Environmental Impacts of Subsurface Buildings

Comparing the environmental impacts of a subsurface building with an aboveground building using LCA

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Executive Summary

Population growth, increasing prosperity and urbanization are major challenges for the future that put pressure on land availability. Creating more high rise buildings is one option, but also the less explored subsurface construction could provide an increasing possibility. The question, however, is how subsurface construction compares environmentally to aboveground construction. In this research this is examined for a supermarket using the following research question:

"How does a subsurface supermarket compare environmentally with an aboveground supermarket?"

To give an answer to this question the LCA methodology was used. A subsurface supermarket in Brielle was used as a case study. An aboveground supermarket was designed based on the subsurface supermarket and used for comparison. The material use, energy use, transportation, and excavation were the elements of the life cycle that were examined within this research.

Results were obtained using the software program SimaPro8. The impact methodology chosen was the Hierarchist version of the ReCiPe midpoint methodology with the normalisation values of Europe. Results showed that the electricity use was the determining factor that caused the subsurface supermarket to come out worse. In practice, however, the parking space of the aboveground supermarket could also be placed on top or under the supermarket due to land availability. The elevators, which were the major cause of the electricity difference, would then also be needed for the aboveground building. The materials used in the housing body of the supermarket showed a more positive result for the subsurface supermarket, which was caused by the piles underneath the supermarket. The subsurface supermarket then still provides opportunities for the future. Uncertainties in the data and assumptions, like the lifetime, could in the end be an important factor in the chances of subsurface construction.

Also missing information and impacts not taken into account by the LCA could change the result. Social and local impacts were not taken into account by the LCA. A social LCA or environmental impact assessment could give more insight in this. The depth and climate at which a subsurface building is located can be important factors to examine in the future. The technical feasibility of subsurface construction is also dependant on underground site characteristics and thus might not be an option for every location.

Key words: Environmental impacts, subsurface construction, LCA, ReCiPe

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Abbreviations

AITES	Association Internationale des Tunnels et de L'Espace Souterrain
CBS	Centraal bureau voor de Statistiek (English: Statistics Netherlands)
CED	Cumulative Energy Demand
CHP	Combined Heat and Power
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EPD	Environmental Product Declaration
GWP	Global Warming Potential
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	the International Organization for Standardization
ITA	International Tunnelling and underground space Association
KNMI	Koninklijk Nederlands Meteorologisch Instituut (English: Royal Netherlands Meteorological Institute)
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory analysis
LCIA	Life Cycle Impact Assessment
NAP	Normaal Amsterdams Peil (English: Amsterdam Ordnance Datum)
NVOE	Nederlandse Vereniging voor Ondergrondse Energieopslagsystemen (English: Dutch Association for Underground Energy storage systems)
ODP	Ozone Layer Depletion Potential
PCR	Product Category Rules
RVS	Roestvast staal (English: Stainless steel)
tkm	tonne-kilometre
UHI	Urban Heat Islands
UN	United Nations
US	United States
XPS	Extruded polystyrene
WMO	World Meteorological Organization

List of Symbols

Symbol	***Definition***	***SI Units***
b	Width	m
L	Length	m
h	Height	m
d	Thickness	m
□	Both the length and width of a square	m
Ø	Diameter	m
D	Diameter	m
A	Area	m^2
Aa	Area of minimal needed reinforcement	m^2
V	Volume	m^3
ρ	Density	$kg*m^{-3}$
g	Gravitational acceleration = 9.81 $m*s^{-2}$	$m*s^{-2}$
F	Force	N
m	Mass	kg
Q	Heat flow	W
λ	Thermal conductivity	$W*m^{-1}*K^{-1}$
k	Heat transmission coefficient = λ/d	$W*m^{-2}*K^{-1}$
$k_{c,I}$	Heat transmission coefficient of convection inside the wall	$W*m^{-2}*K^{-1}$
$k_{c,o}$	Heat transmission coefficient of convection outside the wall	$W*m^{-2}*K^{-1}$
R	Thermal resistance	m^2*K*W^{-1}
α	The thermal diffusivity	m^2*day^{-1}
C_M	Specific heat capacity	$J*kg^{-1}K^{-1}$
C_V	Volumetric heat capacity	$J*m^{-3}K^{-1}$
t	Time of the year, where t = 0 at midnight of December 31st	days
t_0	The phase constant (day of minimum surface temperature)	days
T	Temperature	K
ΔT	Temperature difference	K
$T_{(x,t)}$	Subsurface temperature at depth x and time t	°C
T_m	The average surface ground temperature in degree Celsius	°C
HDD	Heating Degree Days	°C
CDD	Cooling Degree Days	°C
A_s	The annual temperature amplitude at the surface (x = 0)	°C
e	The Euler's number	Constant

1. Introduction

The world today faces some major challenges related to sustainability, which need to be solved in order to develop a sustainable future for coming generations. Before these challenges are given it is important to know what is meant by a sustainable development. According to the World Commission on Environment and Development (1987) a sustainable development is described as: "a development that meets the needs of the present without compromising the ability of future generations to meet their own needs". It is thus not a problem to use everything the earth provides, but it has to be used in the correct way to ensure people can live on the planet for many generations to come. Using the earth the correct way is exactly what causes the major challenges. These challenges ahead are distinguished in different directions, namely (World Commission on Environment and Development, 1987):

1. Population and Human Resources
2. Food Security
3. Species and Ecosystems
4. Energy
5. Industry: Producing More with Less
6. The Urban Challenge

Buildings are largely affected by these challenges. According to the World Urbanization Prospects report (2012) from the United Nations (UN) and the Emission Scenarios report (2000) from the Intergovernmental Panel on Climate Change (IPCC) the population size will increase until at least 2050. These organizations, furthermore, expect that more urbanization will be going to take place in the same period of time. This urbanization will not only be caused by an increase of the population, but also due to rural to urban migration. All these people need a lot of space, whether it is for working, living, entertainment or other reasons. A large area of land would be required to create this space, which in turn will put pressure on other species and ecosystems that, as a result of this pressure, might disappear. In order to leave space for these species and ecosystems, constructions should be made more creative by placing more people on a smaller area of land. Nowadays this is already done by using high rise buildings. It can, however, be questioned if this is really a sustainable way of building because building more high rise buildings will, for example, increase the Urban Heat Islands (UHI) effect (EPA, 2008a).

According to the United States (US) Environmental Protection Agency (EPA) (EPA, 2008a) an UHI is: "An urban or suburban area that experiences elevated temperatures compared to its outlying rural surroundings". The UHI effect is caused by the fact that exposed urban surfaces, like roofs and pavement, are heated by the sun to higher temperatures then air is. The more exposed buildings are located in an environment, the larger this effect will be. Increasing or building more high rise buildings will thus increase the UHI effect. Next to increasing the UHI effect by increasing the heating rate, taller buildings also slow the cooling rate in the cities because heat has to cross a larger distance to escape. Building more high rise buildings could thus have a major impact on global temperatures (EPA, 2008a). To reduce the UHI effect, buildings need to be changed. This can be done by, for example, constructing buildings based on new materials. Another option to reduce the UHI effect would be to build in the subsurface instead of aboveground. This option has not yet been explored much, which means less knowledge about it is available. One of the knowledge gaps in subsurface buildings is their sustainability. To really see subsurface construction as an option for a sustainable future it has to be known how sustainable subsurface buildings are compared to aboveground buildings.

Earlier research by van Dronkelaar et al. (2014) compared the energy demands for heating and cooling in buildings in the subsurface and aboveground. Using monthly calculations from EN-ISO 13790, van Dronkelaar et al. (2014) examined the heating and cooling demand of buildings that have a different functionality, and are located in different climates and at different depths. For the research a total of 540 different cases were then obtained for which the indoor temperature was kept stable at 24°C and, looking at potential energy losses and gains, the energy use for cooling or heating was calculated. This differs from research by Pieters (2013), who compared the heat losses through the walls in subsurface and aboveground buildings. For this research a much simpler calculation is used in combination with the heat loss simulation program COMSOL. Results, based on yearly calculations, showed that heat losses from the building heat up the soil around it. The more the soil was heated the less the energy loss of the building. In the end both authors are positive about the difference in heating and cooling of subsurface buildings compared to aboveground ones. Looking at the heating and cooling of the building, building in the subsurface would then be a more environmental friendly way of building. This, however, is only a small part of the environmental impact of a building. The building also has to be constructed and destructed and this also uses e.g. energy and resources. What if the difference in energy use, in the construction and destruction phases of the two buildings, is so much more profitable for the aboveground building that it exceeds its losses in the energy use for heating and cooling? This would mean the subsurface building would not score better on energy. And what if the subsurface building would be scoring better on energy? Then it still does not say it is more environmental friendly. Maybe the subsurface building uses more toxic materials or it uses more scarce materials. Looking at the energy use of a building is not enough to make a fair comparison about its environmental impact. So, how is a more fair comparison based on environmental impacts made then? Life cycle assessment (LCA) is these days one of the main methods used to assess the environmental impact of different types of products or services.

In short, LCA assesses the environmental impact of products or services by looking at the whole industrial system involved in the production, use and waste management of that product or service. Furthermore the LCA takes into account multiple impacts, which also include impacts that are not directly relating to energy use (Baumann & Tillman, 2004). Previous studies already performed a LCA on different types of buildings, at different locations and by using different LCA methodologies (Cuéllar-Franca & Azapagic, 2012; Ecofys, 2010; EPA, 2013; Zabalza et al., 2013). These studies, however, only focus on existing buildings that are located aboveground. There has not yet been any research that focused on a LCA for subsurface buildings. Neither has there been a comparison between subsurface buildings and aboveground buildings. Looking at the positive results from cooling and heating, it seems useful to examine the potential environmental impact between a subsurface and an aboveground building using the LCA methodology.

A building can, however, have multiple functions for which different requirements have to be met regarding the construction and operating conditions. In this research a shopping function, and to be even more specific a supermarket, was chosen based on the fact that this function is not obligated by law to have a certain amount of natural light entering the building (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2013). For other functions laws are present, which could make it more difficult to build these functions in the subsurface. For these functions laws would in the future need to change or technologies will be needed to send natural light in the subsurface. By choosing a supermarket laws would not have to be changed and new technologies, which might not even be optimized yet, would not have to be taken into account. This puts less pressure on data availability and creates a simplified comparison between subsurface and aboveground construction.

The main research question for this research then was as follows:

"How does a subsurface supermarket compare environmentally with an aboveground supermarket?"

