without	n.a.	0.90
	Without	With	n.a.	0.95
Hot water boiler with 150 ˚C water	n.a.	n.a.	Without	0.93
	n.a.	n.a.	With	0.95

D.3 Energy use by ventilators

There are four types of ventilators: 1) natural supply and drain, 2) natural supply and mechanical drain, 3) mechanical supply and natural drain and 4) mechanical supply and drain. The energy use of these ventilators is determined as the product of the maximum running time in a year, the effective power in which a weighting for the control is included and the hours of use imposed. The total primary energy use by ventilators per energy sector can be determined with the Formulas A47 and A48:

$$Q_{prim;vent} = \sum_{i=1}^{n_{month,per}} Q_{prim;vent;i} \quad [A47]$$

$$Q_{prim;vent;i} = \frac{g * t * P_{eff} * f_{use;vent}}{\eta_{el}} \quad [A48]$$

In which:

$Q_{prim;vent}$ = total primary energy use per energy sector by the ventilator(s) in the calculation period [MJ]

$n_{month,per}$ = number of months in the calculation period (=12) [months]

$Q_{prim;vent;i}$ = total primary energy use per energy sector by the ventilator(s) in month i [MJ]

g = factor for converting kWh to MJ (=3.6) [-]

t = maximum running time per year in hours (=8760) [h]

P_{eff} = effective power of the ventilator(s) in the energy sector [kW]

$f_{use;vent}$ = use factor: average time fraction that the ventilators are in use [-]

η_{el} = efficiency of electricity supply [-]

The effective power of the ventilator is determined with Formula A49:

$$P_{eff} = \frac{P_{shaft} * f_{control}}{\eta_{elm}} \quad [A49]$$

In which:

P_{shaft} = total shaft power of the ventilator(s) [kW]

$f_{control}$ = reduction factor for the control of the ventilator(s) [-]

η_{elm} = efficiency of the electric motor(s) (=0.75) [-]

D.3.1 Shaft power of the ventilators

The shaft power of the ventilators is determined with Formula A50:

$$P_{shaft} = \frac{e_{vent} * u_{v;ventilator} * 3.6 * A_u}{1000} \quad [A50]$$

In which:

e_{vent} = specific electricity use by the ventilator(s) [Wh/m^3]

$u_{v;ventilator}$ = the air flow rate to be charged for the calculation of ventilator energy [dm^3/s.m^2]

A_u = use area of the energy sector [m^2]

With mechanical supply or balanced ventilation, the following applies:

$$u_{v;ventilator} = u_{v;m;max} \quad [A51]$$

With mechanical extraction, the following applies:

$$u_{v;ventilator} = f_{use\ area} * u_{v;min} \quad [A52]$$

In which:

$u_{v;ventilator}$ = the air flow rate to be charged for the calculation of ventilator energy [dm^3/s.m^2]

$u_{v;m;max}$ = maximum air flow rate by mechanical ventilation [dm^3/s.m^2]

$u_{v;min}$ = minimal air flow rate [dm^3/s.m^2]

$f_{use\ area}$ = correction factor for surface of use area (=0.8) [-]

The specific electricity use by the ventilators follows from Table 55.

Table 55: Specific electricity use by ventilators

Ventilation system	**System number**	e_{vent} [Wh/m^3]
Natural ventilation		0
Mechanical extraction		0.25
Mechanical supply or balanced ventilation	3 or 7 (cooling by air)	0.62
	Other	0.41

D.3.2 Reduction of the electricity consumption of ventilators by arrangements

The electricity use by ventilators can be reduced using flow control. The factor $f_{control}$ depends on the type of arrangement according to Table 56.

Table 56: Reduction factor for the control of the ventilators

Arrangement	$f_{control}$
No arrangement or throttle control	1
Flow control	0.7

D.4 Energy use by lighting

The energy use for lightning depends on the type and amount of lights installed, the operating hours and the type of switch (movement sensors or not). The assumption is made that an office building yearly has 2400 operating hours for lighting. Furthermore, when movement sensors are installed, this reduces 20% in energy use for lightning than when normal switches are used. The total energy use for lighting is calculated with Formula A53.

$$Q_{prim;light} = \sum_{i=1}^{n_{month;per}} Q_{light;i} \quad [A53]$$

In which:

$Q_{prim;light}$ = total primary energy use for lighting [MJ]

$Q_{light;i}$ = primary energy use for lighting in the energy sector in month i [MJ]

$n_{month,per}$ = number of months in the calculation period (=12) [-]

For lighting it is possible to divide an energy sector into zones. Separate preconditions can be specified for each zone. The energy consumption for lighting is equal to the sum of the energy consumption for lighting per zone. See Formula A54.

$$Q_{light;i} = \sum_{z} Q_{light;z;i} \quad [A54]$$

In which:

$Q_{light;i}$ = primary energy use for lighting in the energy sector in month i [MJ]

$Q_{light;z;i}$ = primary energy use for lighting in the energy sector in month i in zone z [MJ]

The energy consumption for lighting is determined per zone using the installed power per m^2. See Formula A55.

$$Q_{light;z;i} = \frac{p_{light} * g}{\eta_{el} * m_{year}} * \left(f_{cont;dayl} * A_{dayl} + f_{cont;artl} * A_{artl}\right) * f_{presence} * t_{light} \quad [A55]$$

In which:

p_{light} = installed power for lightning per m^2 [kW/m^2]

g = factor for converting kWh to MJ (=3.6) [-]

η_{el} = efficiency of electricity supply [-]

m_{year} = number of months per year (=12) [-]

$f_{cont;dayl}$ = factor for the switch/control system in the daylight sector [-]

A_{dayl} = area of daylight sector [m^2]

$f_{cont;artl}$ = factor for the switch/control system in the artificial light sector [-]

A_{artl} = area of artificial light sector [m^2]

f_{move} = valuation factor for movement detection [-]

t_{light} = hours of illumination [h]

The installed power for lightning per m^2 is determined with Formula A56.

$$p_{light} = \frac{P_{light}}{A_{use;zone}} \quad [A56]$$

In which:

P_{light} = total installed power of lightning [kW]

$A_{use;zone}$ = use area of lightning zone [m^2]

The surface area of the daylight sector is a fixed fraction of the usage area of the lighting zone depending on the usage function within which the lighting zone is located. The surface area of the artificial light sector is equal to the total surface area of the lighting zone minus the surface area of the daylight sector. See Formulas A57 and A58.

$$A_{dayl} = f_{dayl} * A_{use;zone} \quad [A57]$$

$$A_{artl} = A_{use;zone} - A_{dayl} \quad [A58]$$

In which:

A_{dayl} = area of daylight sector [m^2]

A_{artl} = area of artificial light sector [m^2]

$A_{use;zone}$ = use area of lightning zone [m^2]

f_{dayl} = ratio between the area of the daylight sector and the total area of use of the lighting zone (A_{dayl} / $A_{use;zone}$) [-] (=0.2 for offices)

The annual number of hours of illumination are depended on the use function in which the lightning zone lies. For office buildings, this is 2400 h.

Table 57 presents the factors of the control/switch systems.

Table 57:Factor for the type of switch

Description control/switch	$f_{cont;dayl}$	$f_{cont;artl}$
Centrally on/off	1	1
Sweep pulse switch	0.75	0.75
Sweep pulse switch in combination with daylight depending control	0.55	0.7
Departure switch	0.9	0.9
Departure switch with separation daylight-/artificial light sector	0.75	0.9
Daylight dependent switch	0.6	0.8

The valuation factor for the presence of movement detection is presented in Table 58.

Table 58: Factor for the presence of movement detection

Description control	f_{move}
Movement detection	0.8
No movement detection	1

D.5 Energy use for pumps

The primary energy use by pumps per energy sector follows from Equation A59.

$$Q_{prim;pumps} = \frac{e_{pump}}{\eta_{el} * m_{year}} * (f_{control;heat} * A_u * month\{Q_{heat;dem;i} > 0\} + f_{control;cool} * A_u * month\{Q_{cool;dem;i} > 0\}) \quad [A59]$$

In which:

$Q_{prim;pumps}$ = total primary energy use for pumps [MJ]

e_{pump} = specific electricity use by pumps (=8) [MJ/m^2]

η_{el} = efficiency of electricity supply [-]

m_{year} = number of months per year (=12) [-]

$f_{control;heat}$ = weighting factor for the type of control in the heating system [-]

A_u = use area of the energy sector [m^2]

$month\{Q_{heat;dem;i} > 0\}$ = total amount of months in which the heat demand is higher than zero [-]

$f_{control;cool}$ = weighting factor for the type of control in the cooling system [-]

$month\{Q_{cool;dem;i} > 0\}$ = total amount of months in which the cooling demand is higher than zero [-]

The weighting factor for the pump control type for cooling depends on the presence of cooling. The presence of cooling can be deduced from the system number. The weighting factor for heating is a constant. See Table 59.