This research focussed on the environmental impacts of a subsurface supermarket compared to an aboveground supermarket. This was done by using the LCA methodology. To make a correct comparison between the two supermarkets the most important functions of the supermarket were kept the same. The first sub-question was as follows:

- *What important functions of a supermarket building will lead to different results when building in the subsurface compared to aboveground construction?*

When these important functions were known, one case study in the subsurface was chosen and an aboveground supermarket was designed which was as much as possible comparable in these important functions. When the two supermarkets were known the life cycle of the two buildings was designed. The next sub-question was as follows:

- *What does the life cycle of a supermarket look like?*

When the life cycle was known, information was needed about the materials the supermarkets were built of. Not only were the types of materials important. The amounts of these materials also needed to be known. Furthermore, the processes used to construct and operate a subsurface and aboveground supermarket were important. In a full LCA disposal also would have been taken into account but because of data availability and time constraints this was not taken into account in this research. Furthermore, in many LCAs elementary inputs and outputs in the different phases are taken into account. Elementary flows, like for example water, were not taken into account in the use phase in this research. These were assumed the same between the two supermarkets or they were unknown. In the use phase only electricity and heating were taken into account, which are non-elementary flows. The elementary flows in the production or transport of the materials, in the construction works that were taken into account, and in the production of electricity were included. These were part of the processes and materials selected in the LCA. Processes and materials could differ for subsurface supermarkets compared to aboveground supermarkets, which gave the following two sub-questions:

- *What materials and what amount of these materials are used in the construction of the subsurface and the aboveground supermarket?*

- *Which processes are used to construct and operate a subsurface and an aboveground supermarket?*

The types and amount of materials, and the processes used to construct and operate the supermarkets were not actual environmental impacts. For this they still needed to be converted into environmental impacts. Different impact methodologies were available which include different environmental impacts and different values to calculate the results. Depending on the research an impact methodology and to be examined environmental impacts should be chosen. The next sub-question thus was as follows:

- *What impact methodology and environmental impacts are most suitable to examine the difference between a subsurface and an aboveground supermarket?*

This research is focussed on comparing how a subsurface supermarket performs environmentally compared to an aboveground supermarket. To make a good comparison it was important to observe where the strengths and weaknesses of the subsurface building are located. These could give directions for future research. This gave the following sub-question:

- *Which parts of the LCA of a subsurface supermarket have a higher impact than the aboveground supermarket and which parts have a lower impact?*

Some parts of the data used contained assumptions. These contain some uncertainty which could have had a large influence on the results. To ensure the trustworthiness of the results the sensitivity for change of some assumptions had to be checked. The final sub-question then became as follows:

- *How sensitive are the results to certain variables and assumptions?*

By answering the sub-questions it was possible to answer the main research question. The answer to the research question will contribute to the possibility of building supermarkets in the subsurface. This information can be important for a broad range of audience. Researchers in the field of subsurface construction can use the information to see if building in the subsurface, from an environmental perspective, has potential and if this is not the case, where major issues are located. Other researchers in the field of construction might also be interested, because building in the subsurface will need new types of building techniques or improvements in already existing building techniques. For politicians the results can be useful in the planning of future urban environments. Next to these groups also other people could be interested like for example architects. The results of this research can thus be useful for different types of audience. In the next chapter the theory and methodology that were used in the research will be elaborated on. Chapter 3 is the inventory analysis in which the data will be obtained and prepared for implementation in the LCA. Chapter 4 is a combination of the impact assessment and interpretation. Here the results will be presented and sensitivities will be analysed. Based on these results the conclusion (chapter 5), discussion (chapter 6) and recommendations (chapter 7) will be given.

2. Methodology

As explained in the introduction, in this research a comparison was made of the potential environmental impacts between an aboveground supermarket and a subsurface supermarket, using the LCA methodology. According to ISO 14040 (1997) LCA is a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". Thus, LCA is a tool that analyses the potential environmental impacts during a product's life cycle (Guinée et al., 2002; ISO, 1997). The life cycle of a product contains all the processes from cradle to grave. These processes can differ a lot between products. The main stages of a product's life cycle, or product system, are: Resource extraction, manufacturing, usage, and waste management (see figure 1) (Baumann & Tillman, 2004; ISO, 1997). The term product in LCA not only refers to material products but also to services. When talking about a product in this report, both material products and services are meant (Baumann & Tillman, 2004; Guinée et al., 2002). The LCA methodology consists of four steps: Goal and scope definition, inventory analysis, impact assessment, and interpretation (see figure 2) (Baumann & Tillman, 2004; ISO, 1997). Sometimes the "goal and scope definition" is separated in two phases (Wolf et al., 2010). The LCA framework will form the backbone of this report.

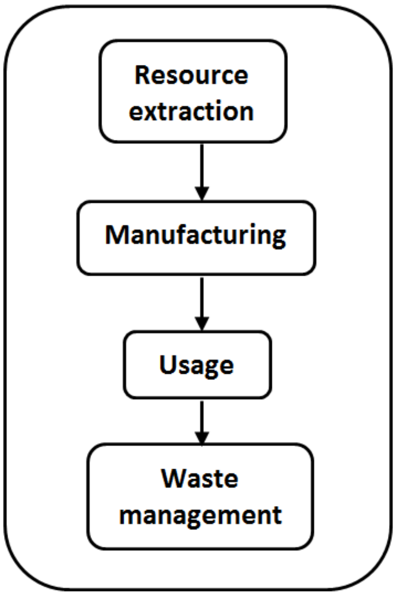

Figure 1 Main stages in the product system.

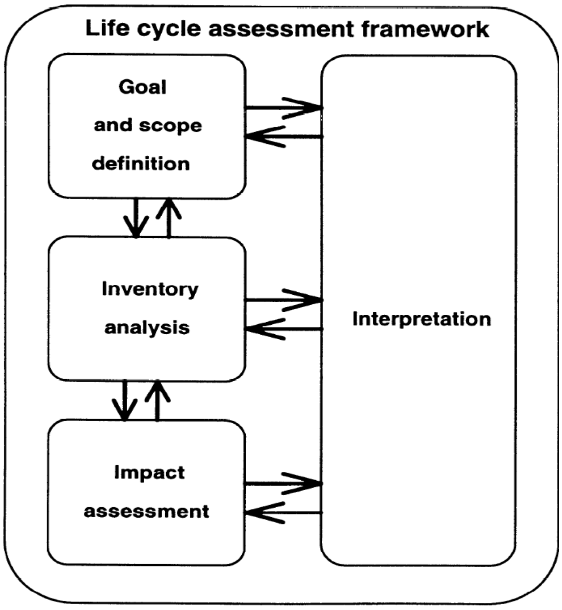

Figure 2 Phases of the LCA framework.

2.1 Goal and scope definition

In the goal and scope definition phase of the LCA, the initial decisions related to the work plan (e.g. the product studied, purpose of the study, location of the study) for the LCA were made (Baumann & Tillman, 2004; Guinée et al., 2002; ISO, 2006). According to some ISO standards (ISO, 1997, 1998, 2006), Baumann and Tillman (2004), and Guinée et al. (2002) the goal definition has three aspects. ISO 14044 (2006) contains an additional aspect bringing the total to four:

- The intended application
- The reasons for carrying out the study
- The intended audience, i.e. to whom the results are intended to be communicated
- Whether the results are intended to be used in comparative assertions intended to be disclosed to the public (added by ISO 14044 (2006))

In the introduction these four aspects were used to define the goal of this research. The next step was the scope definition. In the scope definition specific choices have been made. According to ISO 14040 (1997), Baumann and Tillman (2004), and Guinée et al. (2002) the following aspects should have been taken into account in the scope definition:

- The function of the system and functional unit used.
- The product system to be studied and its system boundaries
- The types of impact and the methodology of impact assessment, and subsequent interpretation to be used.
- Data requirements and allocation procedures
- Assumptions and limitations
- The initial data quality requirements
- The type of critical review, if any
- The type and format of the report required for the study

2.1.1 The function and functional unit

The amount of aspects to be taken into account shows that there were a lot of choices that had to be made. Before all these choices could have been made accurately, the products to be examined had to be clear and comparable. The products in this research were an aboveground and a subsurface building. In LCA the function of these products needs to be the same as much as possible. The function in case of a building actually explains what the building is used for, like for example an office, a residential house, a shop, an educational building, etc. In theory, the function of the system clearly specifies the primary function(s) (performance characteristics) that need to be or are fulfilled by the (product) system that is being studied (Guinée et al., 2002; ISO, 1997, 1998, 2006). This means that taking a building as a product system would not have been specific enough, because their functions differ based on their application. The product system chosen in this research was a supermarket, whose function is to *"Provide a comfortable environment to obtain provisions"*. Following this function, the functional unit defines the quantification of the specified function. The functional unit used was: *"a net* m^2 *of comfortable retail floor space to obtain provisions for 100 years"*. This functional unit provides a reference to which all modelled flows (input and output) in the LCA study were normalized, which ensured that the LCA results were comparable (Baumann & Tillman, 2004; Guinée et al., 2002; ISO, 1997, 1998, 2006). To be able to use this functional unit it had to be known what a net area of retail floor space means. In this research it is a combination of the net floor space and the used floor space (Architectenweb, 2008; Calcsoft bv, 2014; Participaties.nl, 2014). It is the sum of all accessible floor space inside the building that enables customers to obtain provisions. This includes e.g. restrooms, offices, storage areas and ramps, but will exclude the area of stairs and elevators.

2.2 The product system to be studied

As explained earlier, the product system is actually the life cycle of a product, which can also be seen in the theory. According to Guinée et al. (2002), the product system is "the total system of unit processes involved in the life cycle of a product". ISO (1998) uses a different definition of a product system and states that it is a "collection of unit processes connected by flows of intermediate products which perform one or more defined functions". Both definitions explain that the product system contains all the processes that are involved in the entire life cycle of a specific product. The main stages of a product system were already shown in figure 1. This, however, was a very basic product system which is applicable to all types of products. Baumann and Tillman (2004) mention that it is very helpful to already make a first general flow chart of the system to be studied at a very early stage. Using the flow charts of The International EPD System (2014) and Khasreen et al. (2009)

a general flow chart of the product system examined, which was a supermarket, was designed (see figure 3). The flowchart shows the different phases that occur in the life cycle of a supermarket, including sub-phases like e.g. material manufacturing. In order to get a more specific flowchart for the product system under study, the product system was specified further. Although having a very specific flowchart, containing all sub-processes of the product system under study, seems useful, some parts of the product system might not even need to be examined. In practice, it is not always possible to examine the total product system due to several factors (e.g. data, time and cost constraints). These factors lead to system boundaries, which in turn define the unit processes that are included in the LCA (ISO, 1997, 1998, 2006). Some factors that influence the system boundaries include, the intended application of the study, cut-off criteria, the assumptions made, the intended audience, and the data and cost constraints (ISO, 1997). The application of the study, which was a comparison in this research, is thus important for the system boundaries. This was already taken into account in the following of this report where the cases are specified and the further methodology is explained.

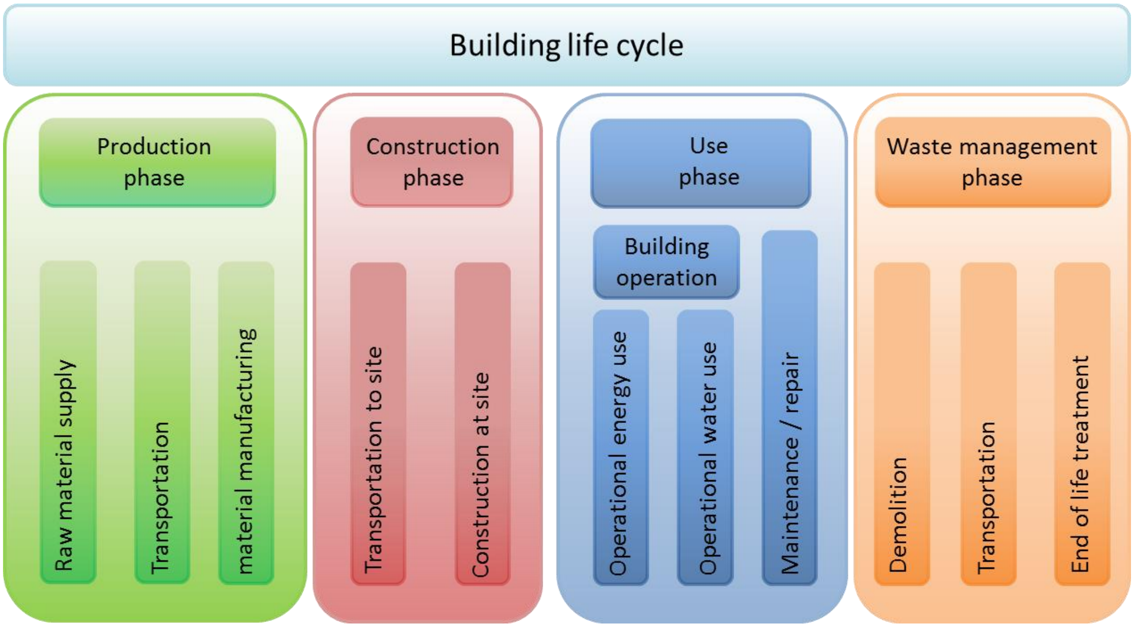

Figure 3 General life cycle of a building (Khasreen et al., 2009; The International EPD System, 2014).

The first boundary on the product system involves the waste management phase. Due to data and time constraints this phase was not examined within this research. The importance of examining the waste management phase can in the end be seen by looking at the impact of the construction phase. Both the construction and waste management phase are phases that have to be performed ones in the examined period of time. This is different from the use phase which has a constant impact over the examined period of time. As was the case for the waste management, data availability was also lacking for the maintenance and repair. In the baseline scenarios the lifetime of the materials was assumed the same, meaning the maintenance and repair would be the same. The lifetime of the materials was in the end changed, by changing the material use over the examined period of time, to see its effect. With maintenance and repair the materials would not be fully replaced. For maintenance and repair this was then probably an overestimation. Still the direction of the effect of maintenance and repair can be seen this way. The effect of maintenance and repair would be a fraction of the effect of full replacement of the materials.

The product system that was examined was specified based on the function of the building, which in this case was: *"Provide a comfortable environment to obtain provisions"*. In order to provide this comfortable environment, a building had to comply with certain building characteristics. There are five main building characteristics that were applicable to different types of building functions, namely light, ventilation, temperature, humidity and building strength (see figure 4). These building characteristics will most likely be the same within one function, but they will change between functions due to regulations. In the introduction an example was already shown based on the amount of natural light that has to enter a building due to regulations (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2013). In this research the same building function, a supermarket, was chosen, which meant the same regulations apply. Although the function was the same, the supermarkets could still differ. Take for example the strength of a supermarkets housing body. Regulations did not oblige any specific level of strength. The supermarket building just has to be safe. The strength of a building is determined by the forces that act on it, which means it is affected by the location and size of the building. A supermarket located in the subsurface thus has to withstand different forces than an aboveground supermarket, which means they need different housing bodies. If the housing body of a supermarket changes this has an effect on the heat loss of the building and thus on its environmental impact. According to The International EPD System (2014) the housing body includes the building structure such as number of storeys, structural frame and foundations, beams, columns, slabs, external and internal walls, windows, doors, stairs, roof, ceiling, floor, etc. This meaning for the housing body was also used in this research.

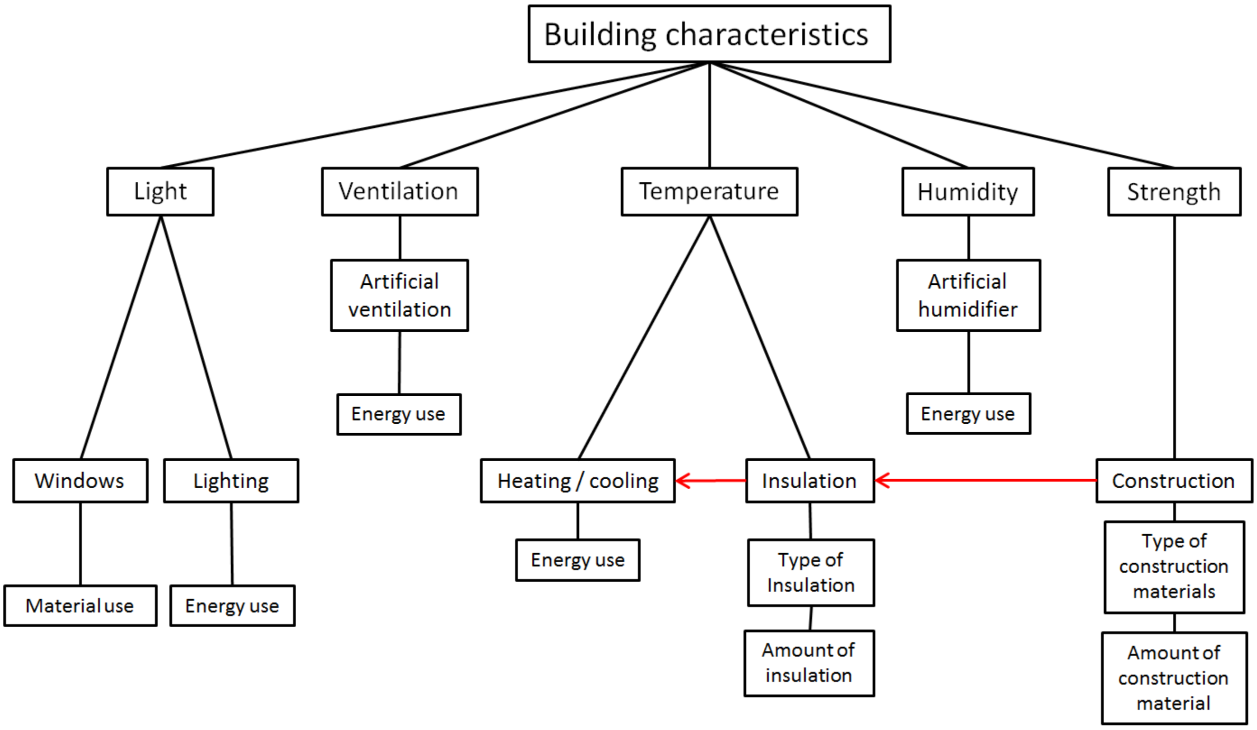

Figure 4 Building characteristics applicable to all building functions.

2.2.1 The case

To illustrate the difference in environmental impact between a subsurface and an aboveground supermarket, a case study was chosen. The subsurface case study in this research was a supermarket located in Brielle (Zuid-Holland). The supermarket was built in the year 2003 and it has an approximated area of around 2500 m^2 (HDK Architecten, 2014). For an aerial view of the supermarket see figure 5 (de Vette, 2004). The owner of the building explained how the idea of building subsurface came to mind (de Vette, 2014). According to him, he really saw potential in the location where the supermarket is build. The city walls of the city of Brielle are, however, a protected cityscape due to its value as cultural heritage, which means nothing can be build that impacts the sighting. A big supermarket aboveground would do exactly that, which led the municipality, province and other parties to not approve for a supermarket to be built there. As a joke the owner of the supermarket said to the major: “Then I will go under the ground”. The major responded that this was not a bad idea, which was the start of this building project. Although there was still some opposition against the newly planned supermarket, it in the end got approved and built (de Vette, 2014).

Figure 5 Aerial view of the subsurface supermarket in Brielle (courtesy: H. de Vette) (de Vette, 2004).

2.3 The system boundaries

With the subsurface case known, it was important to find an aboveground supermarket based on the available data of the subsurface building and set some system boundaries for the product in this research. As explained in paragraph 2.2, the system boundaries are influenced by factors like the intended application of the study, cut-off criteria, the assumptions made, the intended audience, and the data and cost constraints (ISO, 1997).

The intended application of the study was to see if building a supermarket in the subsurface or constructing it aboveground is better from an environmental point of view. Furthermore it was important to discover where possible environmental improvements are located in the LCA of a subsurface supermarket compared to an aboveground supermarket. This could in the end show some strengths and weaknesses of overall subsurface construction compared to aboveground construction. The intended application of the study was already specified when defining the research questions.

The cut-off criteria in LCA are criteria that decide which inputs are to be included in the assessment. These criteria can be based on e.g. mass, energy, and environmental significance (ISO, 1998, 2006). It was, however, not possible to already decide this at the start, because the inputs and outputs, that have the largest contribution in the product system, were unknown. The only thing known was that processes in the foreground system will probably be more important to take into account than processes in the background system. According to Wolf et al. (2010) the processes in the foreground system are specific for the analysed system i.e. own operations and fixed suppliers. For the supermarket, which is the product in this research, this includes for example the producer of the reinforcement steel for the floor. Processes in the background system are not specific but purchased via the market. This means the background system processes are further away from the actual product. For the supermarket this includes for example the production of iron, which is used for the steel. The fraction of iron in the housing body of the supermarket is smaller than the fraction of steel. The fraction of material from the background processes will thus be less than material from the foreground system. Even if the fraction of a material is only small, this material can still be significant depending on its environmental impact. Especially in a comparative LCA where large amounts of materials and processes are the same, the seemingly insignificant processes can play a major role. The significance of the different flows is thus not always known at the start of the LCA. Still, by doing a comparative LCA some major processes could be exactly the same and would then not be important to take into account because they would not influence the final results. This was very much dependent on the case studies found and the data available from these case studies. The data availability factor is mostly found in the inventory analysis phase of the LCA framework. Exact details about the system boundaries will then change according to the findings during the inventory analysis (Baumann & Tillman, 2004). In the end it is important that, when choosing the system boundaries, it is clearly stated why certain stages, processes, inputs or outputs are left out of the assessment. Furthermore, it must be explained what the implications are from leaving these out (ISO, 1997, 2006). By describing these boundaries in sufficient detail and clarity, it is possible for another practitioner to duplicate the inventory analysis (ISO, 1998). This, however, not only counts for the system boundaries but for all aspects in the scope definition. When the important aspects of setting system boundaries were known, some system boundaries were set.

2.3.1 Designing the aboveground supermarket

In order to really compare subsurface with aboveground construction an aboveground supermarket had to be found which only differed due to building subsurface. Otherwise the comparison was made between two supermarkets instead of two situations. The building itself did not have to be exactly comparable, because corrections could have been made. Take for example the energy use of a supermarket. This most likely depends on the size of the supermarket and on how it is used, which probably depends largely on the number of clients served by the supermarket. The energy use of a supermarket should thus directly change in proportion to the amount of people that use the supermarket. Looking deeper into the energy use of a supermarket shows that this assumption is simplistic. According to EPA (2008b) and EIA (2003) most electricity consumption in a supermarket comes from refrigeration (see figure 6). The type of refrigerators, including their characteristics, can be very different per supermarket. Taking all of this into account would have been possible, but it would also have used a lot of time. Next to this difficulty with refrigeration, it was also hard to obtain data for an aboveground supermarket. For these reasons it was assumed, in consultation with professional constructors, what the changes on the subsurface case study would be when it had been built aboveground. A simplified version of the subsurface supermarket was then designed for the aboveground using these changes. Aspects like for example the interior and the doors were assumed to be the same and thus not taken into account in the comparison.

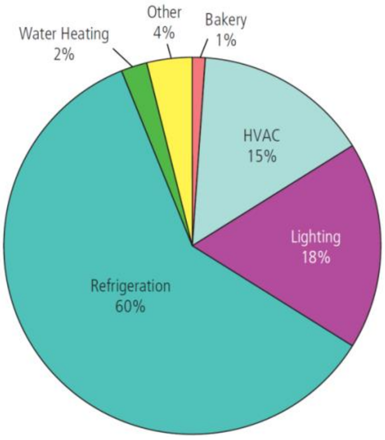

Figure 6 Electricity consumption in a supermarket by end use (EPA, 2008).