Table 59: Weighting factor for type of control

System number	$f_{control;cool}$	$f_{control;heat}$
1, 5, 9, 10 (no or local cooling)	0	0.75
11, 12 (no or local cooling and local heating)	0	0
Other	0.75	0.75

D.6 Energy use for cooling

The primary energy use for cooling per energy sector is calculated with Formula A60.

$$Q_{prim;cooling} = Q_{cooling} \quad [A60]$$

In which:

$Q_{prim;cooling}$ = primary energy use for cooling [MJ]

$Q_{cooling}$ = energy use for cooling [MJ]

The energy use for cooling in the total period is equal to the sum of the energy use per month.

$$Q_{cooling} = \sum_{i=1}^{n_{month;per}} Q_{cooling;i} \quad [A61]$$

In which:

$Q_{cooling;i}$ = energy use for cooling in month i [MJ]

$n_{month;per}$ = total amount of months in calculation period (=12) [months]

The energy use for cooling per month is calculated with Formula A62.

$$Q_{cooling;i} = \frac{Q_{cooling;c;i}}{\eta_{gen;cooling;res} * \eta_{sys;cooling}} \quad [A62]$$

In which:

$Q_{cooling;c;i}$ = (corrected) cooling requirement in month [MJ]

$\eta_{gen;cooling;res}$ = resulting efficiency of cold generation [-]

$\eta_{sys;cooling}$ = annual average system efficiency for cooling [-]

D.6.1 Cooling requirement

The cooling requirement per year (needed for the calculation of the system efficiency) is equal to:

$$Q_{cooling;req;year} = \sum_{i=1}^{n_{month;per}} Q_{cooling;c;i} \quad [A63]$$

In which:

$Q_{cooling;req;year}$ = annual cooling requirement [MJ]

$Q_{cooling;c;i}$ = (corrected) cooling requirement in month i [MJ]

$n_{month;per}$ = total amount of months in calculation period (=12) [months]

The corrected cooling requirement, including latent cooling load, is calculated with Formula A64.

$$Q_{cooling;c;i} = f_{latent} * Q_{cooling;req;i} \quad [A64]$$

In which:

f_{latent} = correction factor for the calculation of the latent cooling load (=1.1)

$Q_{cooling;req;i}$ = cooling requirement in month i [MJ]

The cooling requirement in month i is calculated with Formulas A65 and A66.

$$Q_{cooling;req;i} = Q_{intern;cr;i} + Q_{sun;t;i} + Q_{sun;nt;i} - \eta_{u;cooling;i} * \left(Q_{tr;cooling;i} + Q_{vent;cooling;i}\right) \; if \; \lambda_i \leq 2.5 \quad [A65]$$

$$Q_{cooling;req;i} = 0 \; if \; \lambda_i > 2.5 \quad [A66]$$

In which:

λ_i = profit / loss ratio in month i [-]

$Q_{intern;cr;i}$ = internal heat production used for the cold requirement calculation in month i [MJ]

$Q_{sun;t;i}$ = sun heat gain through transparent construction parts in month i [MJ]

$Q_{sun;nt;i}$ = sun heat gain through non-transparent construction parts being part of the outside construction in month i [MJ]

$\eta_{u;cooling;i}$ = utilization factor for heat losses in month i [-]

$Q_{tr;cooling;i}$ = heat loss through transmission in month i [MJ]

$Q_{vent;cooling;i}$ = heat loss through ventilation in month i [MJ]

D.6.2 Incoming solar heat through non-transparent construction components

The incoming solar heat through non-transparent construction components adjacent to outside, except for floors, is calculated with Formula A67.

$$Q_{sun;nt;i} = \sum_{k} (f * q_{sun;i} * z_{sun;nt} * U_k * A_k) \quad [A67]$$

In which:

f = factor for the absorption coefficient for solar radiation divided by the heat transfer coefficient to the outside air (= 0.9/20 = 0.045) [-]

$q_{sun;i}$ = the amount of solar energy that falls on a horizontal surface per m^2 in month i [MJ]

$z_{sun;nt}$ = average orientation factor for non-transparent parts at an angle of inclination [-]

U_k = the heat transfer coefficient of partition construction k [W/(m^2.K)]

A_k = projected area of the relevant partition construction k [m^2]

$$If\ \frac{A_{shell;outside}}{A_u} < 1.2, than\ Q_{sun;nt;i} = 0 \quad [A68]$$

$$Otherwise\ Q_{sun;nt;i} = Q_{sun;nt;i} \quad [A69]$$

In which:

$A_{shell;outside}$ = total construction area of the energy sector adjacent to outside air [m^2]

A_u = use area of energy sector [m^2]

Construction area adjacent to outside air

The total construction area adjacent to outside air depends on the area of the shell parts of the energy sector and the weighting factor, depending on the space on the other side. The total construction area adjacent to the outside air is calculated with Formula A70.

$$A_{shell;outside} = \sum_k d_k * A_k \quad [A70]$$

In which:

d_k = weighting factor [-]

A_k = surface area of shell part [m^2]

Table 60: Weighting factor d

Construction adjacent to	**d_k [-]**
Outside air	1
Other	0

D.6.3 Heat loss through transmission

The transmission loss per month can be calculated as followed:

$$Q_{tr;cooling;i} = H_{tr;cooling} * \left(T_{in;cooling} - T_{o;i}\right) * t \quad [A71]$$

$$H_{tr;cooling} = \sum_k (a_k * A_k * (U_k + U_{cb})) \quad [A72]$$

In which:

$Q_{tr;cooling;i}$ = heat loss through transmission in month i [MJ]

$H_{tr;cooling}$ = specific heat loss through transmission [W/K]

$T_{in;cooling}$ = inside temperature [°C] → is 24 °C for office buildings

$T_{o;i}$ = monthly average outside temperature in month i [°C]

t = time in a month (= 2.63) [Ms]

a_k = the weighting factor to be assigned to the partition construction k [-]

A_k = area of the projection of partition construction k [m^2]

U_k = heat transfer coefficient of partition construction k [W/(m^{2}K)]

U_{tb} = surcharge for thermal bridges [W/(m^{2}K)] (=0.1)

D.6.4 Heat loss through ventilation

The monthly heat loss through ventilation is calculated as follows:

$$Q_{vent;cooling;i} = H_{vent;cooling} * \left(T_{in;cooling} - T_{st;i}\right) * t \quad [A73]$$

$$H_{vent} = \rho * c_l * \frac{1}{h} * f_u * \left(v_{v;vent;cooling} + v_{v;mech}\right) * V_{sector} \quad [A74]$$

In which:

$H_{vent;cooling}$ = specific heat loss through ventilation [W/K]

$T_{in;cooling}$ = inside temperature (= 24 °C for office buildings) [°C]

$T_{st;i}$ = supply temperature of ventilation air in month i [°C]

t = time in a month (= 2.63) [Ms]

$\rho * c_l$ = heat capacity of air (=1.2) [J/dm^{3}K]

h = conversion factor from dm^3/s to m^3/h (= 3.6) [-]

f_u = use factor: average time fraction that the ventilator is turned on (=0.3) [-]

$v_{v;vent;cooling}$ = ventilation rate of cooling, air coming directly from outside through natural ventilation [1/h]

$v_{v;mech}$ = ventilation rate cooling, air coming directly from outside through mechanical ventilation [1/h]

V_{sector} = net volume of the energy sector [m^3]

The ventilation loss cannot be smaller than 0. If $Q_{vent;i} < 0$ than $Q_{vent;i} = 0$.