The first thing noticed when looking at the building was the top entrance, which has a lot of windows. Building the top part this way was a choice of the architect to make it look nice. Construction wise it has no effect on the difference between aboveground and subsurface construction. The top part could also just have been a concrete block. The whole part above the roof of the supermarket (above "peil" in the drawings obtained from de Vette (2004)) was thus not taken into account in this research. This means the windows on the "Thoelaverweg" side of the building were taken into account. When constructing the same supermarket aboveground these windows, that let natural light enter the supermarket, have been kept the same. Supermarkets generally are not designed efficiently regarding the amount of windows. The reason for this might be that supermarkets are often part of a commercial building with multiple functions. Furthermore, the earlier mentioned absent obligation for supermarkets, to have a certain amount of natural light entering the building, could play a role (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2013). Functions that are obligated by law will be placed where the light can enter, which leaves the less lighted areas for the supermarket.

To transform the subsurface supermarket into an aboveground supermarket with a similar net retail floor space, the elevators and stairs would have to be taken out of the picture. These would not be needed in an aboveground building. Figure 7 shows a top view of the part of the building where these stairs and elevators are located. The blue lines indicate the areas at the surface level of the building that would need to be added to the shopping level when the building is build aboveground. These areas are used for the transformer room, the central heating system, a cold storage room, and the shopping carts. Figure 8 shows a top view of the supermarket at the shopping level. The blue lines indicate the areas that are used for stairs and elevators, including the machine room for the elevators. These would thus not be needed for the aboveground building. The blue areas from the subsurface level in figure 7 could be moved to the blue areas from the shopping level in figure 8. The blue areas in figure 7 and figure 8 do not differ much in area, which means that the total area of the aboveground building will not differ from the total area of the subsurface building.

Using figure 7 and figure 8 the net retail floor space can also be determined. The blue areas in figure 8 are part of the elevators and stairs. Elevators and stairs do not count in the net retail floor space, which meant the blue areas in figure 8 do also not count in the net retail floor space. The blue areas in figure 7 are, however, functional parts of the building that enable customers to obtain provisions. These count in the net retail floor space and were thus taken into account. The moving walks in the building are a ramp. The area underneath the moving walks is used for storage. Both storage areas and ramps need to be included in the net retail floor space. For this reason the area of the moving walks was also taken into account in the net retail floor space. The net retail floor space in this research then was the area within the green borders in figure 8. When it was known what the aboveground building area looked like and what the net retail floor spaces were, it was important to look further into the materials used in the building and how these were taken into account.

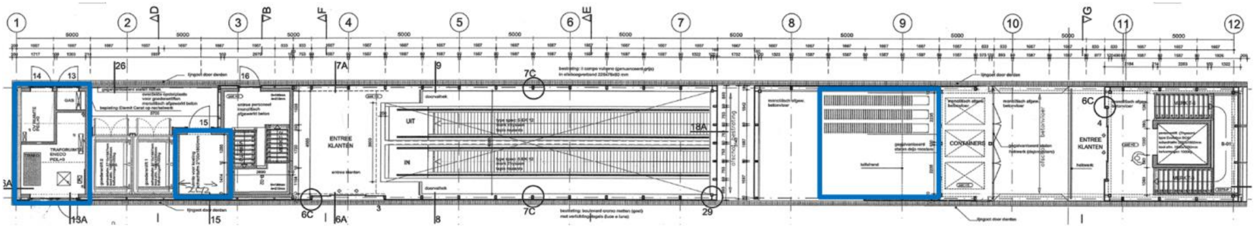

Figure 7 Top view drawing of the entrance at the surface level of the subsurface supermarket in Brielle. In blue are the areas used for the transformer room, the central heating system, a cold storage room, and the shopping carts (de Vette, 2004).

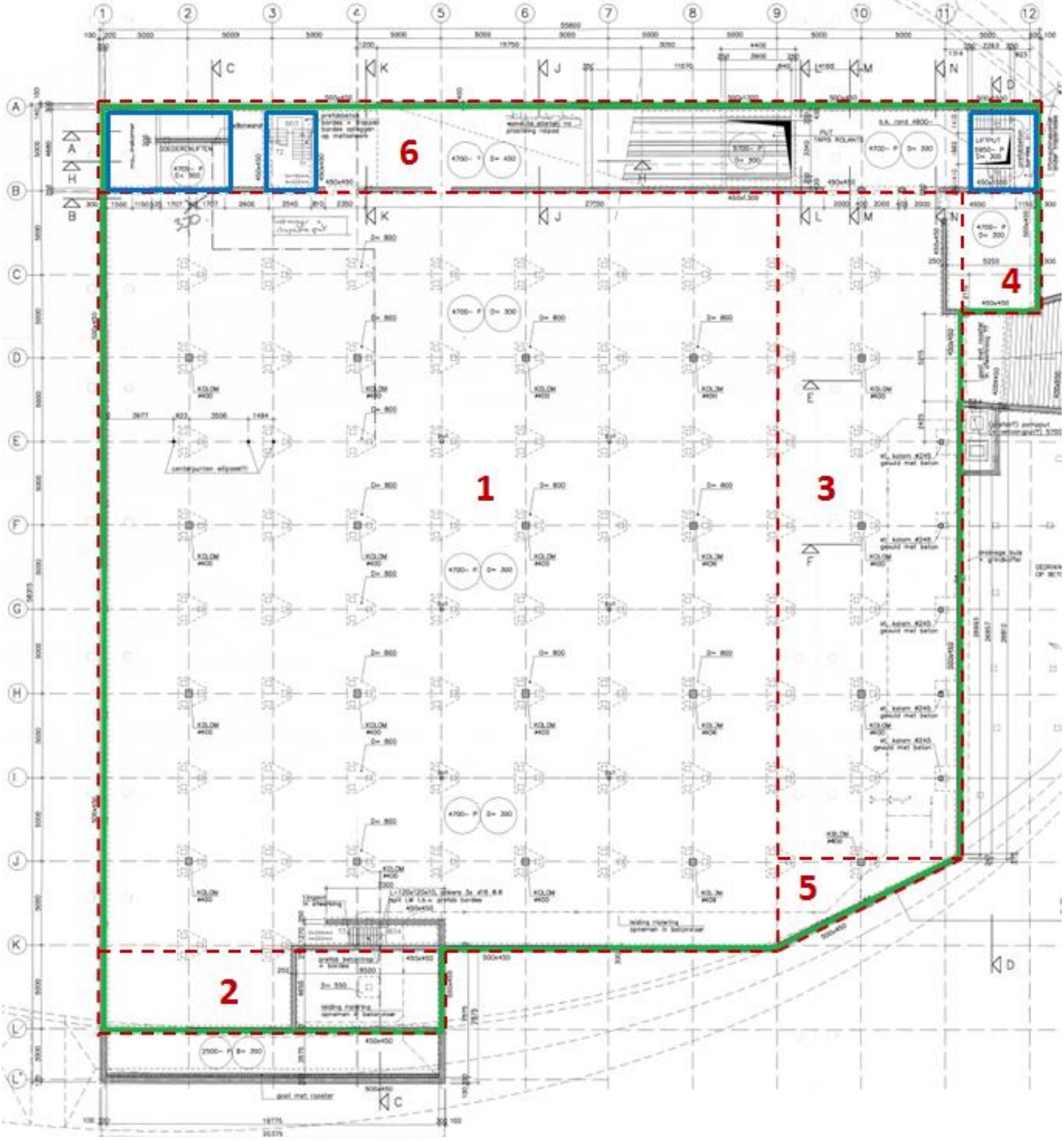

Figure 8 Top view drawing of the supermarket at the shopping level of the subsurface supermarket in Brielle. Green area is the net retail floor space and the red areas are the calculated areas that were added up to obtain the green area. The blue areas are the areas used for elevators and stairs (de Vette, 2004).

2.3.2 Boundaries regarding material use

The housing body of the supermarket is mainly composed of steel and concrete. In consultation with the IOB (2014), who was the constructor of the subsurface supermarket, it was determined that building in the subsurface uses 1.5 times the amount of concrete and steel for the walls, roof, floor and columns as would have been used for the aboveground structure. To obtain the amount of materials in the aboveground building, the amount of concrete and steel in the subsurface building was therefore divided by 1.5 (or multiplied with 0.67). Instead of only taking this factor into account, three scenarios were made with different factors for the concrete and steel in the aboveground structure, namely a factor 1, 1.5 and 2. The factor 1.5 is then the default factor used in this research. Next to adding these factors, the roofs in both buildings will fully cover the supermarket by the same composition of prefab concrete panel. If this would not be done there could be a large uncertainty in the calculations of the heat loss. The openings in the roof of the subsurface building are openings for the elevators and stairs, which need to be covered from different types of weather. This meant assuming a closed roof is actually assuming a roof on top of these stairs and elevators. When visualizing this new situation it would show that the elevators are just covered by a prefab concrete panel and no other constructions are located at the surface. To correct the concrete and steel use in the roof their amounts were divided by the area of prefab roof panels and multiplied by the floor area.

For the piles that support the aboveground building, the piles of the subsurface building cannot be multiplied by factors to obtain the amount of materials used in the aboveground building. In this research the number and length of piles were changed and this was calculated according to appendix B.5 for the different scenarios. Not all piles were, however, changed in this research. Some piles were not really carrying the building itself but the surroundings. It was assumed these are the same when building aboveground, so they do not play a role in the difference between building aboveground or subsurface. To create a good picture of the material use in the building, these piles were still taken into account in the same volumes as the subsurface ones.

As explained earlier, the elevators and stairs would not be needed in the aboveground building. The material use for the stairs was thus not taken into account in the aboveground building. For the elevators the material use was not taken into account for both buildings, because this was impossible to figure out in the time span available for this research. For the elevators the electricity use was, however, taken into account by subtracting it from the electricity use from the subsurface building to obtain the electricity use without elevators of the aboveground building. This is explained in appendix C.2. This, however, was not the final electricity use of the aboveground building. Corrections for the electricity use of air-conditioning were still needed. This is explained in the next paragraph. When the design of both buildings and the material usage of their housing body were known, the further examination of the characteristics was performed, which included the heating, cooling and the construction activities for the building.

2.3.3 Boundaries regarding energy use and construction

In a supermarket the temperature is normally kept constant over the year with a centralized system. Because the temperature is kept stable, the windows do not have to be opened during the year. Natural ventilation will then only occur through doors that open. This will be the case for both the aboveground and the subsurface building, which meant ventilation did not have an effect on the LCA. Ventilation systems are most times linked to humidifiers which stabilize the humidity in buildings. The humidity can change due to water moving through the outer walls, leakages and ventilation. It is assumed the building is constructed correctly and no leakages occur. Furthermore, it is assumed the water movement trough the wall is the same for both buildings. Both buildings should be designed in a way that this water flowing through the wall is at the same level. A very small difference between the two buildings might be possible due to groundwater in the subsurface. This is assumed negligible. Because no windows open, humidity in the building did not differ between the aboveground and subsurface building. Windows also make sure natural light enters the building. As explained earlier, in this research the same amount windows, and thus natural lighting, was assumed. Both buildings would then need the same amount of artificial lighting. Lighting, ventilation and humidity were thus most likely not important to take into account in this comparative research.

Where lighting, humidity, and ventilation were expected to be comparable, this was not the case for the temperature change within the building. As mentioned in the introduction, earlier research by van Dronkelaar et al. (2014) and Pieters (2013) has shown that the heat loss differs between subsurface and the aboveground buildings. Both researches did not take into account any changes in the building envelope. The building envelope includes only the walls, floors, roof and windows, which makes it different from the housing body. Thicker walls in either the aboveground or the subsurface building create already more insulation, which means the outer construction also has an effect on the insulation. The amount of insulation and the type of insulation installed, combined have an effect on the heat transfer between the building and its surroundings. The following temperature increase or decrease in the building has to be regulated by artificial heating or cooling. In figure 4 the red lines show that the construction, or in this case the housing body, has an effect on insulation, which in turn has an effect on the heating and cooling demand. These energy uses were calculated using the heat losses of both buildings.

As explained earlier, in this research an existing subsurface supermarket was used as a case and an aboveground supermarket was designed. Next to the concrete and steel that create a small insulation layer the subsurface supermarket also had an extra insulation layer which is better in preventing heat loss. This insulation layer differed in type and amount for walls, floor and roof. The thickness and specific type of insulation of the walls and floor was not available in the data obtained. For this reason three scenarios were used in this research for the thickness of the insulation in the walls and floor. The manufacturer of this floor and wall insulation was Rockwool B.V., which produces stone wool insulation. The main scenario contained 80 mm of wall insulation of product number 123 and 80 mm of floor insulation of product number 211 Vario. The other two scenarios contained no wall and floor insulation at all and 110 mm of wall insulation of product number 123, and 120 mm of floor insulation of product number 211 Vario. Rockwool number 123 has a density of 23 kg*m^{-3} and a thermal conductivity of 0.040 W*m^{-1}*K^{-1}, and Rockwool number 211 Vario has a density of 45 kg*m^{-3} and a thermal conductivity of 0.034 W*m^{-1}*K^{-1} (de Vette, 2004; Isorex, 2014). From the insulation of the roof only an advice was available which said extruded polystyrene (XPS) should be used and to be more specific the XPS 500. For the thickness of the insulation layer it was advised that the layer should have a thermal resistance bigger than 2.5 m^{2}*K*W^{-1} (de Vette, 2004). To calculate the thickness of the layer the thermal conductivity of the XPS 500 needed to be known. As an assumption information of the Gematherm XC5 from Sirap Insulation was used (Nofisol Group, 2014). This has a thermal conductivity of 0.036 W*m^{-1}*K^{-1} and a density of 33 kg*m^{-3}. Using formula 1 this gave a thickness of 90 mm of XPS at the roof. The advice, however, also explained that the thickness of the insulation should be increased by 50% to ensure a high enough resistance of the insulation over a longer time period (de Vette, 2004). A thickness of 135 mm for the roof insulation was thus used in this research. Table 1 shows the examined compositions of the building envelope using different scenarios that were examined within this research.

Formula 1 Determination of the minimal thickness of the XPS using the advice of BDA dakadvies B.V.

$$d = \frac{\lambda}{k} = \frac{\lambda}{R^{-1}} = \frac{0.036}{2.5^{-1}} = \frac{0.036}{0.4} = 0.09m = 90mm$$

In order to calculate the heat loss only additional information about the windows was still needed. The windows, delivered by van den Heuvel glas (de Vette, 2004), are double glazing laminated safety glass with brand name “SGG Parsol Groen Securit”. According to PRé Consultants bv (2014b), double glazing laminated safety glass has a heat transfer coefficient smaller than 1.1 W*m^{-2}*K^{-1}. This value was then used for the heat loss of the windows. With the structure of the building envelope known the heat loss of the building was calculated using the calculations in appendix C.1. The temperature change caused by the heat loss is regulated by artificial cooling and heating, which requires electricity and natural gas. The electricity and natural gas use could have been calculated using efficiencies for artificial cooling and heating. However, in this research the data was analysed using the LCA program SimaPro, in which the delivered energies, heat losses in this research, had to be filled in. No electricity and natural gas use then had to be calculated. In the next chapter, which is the inventory analysis, the data was examined. This produced values that were implemented in and analysed by SimaPro. This is the impact assessment step of the LCA framework.

Table 1 Examined compositions of the building envelope in different scenarios.

			Insulation thickness wall/roof (mm)		
			80/80	*0/0*	*110/120*
Aboveground material use factor in floor, roof and walls compared to subsurface	*Aboveground*[1]	0.67	Aboveground 1 (A1)	Aboveground 4 (A4)	Aboveground 5 (A5)
		1	Aboveground 2 (A2)		
		0.5	Aboveground 3 (A3)		
	Subsurface[2]	1	Subsurface 1 (S1)	Subsurface 2 (S2)	Subsurface 3 (S3)

2.4 The Life Cycle Inventory model

When the boundaries of the system were known, data was collected. The Life Cycle Inventory analysis (LCI) is the stage where the data collection and calculation procedures are presented. The steps that need to be followed in the LCI stage, according to ISO (1998, 2006), are shown in figure 9.

Before the data collection was started it was important to know what type of LCI modelling should be used. Scientists agree that there are two main types of LCI modelling, which are attributional and consequential LCA (Wolf et al., 2010). The attributional LCA is also referred to as “accounting LCA”, “book-keeping LCA”, “retrospective LCA”, or “descriptive LCA”. In this type of LCA the product, over its life cycle, is assigned (attributed) with a certain potential environmental impact. The product is assessed as it is or as it was. This means data used needs to be historical, fact-based, measurable data. For background processes two types of data can be used depending on the situation. According to Wolf et al. (2010) producer specific data is best to be used when specific producers provide a background service or good. This way the attributional LCA can make a more accurate distinction between, for example, products from different suppliers. For this reason producer specific data is mainly used for eco-labelling or market communication. If the good or service is delivered by a wide mix of producers or technologies, the average or generic data is used. The electricity use of a company, obtained from the grid, is for example almost impossible to trace back to the exact production source. Here the average electricity mix of a specific country would be used

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[1] In the aboveground building the stairs and elevators are not taken into account.

[2] In the subsurface building the stairs and elevators are taken into account.

(Wolf et al., 2010). The most widely used type of data for background processes in practice is the average data. According to Baumann and Tillman (2004) in attributional type LCA the producers of LCA information are not identical to the users of the information.

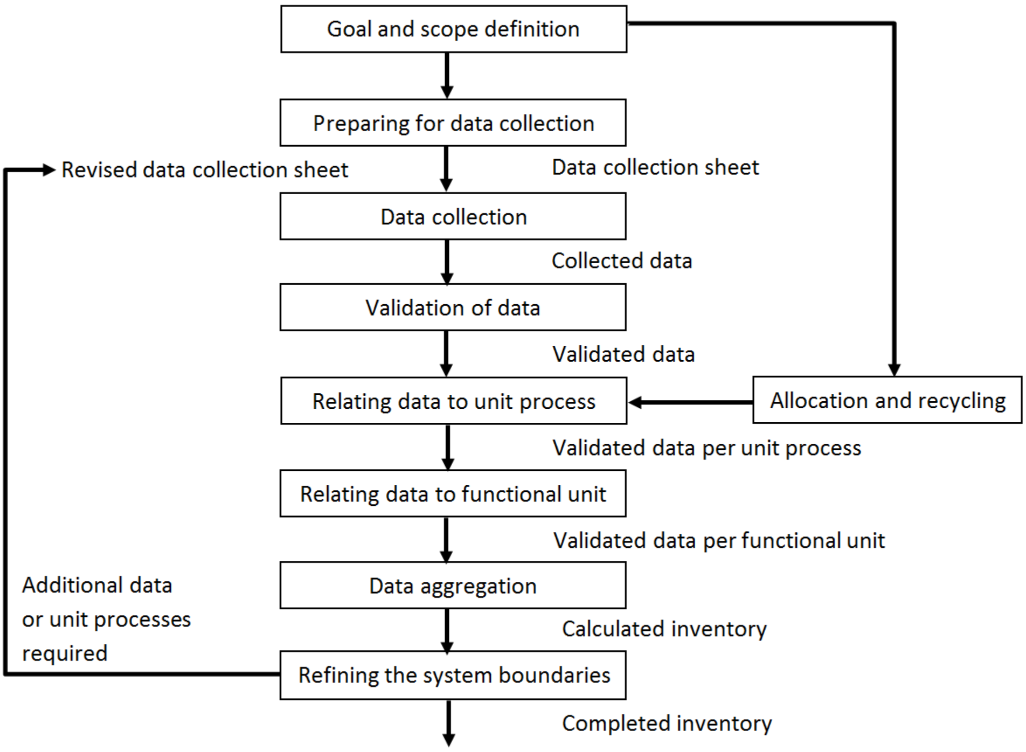


Figure 9 Simplified procedures for inventory analysis (ISO, 1998, 2006).

This is different from the consequential LCA, which is also referred to as “change-oriented”, “effect-oriented”, “decision-based”, or “market-based”. In this type of LCA a product is changed in one way or another. This change has an effect on (parts of) the life cycle of the product or on other systems. These changes are implemented in a newly modelled life cycle. This means the consequential life-cycle model is examining a hypothetic supply chain which is adjusted based on future prospects like market-mechanisms, political interactions and consumer behaviour (Wolf et al., 2010). The producers of LCA information will in this case be identical to the users of the information (Baumann & Tillman, 2004). In consequential LCA more accurate (or marginal) data is needed to observe the real difference a change makes.

In the end, both attributional and consequential LCA can be used for a comparison. As explained before, attributional LCA can be used to compare a specific product from different suppliers. Although the type of product is the same, the product system and its subsystems can be totally different. This means that in attributional LCA a full LCA of both products needs to be produced. The final results then show which product scores better on which impacts. In consequential LCA the product of one of the suppliers is examined. The effect of a small change in the product system is here analysed. Small changes in this case can be for example a change of resource supplier, change of material used, change of production process etc. In consequential LCA the starting point is the product system at hand. It is the change in impact that is important and not the impact itself. The aim is to make an improvement to the existing product system. The importance of the change in impact is also the importance in this research, which means in this research a consequential LCA was used. The subsurface building was taken as a starting point and an aboveground building was designed based on changes that needed to be made on the subsurface building. The effect of the changes between the subsurface and aboveground building was examined. In consequential LCA some parts of the product system might stay the same between the examined products. These were then left out, because they were not important to decide whether a change in the product system has a positive or negative effect on its environmental impact. This was already done in paragraph 2.3. The next step in the process was to collect the data. This is shown in the inventory analysis in chapter 3. After the data is obtained it needs to be processed to obtain all different types of environmental impacts of the buildings. This is done in the impact assessment phase of the life cycle assessment framework for which the methodology is explained in the next paragraph.

2.5. Impact assessment methodology

After the inventory analysis, the Life Cycle Impact Assessment (LCIA) took place. The LCIA has some mandatory and some optional steps (Guinée et al., 2002; ISO, 2000a). All these steps should be taken in order.

Mandatory steps are:
1. Selection of impact categories, category indicators, and characterization models.
2. Classification
3. Characterisation

Optional steps are:
4. Normalisation
5. Grouping
6. Weighting
7. Data quality analysis

In the first step the environmental impact categories that are taken into account are chosen (Baumann & Tillman, 2004). Several default lists of impact categories are already available (Guinée et al., 2002; PRé Consultants, 2008). According to Baumann and Tillman (2004) the inventory data that needs to be collected, depends on the choice of these impact categories. Some inputs or outputs only affect one type of impact. If this impact is not affected or even not taken into account, it is also not useful to take into account the input or output. An overview of the LCIA and some of the impact categories can be seen in figure 10.