Ventilation rate of cooling, air coming directly from outside through natural ventilation

$$v_{v;vent;cooling} = u_{v;vent;cooling} * h * \frac{A_{u;sector}}{V_{sector}} \quad [A75]$$

In which:

$u_{v;vent;cooling}$ = air volume flow through natural ventilation during a period with cooling needs [dm^3/s.m^2]

h = conversion factor from dm^3/s to m^3/h (= 3.6)

$A_{u;sector}$ = area of use from energy sector [m^2]

V_{sector} = net volume of the energy sector [m^3]

Table 61: Flow of air by natural ventilation in a period with cooling demand

Ventilation facility	$\boldsymbol{u_{v;vent;cooling}}$ [dm^3/s.m^2]
Non	0
Ventilation grilles	0.5
Windows to be opened	2

D.6.5 Utilization factor for heat losses $\eta_{u;cooling;i}$

The utilization factor for cooling depends on the profit / loss ratio. As the profit / loss ratio becomes smaller, the usability of the coolness increases.

$$\eta_{u;cooling;i} = \frac{(1-\lambda_i^a)}{(1-\lambda_i^{a+1})}, when\ \lambda \neq 1 \quad [A76]$$

$$\eta_{u;cooling;i} = \frac{a}{(1+a)}, when\ \lambda = 1 \quad [A77]$$

In which:

$\eta_{u;cooling;i}$ = utilization factor for cooling in month i [-]

λ_i = loss / profit ratio in month i [-]

a = auxiliary variable [-]

Loss / profit ratio

The profit / loss ratio follows from the following formulas.

$$\lambda_i = \frac{Q_{loss;i}}{Q_{profit;i}} \quad [A78]$$

$$Q_{profit;i} = Q_{intern;i} + Q_{sun;t;i} + Q_{sun;ze;i} \quad [A79]$$

$$Q_{loss;i} = Q_{tr;cooling;i} + Q_{vent;cooling;i} \quad [A80]$$

In which:

λ_i = loss / profit ratio in month i [-]

$Q_{profit;i}$ = heat gain through solar and internal heat production in month i [MJ]

$Q_{loss;i}$ = heat loss through transmission and ventilation in month i [MJ]

$Q_{intern;i}$ = heat gain through internal heat production in month i [MJ]

$Q_{sun;t;i}$ = solar heat gain through transparent construction parts in month i [MJ]

$Q_{sun;ze;i}$ = solar heat gain through solar collectors for space heating in month i [MJ]

$Q_{tr;cooling;i}$ = heat loss through transmission in month i [MJ]

$Q_{vent;cooling;i}$ = heat loss through ventilation in month i [MJ]

Auxiliary variable

The value for the auxiliary variable follows from Formula A81:

$$a = c_{1;cooling} + \frac{1}{c_{2;cooling}} * \frac{D * A_u}{H_{tr;cooling} + H_{vent;cooling}} \quad [A81]$$

In which:

$c_{1;cooling}$ = constant (=1.83 for office buildings) [-]

$c_{2;cooling}$ = constant (=83.3 for office buildings) [-]

D = specific effective thermal capacity per m^2 of use area [Wh/(m^{2}K)]

A_u = use area [m^2]

$H_{tr;cooling}$ = specific heat loss through transmission [W/K]

$H_{vent;cooling}$ = specific heat loss through ventilation [W/K]

D.6.6 Generation efficiency for cold generators

In the presence of one cold generator or a combination of cold generators with the same efficiency, the generation efficiency for cold is equal to:

$$\eta_{gen;cooling;res} = \eta_{gen;cooling} \quad [A82]$$

In which:

$\eta_{gen;cooling;res}$ = resulting generation efficiency of cold generators [-]

$\eta_{gen;cooling}$ = generation efficiency of cold generators [-]

In the other cases, the following applies:

$$\eta_{gen;cooling;res} = \frac{1}{\frac{\alpha_{cooling}}{\eta_{gen;cooling;pref}} + \frac{(1 - \alpha_{cooling})}{\eta_{gen;cooling;npref}}} \quad [A83]$$

In which:

$\eta_{gen;cooling;res}$ = resulting generation efficiency of cold generators [-]

$\alpha_{cooling}$ = ratio between the cold requirement coverage by the applied cold generators with the highest efficiency and the total cold requirement (=0.8) [-]

$\eta_{gen;cooling;pref}$ = efficiency of the preferentially switched cooling appliances [-]

$\eta_{gen;cooling;npref}$ = efficiency of the other cold generating devices [-]

<u>Generation efficiencies</u>

The generation efficiency of a device depends on the type of device and the type of source. See Table 62.

Table 62: Generation efficiencies for cold suppliers

Cold supplier	Generation efficiency	Type of fuel
Compression cooling machine	$4 * \eta_{el}$	Electricity
Absorption cooling machine on heat supply by third parties	$0.7 * \eta_{th}$	Heat
Absorption cooling machine on CHP	$1.0 * \varepsilon_{CHP;th}$	Gas
Cold storage	$12 * \eta_{el}$	Electricity
Heat pump in summer operation (in combination with cold storage)	$5 * \eta_{el}$	Electricity

D.7 Energy use for humidification

The primary energy use for humidification per energy sector is calculated with Formula A84.

$$Q_{prim;hum} = \sum_{i=1}^{n_{month;period}} Q_{hum;i} \quad [A84]$$

In which:

$Q_{prim;hum}$ = total primary energy use per energy sector for humidification [MJ]

$n_{month,per}$ = number of months in the calculation period (=12)

$Q_{hum;i}$ = primary energy use for humidification in month i [MJ]

The energy use for humidification per month follows from Formula A85.

$$Q_{hum;i} = \frac{a_{hum} * v_{v;mech;hum} * V_{sector} * X_h * y_i * A_{u;hum}}{h * A_{u;sector}} \quad [A85]$$

In which:

a_{hum} = weighting factor for the generation efficiency of the required heat and the efficiency of moisture recovery [MJ.s/g.h]

$v_{v;mech;hum}$ = mechanical ventilation rate for humidification [1/h]

V_{sector} = net volume of the energy sector [m^3]

X_h= number of grams of moisture to be supplied per dm^3 of dry air for the energy sector [g.h/dm^3] (=5 for offices)

y_i = weighting factor for humidification in month i [-]

$A_{u;hum}$ = surface area of the wetted part of the energy sector [m^2]

h = conversion factor from dm^3/s to m^3/h (= 3.6)

$A_{u;sector}$ = area of use from energy sector [m^2]

The weighting factor for humidification per month is presented in Table 63.

Table 63: Weighting factor for humidification per month

Month i	**Weighting factor y_i**
January	0.26
February	0.25
March	0.15
April	0.01
May	0
June	0
July	0
August	0
September	0
October	0
November	0.11
December	0.22
Total	*1*

D.7.1 Weighting factor a_{hum}

The weighting factor a_{hum} is depended on the presence of moisture recovery and the type of humidification, see Table 64.

Table 64: Weighting factor for the generation efficiency with or without moisture recovery

Type humidification installation	**Type**	
	With moisture recovery	**No moisture recovery**
Electrically powered steam humidification	$4/\eta_{el}$	$9.5/\eta_{el}$
Non-electrically powered steam humidification	$4/(\eta_{steam} * f_{loss;st})$	$9.5/(\eta_{steam} * f_{loss;st})$
Adiabatic humidification	$4/\eta_{gen;heat}$	$9.5/\eta_{gen;heat}$

In which:

η_{el} = efficiency of the electricity supply [-]

η_{steam} = the generation efficiency of a steam boiler to be used [-]

$f_{loss;st}$ = factor for standstill losses for steam installations (=0.8)

$\eta_{gen;heat}$ = generation efficiency of heat generation determined [-]

D.8 Energy use for the preparation of hot tap water

The primary energy use for the preparation of hot tap water is calculated using Formula A86.

$$Q_{prim;tap} = \frac{\sum_{i=1}^{n_{month;per}} \left(\frac{Q_{tap;dem;i}}{\eta_{sys;tap}} - Q_{sun;tap;i} \right)}{\eta_{gen;tap}} \quad [A86]$$

In which:

$Q_{prim;tap}$ = primary energy use for the preparation of hot tap water [MJ]

$Q_{tap;dem;i}$ = heat demand for the preparation of hot tap water in month i [MJ]

$\eta_{sys;tap}$ = system efficiency for the distribution of hot tap water [-]

$Q_{sun;tap;i}$ = energy contribution of solar energy system to the preparation of hot tap water in month i [MJ]

$\eta_{gen;tap}$ = generation efficiency of the preparation of hot tap water [-]

The total heat demand for the preparation of hot tap water per month is calculated using Formula A87.

$$Q_{tap;dem;i} = \frac{c_{hd;tap} * A_{u;sector}}{n_{month;year}} \quad [A87]$$

In which:

$c_{hd;tap}$ = net heat requirement for the energy sector to be considered [MJ/m^2] (=5 for offices)

$A_{u;sector}$ = use area of energy sector [m^2]

$n_{month;year}$ = number of months per year (=12)

The system efficiency for the distribution of hot tap water follows from Table 65.