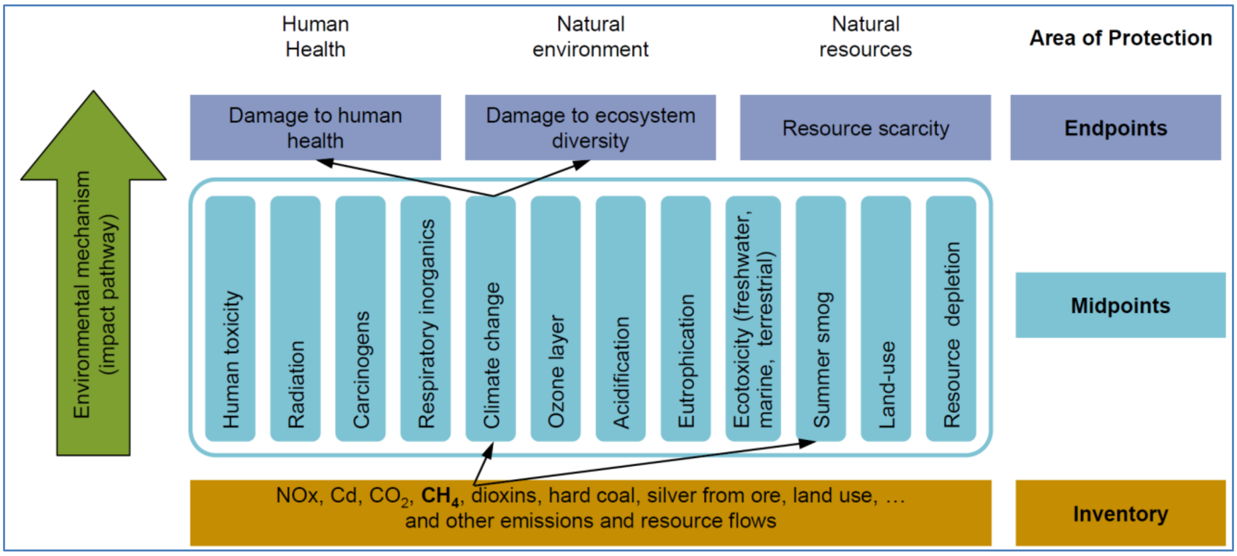


Figure 10 Schematic overview of the Life Cycle Impact Assessment (Wolf et al., 2010).

The impact categories examined differ per impact methodology. The impact methodologies not only differ in the impact categories, but also on the point in the environmental mechanism at which the category indicators are defined. This can be endpoint or midpoint. In midpoint, the results are checked and weight at the impact categories (e.g. Climate change, acidification). In endpoint, the results are checked and weight at the category endpoints (e.g. damage to human health, damage to ecosystem diversity) (Guinée et al., 2002; ISO, 2000a). In this research a midpoint approach would be best suited to have a more specific insight in the impact difference between the two buildings. The method that will be used is the ReCiPe method, which can be both midpoint and endpoint. Furthermore it has a large amount of impact categories. The impact categories used in this method and its units are shown in table 2 (PRé Consultants, 2014). These impact categories comply with the key topics that need to be considered in underground construction according to ITA-AITES Working group 15 (2010).

Table 2 Impact categories and its units in ReCiPe (PRé Consultants, 2014) .

Impact category	Unit
Ozone depletion	Yr/kg CFC-11 equivalents
Human toxicity	Yr/kg 1,4-dichlorobenzene equivalents (14DCB)
Ionizing radiation	Yr/kg Uranium 235 equivalents
Photochemical oxidant formation	Yr/kg non-methane volatile organic compounds (NMVOC)
Particulate matter formation	Yr/kg Particulate Matter <10 micrometre (PM10) equivalents
Terrestrial acidification	Yr/kg sulphur dioxide equivalents (kg SO_2-eq.)
Climate change	Yr/kg carbon dioxide equivalents (kg CO_2-eq.)
Terrestrial ecotoxicity	Yr/kg 1,4-dichlorobenzene equivalents (14DCB)
Agricultural land occupation	m^2*yr
Urban land occupation	m^2*yr
Natural land transformation	m^2*yr
Marine ecotoxicity	Yr/kg 1,4-dichlorobenzene equivalents (14DCB)
Marine eutrophication	Yr/kg nitrogen (N) to freshwater equivalents
Fresh water eutrophication	Yr/kg Phosphor (P) to freshwater equivalents
Fresh water ecotoxicity	Yr/kg 1,4-dichlorobenzene equivalents (14DCB)
Fossil fuel depletion	Kg oil equivalent
Minerals depletion	Kg Iron (Fe) equivalents
Fresh water depletion	m^3

In the ReCiPe methodology there is one additional aspect which is taken into account and that is the cultural perspective. According to Goedkoop et al. (2009) there are three cultural perspectives that can be chosen from, which are the Individualist (I), Hierarchist (H) and Egalitarian (E). The individualist perspective looks short term and assumes that technology will solve possible future problems. It only takes into account impacts that are undisputed. The egalitarian perspective is the opposite and looks on the long term. This perspective is extremely careful with new technologies for which long term impacts are uncertain. It even takes into account impacts for which only indications are present. The hierarchist perspective is an average of the two other perspectives. In ReCiPe the difference between the perspectives is seen in the characterization factors which differ per perspective. The hierarchist perspective has the average characterization factors. For this reason this perspective is mostly used in LCA and it was also used in this research as the default perspective (Goedkoop et al., 2009). The impact assessment methodology used in this research thus was the Hierarchist version of the ReCiPe midpoint methodology.

The next step is the classification. In the classification step the LCI results are assigned to the different impact categories. In this step LCI results can be assigned to multiple impact categories. In the characterization step the LCI results are converted to the unit of the impact category. Results per impact category will, at the end of this step, all have the same unit. The normalization step then takes into account reference information about each impact category (ISO, 2000a). The results will be a fraction or a percentage of impact compared to a certain regional value. This could for example be the share of the impact on the total yearly national impact of that impact category. In this research the results were normalized using the average yearly impact of an average European citizen (PRé Consultants, 2014). The next optional step is grouping. Grouping is a step where the results are grouped into one or more sets (endpoint categories). In weighting some impacts are given more importance than other impacts based on value-choices. This can be based on expert judgement, but also on preferences of a company. There are two types of weighting, midpoint and endpoint. Midpoint weighting is weighting at the impact categories. Endpoint weighting is weighting after the grouping took place (ISO, 2000a). In this research grouping and weighting were not applied. Normalization on the other hand was used. The final optional step is the data quality analysis, which is part of the interpretation step and will thus be explained in paragraph 2.6.

All the steps of the impact assessment were performed using the LCA software program SimaPro8. SimaPro at the moment is the most widely used LCA software in the world. It contains a large amount of databases and impact assessment methods. A large part of the material data is related to materials which are also used in buildings. This was especially useful in this research. Another strong point of the SimaPro software was its ability to perform an uncertainty and sensitivity analysis (PRé Consultants bv, 2014a; The Green House, 2014). This will be explained in the next paragraph, which is the interpretation.

2.6 Interpretation

After the impact assessment the interpretation of the results is needed. According to ISO (2000b) the interpretation step comprises three elements, which are:

1. Identification of the significant issues based on the results of the LCI and LCIA phases of LCA.
2. An evaluation that considers completeness, sensitivity and consistency checks.
3. Conclusions, recommendations and reporting.

The first two elements can be seen as a quality analysis to observe the quality of the results. These are very comparable with the data quality analysis as described by ISO (2000a), which includes a dominance analysis, uncertainty analysis and sensitivity analysis. In this research a dominance analysis, completeness check and sensitivity analysis were performed. The uncertainty of the results is part of the sensitivity analysis. Because of the data used, an uncertainty analysis based on a statistical method was not possible.

The dominance analysis is used to examine which parts of the LCA cause the biggest impact. It thus shows what the dominant factors are in the obtained results. These parts are then more important to examine further during the completeness check and sensitivity analysis (ISO, 2000a). In this research it was also important to do a dominance analysis in order to be able to observe where possible impact differences between a subsurface and aboveground supermarket are located. Furthermore, this was used to find the strengths and weaknesses of the subsurface supermarket compared to the aboveground supermarket. In the completeness check it is examined if all relevant information and data needed for the interpretation are available and complete (ISO, 2000b). For missing information the importance of this information, and its effect on the results, can be explained. In this research the effect on the results was examined for the important missing information in accordance to the dominance analysis. Other missing information will just be mentioned in the discussion.

The sensitivity analysis is used to assess the reliability of the final results and conclusions. This is done by checking if the results are affected by uncertainties in the data or the used methods calculation of category indicator results (ISO, 2000b). The uncertainties in the data are mostly caused by assumptions, which had to be examined. Furthermore some uncertainty in the data could be caused by the choice of database. The database used in this research was the consequential database. This is a new type of database, which means it is not yet used a lot. The type of database used was changed to examine if it had any influence on the final results. The effects of the used methods and calculation of category indicator results are actually both dependent on the method used. By changing the method, the point at which the category indicators are defined, and the cultural perspective a good examination of the sensitivity of the results was produced. For a second method the Cumulative Energy Demand (CED) method was chosen, because according to results from Cabeza et al. (2014) Cuéllar-Franca and Azapagic (2012), and EPA (2013) the use phase (e.g. energy use) of a building plays the dominant role in its LCA. The CED measures both the direct and indirect consumption of energy, which includes energies to produce materials (Frischknecht et al., 2007). This makes it an interesting method for this research. It, however, has to be noted that the CED method as it is currently develop only takes into account non-renewable energy.

When the interpretation is completed a discussion on the results was performed, and conclusions and recommendations were given. With the methodology known, the inventory analysis of this research was performed. This is shown in the next chapter.

3. Inventory analysis

In paragraph 2.2.1 the case study was chosen to be a subsurface supermarket located in Brielle. To get insight in the construction of the building, the owner of the building, Mr de Vette (2014), was contacted. The owner provided a large amount of information concerning all different aspects of the building process, which included e.g. drawings and quality certificates (see appendix F). From the information obtained the suppliers and constructors of the different aspects of the building were found. For some parts of the building amounts of materials and energy were calculated using the information obtained. For other parts information was too difficult to calculate using the obtained data. Here the suppliers were contacted, who supplied further information regarding the amounts of material used. For all data it was noted where it came from. Data found using the information obtained from the owner of the building was in this research cited as de Vette (2004). In appendix F.1 is then shown which document is used for which information. For data that was obtained through contacting a supplier, the supplier will be mentioned as a reference. The materials used in the housing body that would change between an aboveground and a subsurface building were concrete, steel, glass and insulation material. As explained in the methodology section (paragraph 2.3.2), some parts of the housing body were not taken into account (e.g. the doors) because these were assumed the same for the aboveground and subsurface building. Material usages from appliances (e.g. elevators and refrigerators) were also not taken into account. These were not known or also assumed the same. Other things that were, next to the material and energy use, taken into account were the transportation and parts of the construction of the building. The first thing examined was the material use.

3.1 Material use

A building exists of many different elements which combined form the building. As explained earlier, in this research the housing body's material use will be examined. In case of the subsurface building, the housing body taken into account exists of the floor, roof, walls, insulation, stairs, railings, columns, piles and the windows. For the aboveground building the same housing body was used but without the stairs and railings. Furthermore, the aboveground building used a different amount of material due to different forces that act on the building. This was examined in the different scenarios as explained in paragraph 2.3.2. The material use was examined per part of the housing body, starting with the floor and columns.

The floor and columns were examined together in this research. The reason for this was that at the places of the columns a support is located which makes the floor thicker. In this support the amount of reinforcement is bigger. Instead of pointing this extra steel and concrete to one of the two parts, the choice was made to just add them together. Next to supports at the places where columns are, there are even more supports located at places where the piles are. These supports were all included in one bigger part which is called the floor, supports and columns. The floor, supports and columns are all made out of steel reinforced concrete. The volume of concrete and steel in the floor, supports and columns was examined for all scenarios using drawings obtained from de Vette (2004), and using geometry and trigonometry principles. The specific calculations are shown in appendix B.1. The floor, supports and columns were produced at location. For this reason the concrete was put in SimaPro as normal concrete, which is different from the roof, walls, stairs and piles.

The roof and walls were both made of precast reinforced concrete panels produced by Atlas Bouwtechnisch Adviesburo (2014). The concrete use was thus implemented in SimaPro as a concrete block. For these panels it was too difficult to calculate the steel use in the panels based on the drawings obtained from de Vette (2004). For this reason Atlas Bouwtechnisch Adviesburo (2014) was contacted for the material use in the panels. An overview of the concrete and steel use in the roof was send by Atlas Bouwtechnisch Adviesburo (2014) and used in this research. The concrete and steel use for the roof given by Atlas Bouwtechnisch Adviesburo (2014) were not used directly. The roof for which the amounts were provided had openings at the stairs and elevators. In this research the roof was assumed fully closed for both the aboveground and subsurface building, which changes the area of the roof from 2512.52 m^2 to 2695.6 m^2. For this a correction in the material use was made. The material use of the walls did not have to be corrected. The mass of steel and concrete used in the roof and walls were then examined for all the different scenarios. The specific calculations are shown in appendix B.2.

The stairs were made of precast reinforced concrete by Steenhuis beton BV (2014) for which the concrete was implemented in SimaPro as a concrete block. With the data obtained from de Vette (2004) it was too difficult to determine the concrete and steel use in the stairs. For this reason Steenhuis beton BV (2014) was contacted for the material use in the different stairs. An overview of the concrete and steel use in the different stairs was send by Steenhuis beton BV (2014) and used in this research. The obtained mass of steel and concrete for the stairs was only applied to the subsurface scenarios. The aboveground building did not have stairs, which meant in none of the aboveground scenarios there was a material usage from stairs.

With stairs present, railings also needed to be applied to the building. The railings were produced out of RVS 304 by Biemans Constructie Rijen B.V. RVS 304 is a stainless steel grade which has around 18% chromium and 8% nickel (Euro Inox, 2014; Stainless Structurals, 2013). This is why in SimaPro chromium steel 18/8 was used. The density of RVS 304 is around 7900 $kg*m^{-3}$ (Euro Inox, 2014; Stainless Structurals, 2013). Volumes of RVS 304 were calculated for all different parts of the railings using the drawings obtained from de Vette (2004), and using geometry and trigonometry principles. The specific calculations are shown in appendix B.4. In the aboveground building no railings were applied because there were no stairs or elevators which need railings. The material use for railings was thus not applied to the aboveground scenarios but only to the subsurface scenarios.

The piles, which were produced by Herrewijnen Heiwerken Spijkenisse B.V. (de Vette, 2004), are part of the foundation of the building and used to support the building. The piles were made of precast reinforced concrete for which the concrete in SimaPro was implemented as a concrete block. In the building different types of piles were used. For the subsurface building the length, dimensions and maximum load of these piles were already given in a table (de Vette, 2004). For the aboveground building the same type of piles were used. The amount of piles was changed according to the changed forces that act on the building. There are two reasons for the force changes between the subsurface and aboveground building, the change of mass of the building and the change of the Archimedes force. Next to the change in the amount of piles, the piles were made longer in the aboveground building because of the height difference between the two buildings. As can be seen from figure 11 the force on the subsurface building was in this research much more positive resulting in fewer piles. Furthermore the figure shows that the aboveground building is located higher, which means longer piles. In this research only the piles that are located under the building were changed in length and amount. The other piles were assumed exactly the same as for the subsurface building. Using the data obtained from de Vette (2004) the volume of the piles could be calculated, but not the volume of concrete and steel in the piles. To obtain both volumes the volume of one of the two materials needed to be calculated. Using information from Martens beton b.v. (2014) about reinforcement in piles, the amount of reinforcement in the piles was calculated for each type of pile separately. With the total pile volume and the volume of steel in the pile known, the volume of concrete was calculated. The volumes of concrete and steel were changed to mass using their corresponding densities of 2300 $kg*m^{-3}$ (Elert, 2001; The Engineering Toolbox, 2014a) and 7800 $kg*m^{-3}$ (Soortelijkgewicht.com, 2014; The Engineering Toolbox, 2014c). The specific calculations regarding the material use in the piles in different scenarios are shown in appendix B.5.

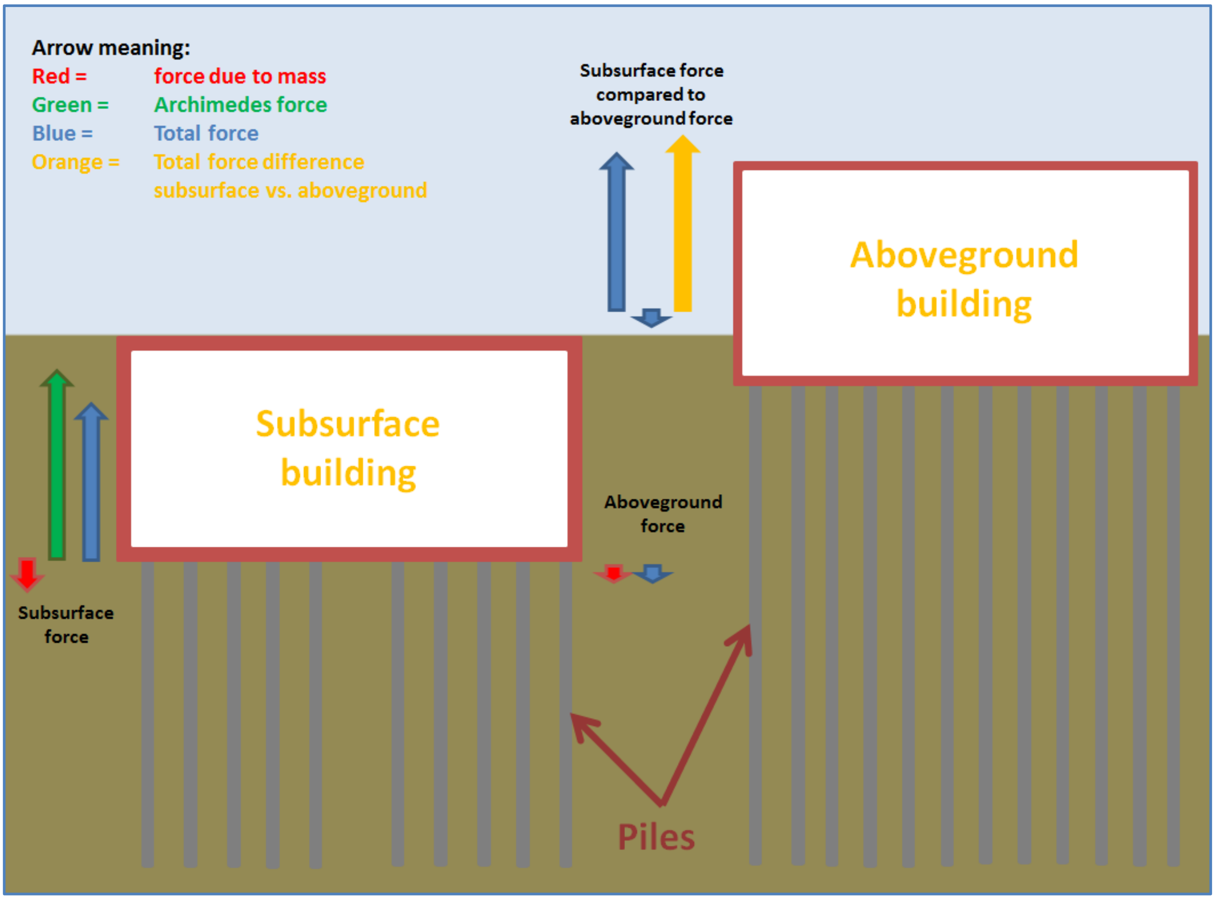


Figure 11 Difference in piles between the subsurface and aboveground supermarket based on the forces active.

Next to concrete and steel there are two more materials applied in the housing body of the buildings, which are insulation and glass. Insulation is applied to the roof, walls and floor. The wall and floor insulation is provided by Rockwool B.V. For the roof insulation no manufacturer was given, but as was explained in paragraph 2.3.3 extruded polystyrene (XPS) with a thickness of 135 mm was used for roof insulation. For the walls and floor Rockwool 123 and Rockwool 211 Vario respectively were assumed to be used as insulation in various thicknesses in accordance to the scenarios in paragraph 2.3.3. Using the thicknesses, areas and densities of these isolation materials, the volume and mass of insulation used were calculated for the different scenarios. More specific information regarding the use of insulation is given in appendix B.6.

The windows of the subsurface supermarket were provided by van den Heuvel glas (de Vette, 2004). The glass used was double glazing laminated safety glass with brand name “SGG Parsol Groen Securit”. In SimaPro this was inserted as double glazing laminated safety glass. In this research only the glass at the facade “Thoelaverweg” and facade “Entreetrap” were taken into account. The area of glass was calculated using the drawings obtained from de Vette (2004) and using geometry and trigonometry principles. Each window had a different number. For windows 146 and 409 only the bottom part, which is located under the roof of the building, was taken into account. The volume of the glass was calculated using the thickness of the glass as found in the detailed drawings obtained from de Vette (2004). The density of common glass, which was assumed to be 2600 kg*m^{-3} (The Engineering Toolbox, 2014b), was used to calculate the mass of the glass. The amount of glass was not changed in different scenarios, which meant it did not have to be adjusted in any way. More specific information regarding the windows is given in appendix B.7. With the glass use of windows known, the material uses in all examined parts of the buildings were known for each scenario. The next aspect examined is the energy use of the building.

3.2 Energy use

Next to the material use in the building, the energy use of the building over the examined period of time played a role. The examined period of time in this research depended on the functional unit, which in this case was *"a net m^2 of comfortable retail floor space to obtain provisions for 100 years"*. The energy use was thus examined over a period of 100 years. The two supermarkets, which were compared in this research, were exactly the same, because the aboveground supermarket was designed in accordance to the subsurface one. Both buildings then applied the same comfortable retail floor space per net m^2, which meant creating this environment then only depended on the energy use of the building. The energy use of a building can be in the form of heat or electricity. It was thus important to examine both of these energy uses, starting with the heat.