Table 65: System efficiencies for the distribution of hot tap water

Distribution system	$\boldsymbol{\eta_{sys;tap}}$
All taps within a 3 m radius of the generating device	1
One or more taps at a distance of more than 3 m from the generating device	0.8
Circulation pipe	0.6

The total contribution of a solar energy system for the preparation of hot tap water per energy sector is calculated using Formulas A88 and A89.

$$Q_{sun;tap} = \sum_{i=1}^{n_{months;per}} Q_{sun;tap;i} \quad [A88]$$

$$Q_{sun;tap;i} = q_{sun;i} * z_{sun} * z_{se;tap} * A_{se} * \eta_{se;av} \quad [A89]$$

With the additional requirement that:

$$Q_{sun;tap;i} \leq \eta_{se;max} * \frac{Q_{tap;dem;i}}{\eta_{sys;tap}} \quad [A90]$$

In which:

$Q_{sun;tap}$ = energy contribution of solar energy system to the preparation of hot tap water in total period [MJ]

$Q_{sun;tap;i}$ = energy contribution of solar energy system to the preparation of hot tap water in month i [MJ]

$q_{sun;i}$ = amount of solar energy per m^2 on a horizontal surface with the relevant climate in month i [MJ]

z_{sun} = orientation factor [-]

$z_{se;tap}$ = slope angle number [-]

A_{se} = surface area of solar collector [m^2]

$\eta_{se;av}$ = average utilization of the incident solar radiation (=0.5) [-]

$\eta_{se;max}$ = fraction of the maximum contribution of the solar energy system to the heat requirement (=0.5) [-]

$Q_{tap;dem;i}$ = heat demand for the preparation of hot tap water in month i [MJ]

$\eta_{sys;tap}$ = system efficiency for the distribution of hot tap water [-]

The generation efficiency for the preparation of hot tap water follows from Table 66. For the values of the given variables, see Section D.2.8.

Table 66: Generation efficiencies for the preparation of hot tap water per device

Type of device	$\boldsymbol{\eta_{gen;tap}}$	**Type of fuel [-]**
Electric boiler	$0.75 * \eta_{el}$	Electricity
VR boiler with central heating boiler, VR combi	0.45	Gas
Gas boiler, geyser, HR boiler with central heating boiler, HR combi	0.55	Gas
Combined heat	$0.9 * \varepsilon_{CHP;th}$	Gas
Heat supply by third parties	$0.9 * \eta_{heat;tap}$	Heat
Heat pump	$1.4 * \eta_{el}$	Electricity
Steam	$\eta_{steam} * f_{loss;st} * f_{tap}$	Gas
Hot water boiler	$\eta_{steam} * f_{loss;hw} * f_{tap}$	Gas

D.9 Energy contribution by photovoltaics

The primary energy contribution by building-related photovoltaic solar energy systems for the entire building is calculated with Formulas A91 and A92.

$$Q_{prim;pv} = \sum_{i=1}^{n_{months;per}} Q_{pv;i} \quad [A91]$$

$$Q_{pv;i} = \frac{q_{sun;i} * z_{sun;i} * z_{pv} * A_{pv} * S_{pv} * r_{pv}}{S_{pv;nor} * \eta_{el}} \quad [A92]$$

In which:

$Q_{pv;i}$ = energy contribution of photovoltaic solar energy systems in month i [MJ]

$q_{sun;i}$ = amount of solar energy per m^2 on a horizontal surface with the relevant climate in month i [MJ]

$z_{sun;i}$ = orientation factor [-]

z_{pv} = slope angle number of solar panel [-]

A_{pv} = surface area of solar panel [m^2]

S_{pv} = peak power of solar panel [W/m^2]

r_{pv} = reduction factor for the degree of insolation (=0.5) [-]

$S_{pv;nor}$ = standard radiation (=1000) [W/m^2]

η_{el} = efficiency of electricity supply (=0.39) [-]

The peak power of a photovoltaic solar energy system depends on the type of pv-system. See Table 67.

Table 67: Peak power per pv system

Type of pv-system	$\boldsymbol{S_{pv}\ (W/m^2)}$
Amorphous cells	45
Mono or multi crystalline cells	120

D.10 Energy contribution through the application of cogeneration

The definition of cogeneration in the certification calculation is: “Combined generation of electricity and heat where the heat consumers are also the buyers of the electricity.” The primary energy contribution through the application of cogeneration is calculated with Formula A93.

$$Q_{prim;CHP} = \left(\frac{\sum_{i=1}^{n_{month;per}} Q_{hd;gross;i}}{\eta_{el;marg} * \frac{\varepsilon_{CHP;th}}{\varepsilon_{CHP;el}}} \right) \quad [A93]$$

In which:

$Q_{prim;CHP}$ = primary energy contribution through the application of cogeneration [MJ]

$Q_{hd;gross;i}$ = gross heat requirement that is covered by combined heat and power in month i [MJ]

$\eta_{el;marg}$ = marginal return for separate generation with new power plants, considering grid losses [-]

$\varepsilon_{CHP;th}$ = thermal conversion number for CHP [-]

$\varepsilon_{CHP;el}$ = electric conversion number for CHP [-]

The monthly gross heat requirement that is covered by combined heat and power, is calculated by Formula A94.

$$Q_{hd;gross;i} = Q_{hd;gross;heat;i} + Q_{hd;gross;cool;i} + Q_{hd;gross;tap;i} \quad [A94]$$

In which:

$Q_{hd;gross;heat;i}$ = gross heat requirement for heating if covered by CHP in month i [MJ]

$Q_{hd;gross;cool;i}$ = gross heat requirement for cooling if covered by CHP in month i [MJ]

$Q_{hd;gross;tap;i}$ = gross heat requirement for the preparation of hot tap water in month i [MJ]

Heating

$$Q_{hd;gross;heat;i} = \frac{f_{pref;i}}{\eta_{distr}} * Q_{heat;dem;i} \quad [A95]$$

In which:

$f_{pref;i}$ = share of CHP in primary energy use for heating in month i [-]

η_{distr} = distribution efficiency for heating [-]

$Q_{heat;dem;i}$ = heat demand in month i [MJ]

Cooling

$$Q_{hd;gross;cool;i} = \frac{Q_{cool;dem;c;i}}{\eta_{sys;cool}} \quad [A96]$$

In which:

$Q_{cool;dem;c;i}$ = cooling demand at floor area in month i [MJ]

$\eta_{sys;cool}$ = system efficiency for cooling [-]

Hot tap water

$$Q_{hd;gross;tap;i} = \frac{Q_{tap;dem;i}}{\eta_{sys;tap}} - Q_{se;tap;i} \quad [A97]$$

In which:

$Q_{tap;dem;i}$ = heat demand for the preparation of hot tap water in month i [MJ]

$\eta_{sys;tap}$ = system efficiency for the distribution of hot tap water [-]

$Q_{se;tap;i}$ = energy contribution of solar energy system to the preparation of hot tap water in month i [MJ]

D.10.1 Cogeneration conversion figures

The electric and thermal conversion figures for cogeneration depend on the type of CHP, the electric or thermal power of the CHP. See Table 68.

Table 68: Electric and thermal conversion numbers for cogeneration

Electric power (kW)	**Thermal power (kW)**	**Type of CHP**	$\varepsilon_{CHP;el}$	$\varepsilon_{CHP;th}$
$P_{CHP;el} < 20$	$P_{CHP} < 40$	Mini CHP	0.28	0.57
$20 < P_{CHP;el} < 200$	$40 < P_{CHP} < 312$	Gas motor	0.30	0.51
$200 < P_{CHP;el} < 500$	$312 < P_{CHP} < 629$	Gas motor	0.32	0.52
$500 < P_{CHP;el} < 1000$	$629 < P_{CHP} < 1111$	Gas motor	0.35	0.46
$1000 < P_{CHP;el} < 25000$	$1111 < P_{CHP} < 27778$	CHP	0.37	0.41

D.10.2 Distribution efficiency for cogeneration by heating

The distribution efficiencies for the heating part of cogeneration depends on the heat transport through pipes and is presented in Table 69.

Table 69: Distribution efficiencies for cogeneration

Type of distribution CHP	η_{distr}
Indoor heat transfer pipes	1.00
Heat transfer pipes (partially) outside the building	0.95

Appendix E - *Weather data*

The weather data used in this research, are based on the Test Reference Year De Bilt (ISSO 75.3). The monthly average outside temperature, the average outside temperature for ventilation in the cooling demand and the solar irradiation on a horizontal surface are presented in Table 70.

Table 70: Monthly T_e, $T_{e;vent}$ and q_{sun}

Month i	**T_e (˚C)**	**$T_{e;vent}$ (˚C)**	**q_{sun} (MJ/m^2)**
January	2.5	16.0	43
February	2.7	16.0	117
March	5.6	16.0	254
April	8.0	16.0	373
May	11.9	16.0	503
June	15.5	17.0	574
July	17.0	18.5	504
August	16.4	17.9	489
September	13.8	16.0	295
October	11.2	16.0	166
November	6.0	16.0	63
December	3.4	16.0	35
Average/total	*9.5*	*16.5*	*3416*

For the solar irradiation on vertical surfaces with a different orientation, the conversion factors in Table 71 are used.

Table 71: Conversion factors solar irradiation

$z_{sun;i}$ (-)									
Month i	**Slope angle β_k**								
	Vertical								Horizontal
	Orientation α_k								
	South	South-East	East	North-East	North	North-West	West	South-West	
January	0.95	0.93	0.91	0.91	0.91	0.91	0.91	0.95	1.00
February	1.22	0.90	0.50	0.41	0.41	0.42	0.62	1.08	1.00
March	1.04	0.78	0.51	0.37	0.35	0.39	0.66	0.96	1.00
April	0.82	0.69	0.52	0.37	0.33	0.43	0.65	0.82	1.00
May	0.61	0.60	0.55	0.42	0.37	0.53	0.70	0.71	1.00
June	0.55	0.56	0.52	0.41	0.40	0.60	0.73	0.66	1.00
July	0.58	0.57	0.52	0.41	0.38	0.55	0.69	0.67	1.00
August	0.75	0.71	0.59	0.40	0.33	0.49	0.68	0.76	1.00
September	0.93	0.72	0.52	0.37	0.36	0.55	0.84	1.00	1.00
October	1.22	0.92	0.52	0.39	0.39	0.40	0.63	1.05	1.00
November	1.16	0.92	0.57	0.52	0.52	0.52	0.63	1.02	1.00
December	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	1.00

For the slope angle of a surface, the conversion factors are presented in Table 72.

Table 72: Conversion factors slope angle

Slope angle	**Slope angle number $z_{se;tap}$ and z_{pv}**
90	1.00
75	1.19
60	1.33
45	1.41
30	1.42
15	1.36
0	1.00

Lastly, the average orientation factor of the surface is used in some calculations. These are given in Table 73.

Table 73: Average orientation factor of a surface

	$z_{sun;nt}$ (-)	
	$Type_{construct}$	
Month i	**Facades**	**Roofs**
January	0.92	1
February	0.70	1
March	0.63	1
April	0.58	1
May	0.56	1
June	0.55	1
July	0.55	1
August	0.59	1
September	0.66	1
October	0.69	1
November	0.73	1
December	0.63	1

Appendix F - *Retrofit measures*

This section describes the considered retrofit measures for office buildings in this research. They are characterized using the Building Retrofit Classification described in Section 2.2.3. For each of the retrofit measures, the costs (investment and maintenance), lifetime and installation time are determined.

F.1 Reduce energy demand

F.1.1 Building Envelope

The first retrofit measures aim to improve the building fabric insulation. This is done for the outside walls, windows, the roof and the floor. Insulation for the inside walls and floors are not considered, since the energy losses within the building are neglectable compared to the losses through the shell.

Walls

Table 74 shows the options for wall insulation. The U-values below are based on 10 mm thick isolation material. Based on experience of SPIE, the assumption was made that no maintenance is required for the insulation of walls, so the maintenance costs are equal to zero.

Table 74: Retrofit characteristics - wall insulation

Installation method	**Material**	**U-value (W/m^2K)**	**Costs (€/m^2) excl. installation**	**Costs (€/m^2) incl. installation**	**Lifetime (years)**	**Source**
Cavity wall	Glass wool	0.32-0.40	1.75	15-20	45	Isolatie-info.nl (n.d.); Isolatiemateriaal.nl 1 (n.d.).
	EPS pearls	0.32-0.36	5.02	20-25	45	
	PUR	0.23-0.35	11.77	25-30	45	
Outside	EPS	0.36	5.02	80-100	45	Isolatie-info.nl (n.d.); Plusisolatie.nl (n.d.)
	XPS	0.34-0.36	9.53	150	45	
Inside	PUR	0.22	11.77	120-130	45	Mijnbenovatie.be (n.d.); Baveco et al. (2015)
	Glass wool	0.30	1.75	100-110	45	
	Rock wool	0.30	4.47	90-100	45	

Roof

The most used roof insulation materials are glass wool, rock wool, PUR and PIR (Dakdek-gigant.nl, 2020). The characteristics are shown in Table 75. Again, the U-values are based on 10 mm thick insulation material. Furthermore, the estimation is made that installation costs are equal between each type of insulation and are set at 20 €/m2 for insulation from the inside and 40 €/m2 for insulation from the outside (Dakisolatie-advies.nl, n.d.). Again, no maintenance costs are assumed based on the experience of SPIE.

Table 75: Retrofit characteristics - roof insulation

Installation method	**Material**	**U-value (W/m^2K)**	**Costs (€/m^2) excl. installation**	**Costs (€/m^2) incl. installation**	**Lifetime (years)**	**Source**

Inside	Glass wool	0.32-0.40	7.50	27.50	45	Dakdek-gigant.nl (2020); Dakisolatie-advies.nl (n.d.); Isolatie-weetjes (n.d.).
	Rock wool	0.32-0.40	8	28	45	
	PUR	0.23-0.35	25	45	45	
Outside	PIR	0.23-0.26	12	52	45	

Floor

For the insulation of the floor, a distinction is made between two types of floors: wood and concrete. The type of insulation material namely depends on the type of floor. The characteristics of these insulation materials are shown in Table 76, again assuming 10 mm thick insulation material. Furthermore, the estimation is made that installation costs are equal between each type of insulation and are set at 15 €/m2 and the maintenance costs are equal to zero (Verbouwkosten.com, n.d; Experience of SPIE).

Table 76: Retrofit characteristics - floor insulation

Type of floor	**Installation method**	**Material**	**U-value (W/m^2 K)**	**Costs (€/m^2) excl. installation**	**Costs (€/m^2) incl. installation**	**Lifetime (years)**	**Source**
Wood	Below	Glass wool	0.22	5.66	21	45	Isolatiemateriaal.nl 2 (n.d.); Verbouwkosten.com (n.d)
		Rock wool	0.54	5.43	20	45	Isolatiemateriaal.nl 2 (n.d.); Verbouwkosten.com (n.d)
Concrete	Below	EPS	0.36	8.18	23	45	Isolatiemateriaal.nl 2 (n.d.); Verbouwkosten.com (n.d)
		PIR	0.31	12.02	27	45	Isolatiemateriaal.nl 2 (n.d.); Verbouwkosten.com (n.d)
	On top	EPS	0.36	8.18	23	45	Isolatie-info.be 1 (n.d.); Isolatiemateriaal.nl 3 (n.d.); Verbouwkosten.com (n.d)
		XPS	0.66	7.56	22	45	Isolatiemateriaal.nl 3 (n.d.); Verbouwkosten.com (n.d)
		PIR	0.31	12.02	27	45	Isolatiemateriaal.nl 3 (n.d.); Verbouwkosten.com (n.d)
		PUR	0.26	15	30-35	45	Isolatie-info.be 1 (n.d.); Isolatie-info.be 2 (n.d.); Verbouwkosten.com (n.d)

Windows

The next retrofit measures regard the outside windows of the building. They impact the energy use of the building by their U-value and the ZTA-value. The ZTA-value is a characteristic of a glazing type and represents the total amount of solar energy transmitted through the glass. This value lies between 0 and 1. The higher the ZTA-value, the more heat enters (help.vabi.nl, n.d.). The characteristics for the different glazing types are shown in Table 77. Single clear glass is chosen as the base of installed glazing type, since it is expected that this is the worst installed glazing possible and when considering a retrofit only better glazing will be installed. Therefore, no data is collected for this type of glass. Again, no maintenance costs are assumed (Experience of SPIE).

Table 77: Retrofit characteristics - glazing

Glazing type	**U-value (W/m² K)**	**ZTA-value**	**Costs (€/m²) excl installation**	**Costs (€/m²) incl installation**	**Lifetime (years)**	**Source**
Single clear glass	5.37	0.73				Help.vabi.nl (n.d.); Ramen-weetjes.be (n.d.); Dubbelglas-weetjes.nl (n.d.); Dubbelglasprijzen.net (n.d.)
Double glazing	3.20	0.63	50-55	115	20	
HR glass	2.00	0.59	55-60	120	20	
HR + glass	1.52	0.56	60-65	125	20	
HR ++ glass	1.10	0.52	65-75	130	20	
Triple glazing	0.80	0.45	100-130	170	20	

<u>Awning</u>

In addition to changing the glazing type, adding awning at outside of the building can reduce the incoming solar irradiation. For office buildings, screens are best suited. Since these can be applied to every floor and can stand strong winds (Zonweringgigant.nl 1., n.d.). In addition, only automatic screens are looked at since manual screen are controlled from the outside which is not practical for an office building. The characteristics of automatic awning are presented in Table 78.

Table 78: Retrofit characteristics - awning

Awning	**Costs (€/m²)**	**Costs (€/sunscreen) control system**	**Total costs (€/m²) incl installation**	**Maintenance costs (€/year/sunscreen)**	**Lifetime (years)**	**Source**
Automatic	170 - 270	160 - 230	300 - 450	20	15	Zonwering-weetjes.nl (n.d.); Unizon.nl (n.d.); Homedeal.nl (n.d.); Offerteadviseur.nl 1 (n.d.)

F.1.2 Equipment System

The equipment systems considered to be suitable for retrofit are the heat generators, cold suppliers, lightning and ventilators.

<u>Heat generators</u>

The ISSO 75.3 describes multiple heat generators. In consultation with SPIE, the ones suitable for office buildings are selected. The characteristics of these heat generators are shown in Table 79. Installation costs are the same as the purchase costs as described in Section 3.1.3. The expected amount of installed Watts needed per m3 for heating is usually set at 85 (CVketelkiezen.nl, n.d.).

Table 79: Retrofit characteristics - heat generators

	Cost (€/unit)	**Costs (€/unit) incl. installation**	**Maintenance costs (€/year)**	**Lifetime (years)**	**Source**

CHP (Cogeneration)	263-356 per kWth	619 (per kW)	7 – 25 €/MWh	15	ISSO 75.3 (2011); Emis (2020).
Electric installation	1,500 per 150 m2	20 per m2	0	15	Liander (n.d.); Verwarming-info.nl (n.d.); Electricaboiler.nl (n.d.).
Heat delivery by third parties	473	16 per m2	0	15	Schepers, Meyer & Burger (2018); CE Delft (2018)
Direct fired air heater	1,500 (per 43 kW)	70 per kW	130-175	15	SPIE; Bengshop.nl (n.d.); Cv-kosten.nl (n.d.)
HR-107 boiler	1,962 (35 kW)	112 per kW	130-175	15	Schepers, Meyer & Burger (2018); SPIE; Cv-kosten.nl (n.d.)
Heat pump					
Soil / outside air	10,000 – 25,000 (12 kW)	584 per kW	125-175	10-15	Warmtepomp-info.nl 1 (n.d.); Comfort Klimaat (n.d.); Warmtepomp-info.nl 2 (n.d.); Cobouw Bouwkosten (n.d.).
Heat from return / exhaust air	4,000 – 7,000 (12 kW)	184 per kW	125-175	10-15	Warmtepomp-info.nl 1 (n.d.); Comfort Klimaat (n.d.); Warmtepomp-info.nl 2 (n.d.); Cobouw Bouwkosten (n.d.).
Ground water	10,000 – 25,000 (12 kW)	584 per kW	125-175	10-15	Warmtepomp-info.nl 1 (n.d.); Comfort Klimaat (n.d.); Warmtepomp-info.nl 2 (n.d.); Cobouw Bouwkosten (n.d.).
Surface water	15,000 (12 kW)	500 per kW	125-175	10-15	Warmtepomp-info.nl 1 (n.d.); Comfort Klimaat (n.d.); Warmtepomp-info.nl 2 (n.d.); Cobouw Bouwkosten (n.d.).

Cold supplier

The cold suppliers considered in this research are the ones mentioned in the ISSO 75.3. They were checked by SPIE on their suitability for office buildings. For the cold storage, SPIE provided an indication for the costs. This is the source for cold storage. These costs should also be considered with the Heat pump in summer operation, including the investment of the heat pump (described in Table 79). Installation costs are assumed to be the same as the costs for purchase, as described in Section 3.1.3. For the cooling requirement, the amount of Watts needed is the total floor area to be cooled in m^3 times 50 (Aircogroep.nl, n.d.). See Table 80 for the characteristics of the cold suppliers.

Table 80: Retrofit characteristics - cold suppliers

Cold supplier	Costs (€)	Costs (€) incl. installation	Maintenance costs (€/year)	Lifetime (years)	Source
Compression cooling machine	233 per kW	466 per kW	14 per kW	25	Berliner Energieagentur GmbH (2009); Alrwashdeh & Ammari (2019)

Absorption cooling machine on heat supply by third parties	229-458 per kWth	687 per kW	0.07 per kW	25	ISSO 75.3 (2011); U.S. Department of Energy (2017)
Absorption cooling machine on CHP	200 - 395 per kW	595 per kW	0.06 per kW	25	Berliner Energieagentur GmbH (2009); RVO (2011); U.S. Department of Energy (2017)
Cold storage	150,000 – 200,000 (Source 150 kW)	2333 per kW	93 per kW (4% of investment)	25	SPIE; Energie vastgoed (2015); RVO 7 (n.d.)
Heat pump in summer operation (in combination with cold storage)	150,000 – 200,000 (Source 150 kW) + heat pump	4333 per kW	243 per kW (4% of investment + 125-175 of heat pump)	15	SPIE; RVO 7 (n.d.)

Lighting

The improvement of lighting considered is from conventional to LED lighting. There are three types of lights who are most used in office buildings according to SPIE. Namely, TL-D, PLC and TL-5 lights. The characteristics of the LED lights are found in Table 81. Price for installation is 40 €/hour, 10 lights changed per hour therefore: 4 €/unit installation costs (Bouwkosten.nl, n.d.).

Table 81: Retrofit characteristics - lighting

Type of light	**Power [W]**	**Energy use incl. ballast [W]**	**Power LED [W]**	**Energy use LED [W]**	**Price [€/unit]**	**Costs (€/unit) incl. installation**	**Lifetime (years)**	**Source**
TLD	18	21	9	9	3.42 – 7.18	9	15	Lampdirect.nl (n.d.); Technische Unie (n.d.); Ledlampen-fabriek.nl (n.d.); Bouwkosten.nl (n.d.)
	36	42	18	18	3.91 - 8.94	10.50	15	
	58	68	20	20	7.99	12	15	
	72	84	~37					
	116	135	~58					
PLC	9	11	4.5	4.5	10.50	14.50	15	
	13	15	4.5	4.5	10.50	14.50	15	
	18	21	6.5	6.5	12.00	16.50	15	
	26	30	9.5	9.5	15.00	19.00	15	
	36	42	~18					
TL5	14	16	8	8	14.99-15.49	19.00	15	
	21	25	12	12	13.94-24.94	22.00	15	
	28	33	16	16	22.00-27.94	29.50	15	
	42	49	20	20	18.21-36.54	30.00	15	
	56	65	26	26	18.21-37.23	31.00	15	

Movement detection lights

Adding movement detection can also save energy needed for lightning. Therefore, movement detection is also added as a retrofit option. The costs of adding movement detection lies around €50,- per unit. One movement detection device covers a space of 30m^2 (Electrototaalmarkt.nl, n.d.). Therefore, the costs of movement detection are set at 1.67 €/m2. The characteristics are shown in Table 82. The installation costs are assumed to be twice as much as for installing lights, since it is expected that this takes more time.

Table 82: Retrofit characteristics - movement detection (lighting)

	Costs (€/m^2)	**Costs (€/m^2) incl. installation**	**Lifetime (years)**	**Source**
Movement detection	1.67	9.67	15	Electrototaalmarkt.nl (n.d.)

Ventilators

For the ventilators, a distinction is made between the type of extraction and supply of air (mechanical or natural). In addition, recirculation or heat recovery and the addition of flow control is considered. The characteristics for ventilators are shown in Table 83.

Table 83: Retrofit characteristics - ventilators

Ventilator type $type_{vent}$	**Costs (€) per unit (Flowrate 350 m^3/H)**	**Costs (€/m^2) incl. installation**	**Maintenance costs (€/year)**	**Lifetime (years)**	**Source**
Only mechanical extraction	3,000	19	65	15	Ventilatieysteemabcd.nl (n.d.); Abelenco.nl (n.d.); Binnenklimaat.be (n.d.)
Only mechanical supply	2,800	18	65	15	Ventilatieysteemabcd.nl (n.d.); Abelenco.nl (n.d.); Binnenklimaat.be (n.d.)
Mechanical supply and drain without recirculation or heat recovery	5,500	34	115	15	Ventilatieysteemabcd.nl (n.d.); Abelenco.nl (n.d.); Binnenklimaat.be (n.d.)
Mechanical supply and drain with recirculation or heat recovery	7,000	44	115	15	Ventilatieysteemabcd.nl (n.d.); Abelenco.nl (n.d.); Binnenklimaat.be (n.d.)
Arrangement					
Flow control	500	3	0	15	Ventilatieysteemabcd.nl (n.d.); Abelenco.nl (n.d.)

F.2 Apply sustainable energy resources

F.2.1 New/Renewable Technology

For the renewable technology systems, only solar energy systems are considered. These are most applicable to office buildings. The other systems, link wind or biomass, are not considered since in most cases there is no space around the office building to realize these solutions. For solar energy systems, two types are chosen: a solar collector used for heating and solar panels to produce electricity. The characteristics are shown in Table 84.

Table 84: Retrofit characteristics - solar energy systems

System	Costs (€) excl. installation	Costs (€) incl. installation	Maintenance costs (€/year)	Lifetime (years)	Source
Solar collector (+boiler)	1500	2,200 (2.5 m^2)	10-30	25	Zonnepanelen-weetjes.nl (n.d.); Zonneboiler-advies.nl 1 (n.d.); Zonneboiler-advies.nl 2 (n.d.); Zonneboiler-info.nl (n.d.); Zonnepaneelprijzen.nl (2020)
Solar panel with amorphous cells	300	400 (1.65 m^2)	2-5 (per panel ~ 1.65 m^2)	25-40	Subsidies-zonnepanelen.nl (n.d.); Zonneplan.nl (n.d.); Zonnepanelen.net (n.d.)
Solar panel with mono or multi crystalline cells	480	600-675 (1.65 m^2)	2-5 (per panel ~ 1.65 m^2)	25-40	Subsidies-zonnepanelen.nl (n.d.); Offerteadviseur.nl 2 (n.d.); Zonneplan.nl (n.d.); Zonnepanelen.net (n.d.)

F.3 Use fossil fuel effectively

F.3.1 Energy Management and Control System

A building energy management system (BEMS) can reduce the energy use of the building by controlling and monitoring energy-related building service plants and equipment. When adding a BEMS, the following reductions are assumed to be achieved: 39.5% for lightning (provided LED) and for HVAC between 14.07% and 16.66% (Lee & Cheng, 2016). The assumption is made that 10% more solar energy can be used when using the BEMS due to flexibility of the energy use. Table 85 shows the retrofit measure characteristics. Cost for installation are around 50 €/hour (Bouwkosten.nl, n.d.). Since SPIE expects the costs for installation to be the same as the price for purchase (as described in Section 3.1.3), this is assumed here as well.

Table 85: Retrofit characteristics - BEMS

	Reduction lightning	Reduction HVAC	Increase solar energy	Costs (€/m^2)	Costs (€/m^2) incl. installation	Lifetime	Source
BEMS	39.5%	15.0%	10%	25 - 70	95	20	Lee & Cheng (2016); Rawal (2016)

Appendix G - *Questionnaire Norit Amersfoort*

Demografische informatie		
Naam kantoorpand:	Norit Amersfoort	
Adres	Textielweg 15 Amersfoort	
Bouwjaar	1960	
Aantal maanden pand is in gebruik	0	maanden

Kantoorpand constructie eigenschappen			
Oppervlakten en maten			
Totale vloeroppervlakte kantoorpand	2649	m^2	
Vloeroppervlakte begane grond	2649	m^2	
Kruipruimte aanwezig?	☑ Ja	☐ Nee	
Hoogte kantoorpand	3.85	m	
Hoogte per verdieping	3.85	m	
Oppervlakte buiten muren (incl. ramen/deuren)	670	m^2	
Oppervlakte dak	1900	m^2	
Oppervlakte ramen grenzend aan buiten	201	m^2	
Issolatie waarden	**U**	**Indien bekend, vul hier in**	
Vloer	5.882		W/m^2K
Muren	2.326		W/m^2K
Dak	1.163		W/m^2K
Eventueel renovatie jaar			
Type vloer, plafond en gevel			
Massa van vloerconstructie [kg/m^2]	Meer dan 400 (steenachtig)		
Type plafond	Gesloten plafond		
Gevel type	Standaard gevel		
Ramen			
Type beglazing	Enkel glas		
Zonwering aanwezig (aan de buitenkant)?	☐ Ja	☑ Nee	
Zo ja, type zonwering			

Kantoorpand installaties		
Klimaat systeem nr	3	Zie tab Climate system nr
Warmte en koude voorziening		
Type verwarmingsinstallatie	Conventionele ketel	

Individuele regeling verwarming	☐ Ja	☑ Nee
Koude leverancier	Compressiekoelmachine	
Oppervlakte van gekoelde zones	1800	m^2

WKK

Aanwezig?	☐ Ja	☑ Nee
Elektrisch vermogen		kW
Thermisch vermogen		kW
Soort distributie		

Gedetailleerde informatie warmte voorziening

Warmtepomp

Bron

Brandstof

Temperatuur niveau warmteaanvoer

Ketel

Type ketel	Conventionele ketel
Temperatuur niveau warmteaanvoer	≤55
Een of meer centrale verwarmingstoestellen die warmte leveren voor een oppervlakte van	500 m2 of meer

Stoomketel

Economizer

Luchtvoorverwarmer

Heetwaterketel

Rookgascondensor

Ventilatoren

Type ventilatie systeem	Alleen mechanische afzuiging
Provision in ventilation system	Geen debietregeling of recirculatie
Regeling	Geen regeling of smoorregeling
Systeem type warmte terugwinning	Geen warmteterugwinning
Ventilatie voorziening voor koelbehoefte	Te openen ramen

Bevochtiging

Type bevochtigingsinstallatie	Geen bevochtiging
Vochtterugwinning	

Warm tap water

Type toestel	Gas boiler, geiser, HR-ketel met cv-boiler, HR combi
Distributie systeem	Een of meerdere tappunten op een afstand van meer dan 3 m van het opwekkingstoestel

Zonne-energie systemen

Zonnepanelen

Aanwezig	☐ Ja	☑ Nee	
Type zonnepaneel			
Indien anders, piekvermogen		W/m^2	
Totaal oppervlakte panelen		m^2	
Orientatie			
Hellingshoek			
Zonne collector			
Aanwezig	☐ Ja	☑ Nee	
Totaal oppervlakte panelen		m^2	
Verlichting (zie box rechts)	-	-	-
Totaal geinstalleerd vermogen verlichting	-	-	-
Conventioneel	35.00	kW	
LED		kW	
Armatuurtype	Overige gevallen		
Type regeling/schakeling	Vertrekschakeling		
Bewegingsmelders	Geen aanwezigheidsdetectie		

Voorkeuren renovatie

Verdeel 100 punten over de onderstaande criteria. Diegene die voor u het belangrijkste is, vul daar de meeste punten in. De tweede belangrijkste iets minder en zo verder.

	Punten	***Voorbeeld***
Laagste inversteringskosten		*50*
Snelste terug verdientijd		*20*
Laagste onderhoudskosten		*0*
Reductie van CO2 uitstoot	20	*10*
Reductie van energie gebruik	80	*20*
	100	

Als laatste wil ik u vragen de verschillende renovatie mogelijkheden te rangschikken op prioriteit. Zet op nummer 1 dat gene neer wat u het liefst aangepakt ziet worden. Op nummer 7 diegene die het laatste gedaan moet worden. Bijvoorbeeld als u net de insolatie heeft vervangen, heeft dit minder prioriteit.

1	Isolatie
2	Ramen
3	Warmte levering
4	Zonne-energie systemen
5	Verlichting
6	Koude levering
7	Ventilators

Appendix H - *Questionnaire Freudenthal UU*

Demografische informatie		
Naam kantoorpand:	UU Freudenthal	
Adres	Princetonplein 5, Utrecht	
Bouwjaar	1975	
Aantal maanden pand is in gebruik	12	maanden

Kantoorpand constructie eigenschappen			
Oppervlakten en maten			
Totale vloeroppervlakte kantoorpand	4578	m^2	
Vloeroppervlakte begane grond	563	m^2	
Kruipruimte aanwezig?	☑ Ja	☐ Nee	
Hoogte kantoorpand	28	m	
Hoogte per verdieping	3.5	m	
Oppervlakte buiten muren (incl. ramen/deuren)	2576	m^2	
Oppervlakte dak	563	m^2	
Oppervlakte ramen grenzend aan buiten	1288	m^2	
Issolatie waarden	**U**	**Indien bekend, vul hier in**	
Vloer	1.923		W/m^{2}K
Muren	0.769		W/m^{2}K
Dak	0.769		W/m^{2}K
Eventueel renovatie jaar			
Type vloer, plafond en gevel			
Massa van vloerconstructie [kg/m^2]	Meer dan 400 (steenachtig)		
Type plafond	Gesloten plafond		
Gevel type	Standaard gevel		
Ramen			
Type beglazing	Dubbel glas		
Zonwering aanwezig (aan de buitenkant)?	☑ Ja	☐ Nee	
Zo ja, type zonwering	Buitenzonwering met handbediening		

Kantoorpand installaties			
Klimaat systeem nr	3		Zie tab Climate system nr
Warmte en koude voorziening			

Type verwarmingsinstallatie	Warmte levering door derden	
Individuele regeling verwarming	☑ Ja	☐ Nee
Koude leverancier	Compressiekoelmachine	
Oppervlakte van gekoelde zones	1141	m^2

WKK

Aanwezig?	☐ Ja	☑ Nee
Elektrisch vermogen		kW
Thermisch vermogen		kW
Soort distributie		

Gedetailleerde informatie warmte voorziening

Warmtepomp

Bron

Brandstof

Temperatuur niveau warmteaanvoer

Ketel

Type ketel

Temperatuur niveau warmteaanvoer

Een of meer centrale verwarmingstoestellen die warmte leveren voor een oppervlakte van

Stoomketel

Economizer

Luchtvoorverwarmer

Heetwaterketel

Rookgascondensor

Ventilatoren

Type ventilatie systeem	Mechanische toe- en afvoer zonder recirculatie of warmteterugwinning
Provision in ventilation system	Geen debietregeling of recirculatie
Regeling	Geen regeling of smoorregeling
Systeem type warmte terugwinning	Geen warmteterugwinning
Ventilatie voorziening voor koelbehoefte	Te openen ramen

Bevochtiging

Type bevochtigingsinstallatie	Elektrisch gevoede stoombevochtiging
Vochtterugwinning	Zonder

Warm tap water

Type toestel	Elektrische boiler
Distributie systeem	Een of meerdere tappunten op een afstand van meer dan 3 m van het opwekkingstoestel

Zonne-energie systemen

Zonnepanelen			
Aanwezig	☐ Ja	☑ Nee	
Type zonnepaneel			
Indien anders, piekvermogen		W/m^2	
Oppervlakte paneel		m^2	
Orientatie			
Hellingshoek			
Zonne collector			
Aanwezig	☐ Ja	☑ Nee	
Oppervlakte paneel		m^2	
Verlichting (zie box rechts)	-	-	-
Totaal geinstalleerd vermogen verlichting	-	-	-
Conventioneel	64.35	kW	
LED	0	kW	
Armatuurtype	Overige gevallen		
Type regeling/schakeling	Vertrekschakeling		
Bewegingsmelders	Geen aanwezigheidsdetectie		

Voorkeuren renovatie – financele manager

Verdeel 100 punten over de onderstaande criteria. Diegene die voor u het belangrijkste is, vul daar de meeste punten in. De tweede belangrijkste iets minder en zo verder.

	Punten	***Voorbeeld***
Laagste inversteringskosten	20	*50*
Snelste terug verdientijd	0	*20*
Laagste onderhoudskosten	50	*0*
Reductie van CO2 uitstoot	10	*10*
Reductie van energie gebruik	20	*20*
	100	

Als laatste wil ik u vragen de verschillende renovatie mogelijkheden te rangschikken op prioriteit. Zet op nummer 1 dat gene neer wat u het liefst aangepakt ziet worden. Op nummer 7 diegene die het laatste gedaan moet worden. Bijvoorbeeld als u net de isolatie heeft vervangen, heeft dit minder prioriteit.

1	Installaties
2	Isolatie
3	
4	
5	
6	
7	

Voorkeuren renovatie – technisch onderhoudsmanager

Verdeel 100 punten over de onderstaande criteria. Diegene die voor u het belangrijkste is, vul daar de meeste punten in. De tweede belangrijkste iets minder en zo verder.

	Punten	***Voorbeeld***
Laagste inversteringskosten	0	*50*
Snelste terug verdientijd	30	*20*
Laagste onderhoudskosten	40	*0*
Reductie van CO2 uitstoot	20	*10*
Reductie van energie gebruik	10	*20*
	100	

Als laatste wil ik u vragen de verschillende renovatie mogelijkheden te rangschikken op prioriteit. Zet op nummer 1 dat gene neer wat u het liefst aangepakt ziet worden. Op nummer 7 diegene die het laatste gedaan moet worden. Bijvoorbeeld als u net de isolatie heeft vervangen, heeft dit minder prioriteit.

1	Warmte voorziening
2	Verlichting
3	Koude voorziening
4	Zonne-panelen
5	
6	
7	

Appendix I - *Questionnaire Office SPIE*

Demografische informatie		
Naam kantoorpand:	Kantoor SPIE	
Adres	Kobaltweg 59-61 Utrecht	
Bouwjaar	1992	
Aantal maanden pand is in gebruik	0	maanden

Kantoorpand constructie eigenschappen			
Oppervlakten en maten			
Totale vloeroppervlakte kantoorpand	4377	m^2	
Vloeroppervlakte begane grond	2935	m^2	
Kruipruimte aanwezig?	☑ Ja	☐ Nee	
Hoogte kantoorpand	14	m	
Hoogte per verdieping	3.25	m	
Oppervlakte buiten muren (incl. ramen/deuren)	1821	m^2	
Oppervlakte dak	630	m^2	
Oppervlakte ramen grenzend aan buiten	486	m^2	
Issolatie waarden	**U**	**Indien bekend, vul hier in**	
Vloer	0.395		W/m^2K
Muren	0.395		W/m^2K
Dak	0.395		W/m^2K
Eventueel renovatie jaar			
Type vloer, plafond en gevel			
Massa van vloerconstructie [kg/m^2]	Meer dan 400 (steenachtig)		
Type plafond	Gesloten plafond		
Gevel type	Standaard gevel		
Ramen			
Type beglazing	Dubbel glas		
Zonwering aanwezig (aan de buitenkant)?	☑ Ja	☐ Nee	
Zo ja, type zonwering	Buitenzonwering met handbediening		

Kantoorpand installaties		
Klimaat systeem nr	3	Zie tab Climate system nr
Warmte en koude voorziening		
Type verwarmingsinstallatie	Locale gasverwarming of olieverwarming	

Individuele regeling verwarming	☑ Ja	☐ Nee
Koude leverancier	Compressiekoelmachine	
Oppervlakte van gekoelde zones		m^2

WKK

Aanwezig?	☐ Ja	☑ Nee
Elektrisch vermogen		kW
Thermisch vermogen		kW
Soort distributie		

Gedetailleerde informatie warmte voorziening

Warmtepomp

Bron

Brandstof

Temperatuur niveau warmteaanvoer

Ketel

Type ketel

Temperatuur niveau warmteaanvoer

Een of meer centrale verwarmingstoestellen die warmte leveren voor een oppervlakte van

Stoomketel

Economizer

Luchtvoorverwarmer

Heetwaterketel

Rookgascondensor

Ventilatoren

Type ventilatie systeem	Mechanische toe- en afvoer zonder recirculatie of warmteterugwinning
Provision in ventilation system	Geen debietregeling of recirculatie
Regeling	Geen regeling of smoorregeling
Systeem type warmte terugwinning	Geen warmteterugwinning
Ventilatie voorziening voor koelbehoefte	Ventilatieroosters

Bevochtiging

Type bevochtigingsinstallatie	Geen bevochtiging
Vochtterugwinning	

Warm tap water

Type toestel	Gas boiler, geiser, HR-ketel met cv-boiler, HR combi
Distributie systeem	Een of meerdere tappunten op een afstand van meer dan 3 m van het opwekkingstoestel

Zonne-energie systemen

Zonnepanelen

Aanwezig	☐ Ja	☑ Nee	
Type zonnepaneel			
Indien anders, piekvermogen		W/m^2	
Oppervlakte paneel		m^2	
Orientatie			
Hellingshoek			

Zonne collector

Aanwezig	☐ Ja	☑ Nee	
Oppervlakte paneel		m^2	

Verlichting (zie box rechts)	-	-	-
Totaal geinstalleerd vermogen verlichting	-	-	-
Conventioneel	43.62	kW	
LED		kW	
Armatuurtype	Overige gevallen		
Type regeling/schakeling	Centraal aan/uit		
Bewegingsmelders	Aanwezigheidsdetectie		

Voorkeuren renovatie

Verdeel 100 punten over de onderstaande criteria. Diegene die voor u het belangrijkste is, vul daar de meeste punten in. De tweede belangrijkste iets minder en zo verder.

	Punten	***Voorbeeld***
Laagste inversteringskosten	30	*50*
Snelste terug verdientijd	20	*20*
Laagste onderhoudskosten	20	*0*
Reductie van CO2 uitstoot	10	*10*
Reductie van energie gebruik	20	*20*
	100	

Als laatste wil ik u vragen de verschillende renovatie mogelijkheden te rangschikken op prioriteit. Zet op nummer 1 dat gene neer wat u het liefst aangepakt ziet worden. Op nummer 7 diegene die het laatste gedaan moet worden. Bijvoorbeeld als u net de insolatie heeft vervangen, heeft dit minder prioriteit.

1	Ramen
2	Verlichting
3	Zonne-energie systemen
4	Koude levering
5	Warmte levering
6	Ventilators
7	Isolatie