The amount of heating and cooling needed depends on the temperature inside the building. When the temperature exceeds a certain level, heating or cooling is needed. In the United Kingdom (UK) supermarkets are obligated to have an indoor temperature of 19 to 21°C in winter and 21 to 23°C in summer (Garstenveld, 2013). It is applicable to assume that these temperature ranges are also used in other countries. In this research 20°C and 22°C were used as the boundary for heating and cooling. Inside the building the temperature was kept stable. The amount of heating and cooling thus depended on the change in temperature. Ventilation was not taken into account, which meant the temperature change was caused by a heat exchange with the outside of the building through the building envelope. The heat flow through the building envelope was calculated in appendix C.1 using a formula obtained from Blok (2007) in combination with the degree days, which are explained in appendix D. For the degree day calculations the temperatures were calculated at different depths using a formula from Labs (Al-Temeemi & Harris, 2001; Mazarron & Canas, 2008; Moustafa et al., 1981; van Dronkelaar et al., 2014), the air temperatures from 1999 to 2013 of the Rotterdam weathering station (KNMI, 2014) and the soil characteristics from the supermarket location (Dinoloket, 2014; NVOE, 2006). Further explanations about these calculations are given in appendix C and D. The resulting heat loss of the building is restored by heating the building with a boiler, which was implemented in SimaPro in this way. Heat can also move the other way around when the outside temperature is higher than the inside temperature. This additional heat from the environment to the inside of the building then needed to be cooled using air-conditioning, which uses electricity. The air-conditioning was thus part of the total electricity use of the building.

As explained in paragraph 2.3.2 the elevators were, next to the air-conditioning, the only electricity using appliances that could differ between the aboveground and subsurface building in this research. Their electricity use influenced the total electricity use of the building. The electricity use of the supermarket was assumed using an electricity bill of December 2013, which was obtained from de Vette (2014). In this research it was assumed that the electricity use on the bill was the average monthly electricity use of the supermarket. Although this assumption is not fully correct, it does not have an effect on the final results. This monthly electricity use was used to calculate the total electricity use of the subsurface 1 scenario. The electricity use of the aboveground building and the other scenarios was corrected for the elevators and air-conditioning to obtain the electricity use in these additional scenarios. The change in electricity use caused by the elevators and air-conditioning was then observed. To see the full effect of electricity use in the LCA of a supermarket the actual electricity use of the supermarket was applied. To be able to examine the electricity use in the different scenarios the electricity use of the elevators and air-conditioning needed to be known.

The subsurface supermarket has three types of elevators. The first elevator is the Evolution Flexible BC61 from ThyssenKrupp (de Vette, 2004). This elevator is used to transport the people inside and outside the building. The second elevator is used for goods. This is the A-1500 from Elsto Boekholt Dynatec (EBD), of which two are installed in the building (de Vette, 2004). Having two elevators installed instead of one does not change the electricity use because the elevator was measured per usage. The third and final elevator installed in the subsurface supermarket is the Orinoco model FS983 moving walk from ThyssenKrupp (de Vette, 2004). From this model also two are installed. In this case the electricity use was calculated over both moving walks because one of the walks is moving upwards and the other is moving downwards. For the calculation of the electricity use of the elevator for goods and the elevator for people, assumptions were made about the amount of times the elevators are used. The elevator for goods was assumed to be used four times a day on average. One use here meant a movement up or a movement down. The reason for this use was that it is assumed that bringing down goods is performed efficiently and empty carts are brought up to be transported back to the distribution center with the truck that brought the goods. The elevator for people was assumed to be used five times a day. The reason for this was that the supermarket also has moving walks which were assumed to be used most often by all the people. It is thus also very likely that this was an overestimation of the amount of usages. The supermarket is opened every day which meant per year the elevator for goods is used 1460 times and the elevator for people is used 1825 times. The moving walks were assumed to be running all the time during opening hours. The supermarket is opened 81 hours per week. Additional to this it was assumed the moving walks are already turned on half an hour before opening and shut down half an hour after closing time. The walking stairs were thus assumed to be used 88 hours a week, 12.6 hours a day or 4588.6 hours a year. This most likely is an overestimation of its use because systems these days are available that make sure the elevators run more efficient. If the electricity use plays a major role in the comparison this should be further examined. Specific calculations on the electricity use of the elevators are shown in appendix C.2.

With the electricity use of the air-conditioning and elevators known the electricity use of the building in the different scenarios was calculated. The air-conditioning was taken into account in the electricity use by first subtracting its electricity use in subsurface scenario 1 (main scenario) from the total electricity use. Then the electricity use for air-conditioning of the specific scenario is added to this electricity use to obtain the total electricity use in that scenario. For the aboveground scenarios the electricity use of the elevators is then subtracted from this electricity use to obtain the total electricity use of the aboveground building. For the subsurface scenarios only the correction from the air-conditioning was applied. The total electricity use and heating needed in all scenarios was in the end multiplied with the examined period of time to obtain the electricity use and heating needed over the examined period of time. The resulting electricity use and heating needed are shown in table 43 and table 44 in appendix C.

3.3 Construction and transport

In LCA all the different elements regarding the building need to be taken into account. The energy use in the building and the materials the building is made of were already mentioned in the previous paragraphs. These were not the only two elements in the LCA that change when the building changes. With a change in the building also comes a change in the construction of the building and with a change of material usage comes a change in transport. This change also had an impact on the LCA of a building. In this research there was not enough time and reliable information to take all differences in construction into account. Facets that could change but were not taken into account were, among others, the pumping of groundwater out of the construction area and the piling of the piles in the subsurface. The facets that were taken into account are the excavation of the construction area, the resulting soil transport and the transport of construction materials to the construction site.

Excavation was needed to prepare the location for construction. Parts of the soil had to be removed by excavators and trucks to create space for the building. The type of excavators and trucks used for this were unknown. In this research it was assumed all the excavation was performed by a hydraulic digger and the sand was all transported by a dump truck. For both the subsurface and aboveground building the same area of building was excavated. The difference was the depth of excavation. For the aboveground building this was 1 m and for the subsurface building this was 5 m. By using the area of the supermarket it was calculated what volume of sand needed to be excavated and transported. This served as input for the excavation in the LCA. For the transport of the soil the weight of the soil was calculated using its average density. The distance of transport of the soil was unknown, but it was assumed this transportation would not be done over a large distance. A distance of 10 km was assumed in this research. Using the distance and weight of the load, the tonne-kilometre (tkm), which was the input in SimaPro, was calculated. Specified calculations and results are shown in appendix E.1.

The transport of the materials that were used in the building depended on their mass and on the distance over which these had to be transported. The distance was dependent on the location of the manufacturer of each product. Manufacturer locations were obtained using a telephone and address list obtained from de Vette (2004) and the distance was determined by planning an optimized route in Google maps (Google, 2014). Using the distances and mass of each material the tkm were calculated, which were implemented in SimaPro. The mass was already calculated in appendix B. The tkm was calculated using the load of a truck, an empty truck returning to the manufacturer is not taken into account. In practice it is, however, most likely that transport companies work efficient and combine their routes to ensure the trucks drive the least empty kilometres. This makes using only the load on a one way direction a viable assumption. The type of truck used for the transport depends on the mass of the part transported. It is, however, assumed that the most efficient trucks were used, which are the EURO5 trucks in SimaPro. More specific calculations on the transportation, including the used trucks, are mentioned in appendix E.2. The tkm per part of the building and in each scenario are shown in table 51 in appendix E.2.

3.4 Overall inventory implemented in SimaPro

In order to analyze all the data collected above it had to be put in the software program SimaPro. In SimaPro a selection off the processes used can be made. SimaPro separates its data in market processes and transformation processes. According to PRé Consultants (2013) market processes are used when a specific supplier is unknown. These are consumption mixes for a specific region or process mixes for a specific product. Transformation processes are more detailed and more specific. Here a more specific product or production process can be chosen (Weidema et al., 2013). In this research for all processes transformation processes were used except for the electricity use for which no transformation processes were available. For electricity use a market process was thus used.

In the ecoinvent 3 database another separation in the data is made between the allocation and consequential modeled database. This separation was not included in previous versions of the ecoinvent database, where the allocation database was used as the default database. Two methodological choices cause the difference in the two datasbases. The first is the method of calculating the data. According to Weidema et al. (2013) the allocation database of Ecoinvent 3 is based on partitioning (allocation) to convert multi-product datasets to single-product datasets. It thus uses allocation to assign impacts to a product. According to PRé Consultants bv (2014a) the allocation modeled database for this reason looks at the environmental impacts of the life cycle and its subsystems. The consequential database is different. It looks not only at the product's life cycle, but also how the product changes the environmental impacts of other life cycles. The consequential database does this by using substitution (system expansion) to convert multi-product datasets to single-product datasets. (PRé Consultants bv, 2014a).

The second methodological choice that is different is based on the supply of products, which is a little trickier. The allocation database uses average data obtained from present-day suppliers (Weidema et al., 2013). Expected future changes are not included in the allocation data. Because average data is used in the allocation database, the technological level of all present-day market suppliers is taken into account (Ecoinvent Centre, 2014). This way even market suppliers that are far from environmentally friendly are taken into account. With allocation data it can thus be observed how a product scores or compares in the present time with the average technologies available. Also decision for the future can be made based on the average present-day data. This, however, does not say anything about future changes caused by adding extra capacity with new processes or replacing old processes with newer ones. This is done in the consequential database.

According to Weidema et al. (2013) the consequential database was intended to reflect the consequences of small-scale, long-term decisions, by taking into account the constraints that are applicable at this scale and time horizon. In the consequential database it is thus a decision that plays a role. This can for example be a decision in choosing between products. A small-scale decision Weidema et al. (2013) describes as a decision that does not affect the direction of the trend in market volume. Furthermore, it does not affect the constraints on and production costs of the involved products and technologies. No new technologies, products, suppliers or markets are thus assumed in this database. The scale is thus actually the same as in the allocation database. The time horizon is, however, different. The consequential database is based on long-term decisions.

Weidema et al. (2013) define a decision as long-term if it affects capital investment. It takes into account the installation of extra capacity and the replacement of old machinery with new machinery. This actually means that the consequential database takes into account possible changing technological levels and changing market capacities (PRé Consultants bv, 2014b). This is different from the allocation database, which only looks at the present time and where the utilization of the existing capacity is only taken into account. Combining the small-scale decisions with the long-term decisions, the consequential database looks at the current technologies and how they perform in the market. It then splits them up in old and modern technologies. The “old” technologies are the least competitive technologies, which are assumed to be phased out in the long term. The modern technologies are the technologies that are competitive (Weidema et al., 2013). These are mostly the less polluting and cheaper technologies. The consequential database thus does not use the average data from all suppliers but it uses an average of the most competitive technologies available, which will most likely form the full market in the future. The database assumes there are no shortages or obligations on the supply of production factors like space, resources etc., which means there is an unconstrained supply of the most competitive technologies.

The decision for a subsurface or an aboveground supermarket is a decision which is more related to the future than it is to the present. The consequential database thus seemed more suited for this research and was thus also used. In order to observe the effect of the choice of the database, the results with the allocation database were examined in the sensitivity analysis.

The last separation in the data is then made between unit processes and system processes. The main difference between these two processes is that the system processes are fully aggregated datasets and unit processes are transparent datasets. The unit processes will thus also show the background processes, which is not the case in the system processes. In system processes these background processes are already inserted in the foreground processes. In this research the unit processes were used.

With all this information known it was possible to construct the LCA. A diagram of the different elements examined and the way the LCA is constructed in SimaPro is shown in figure 12. In table 3 the inventory analysis is then given. This shows the processes in SimaPro that were chosen per aspect and its corresponding value for all the different scenarios. Not all aspects of the building were applied in all scenarios. When aspects of the building did not apply to a specific scenario, the boxes of the table are colored light grey. Using this input the LCA was constructed in SimaPro.

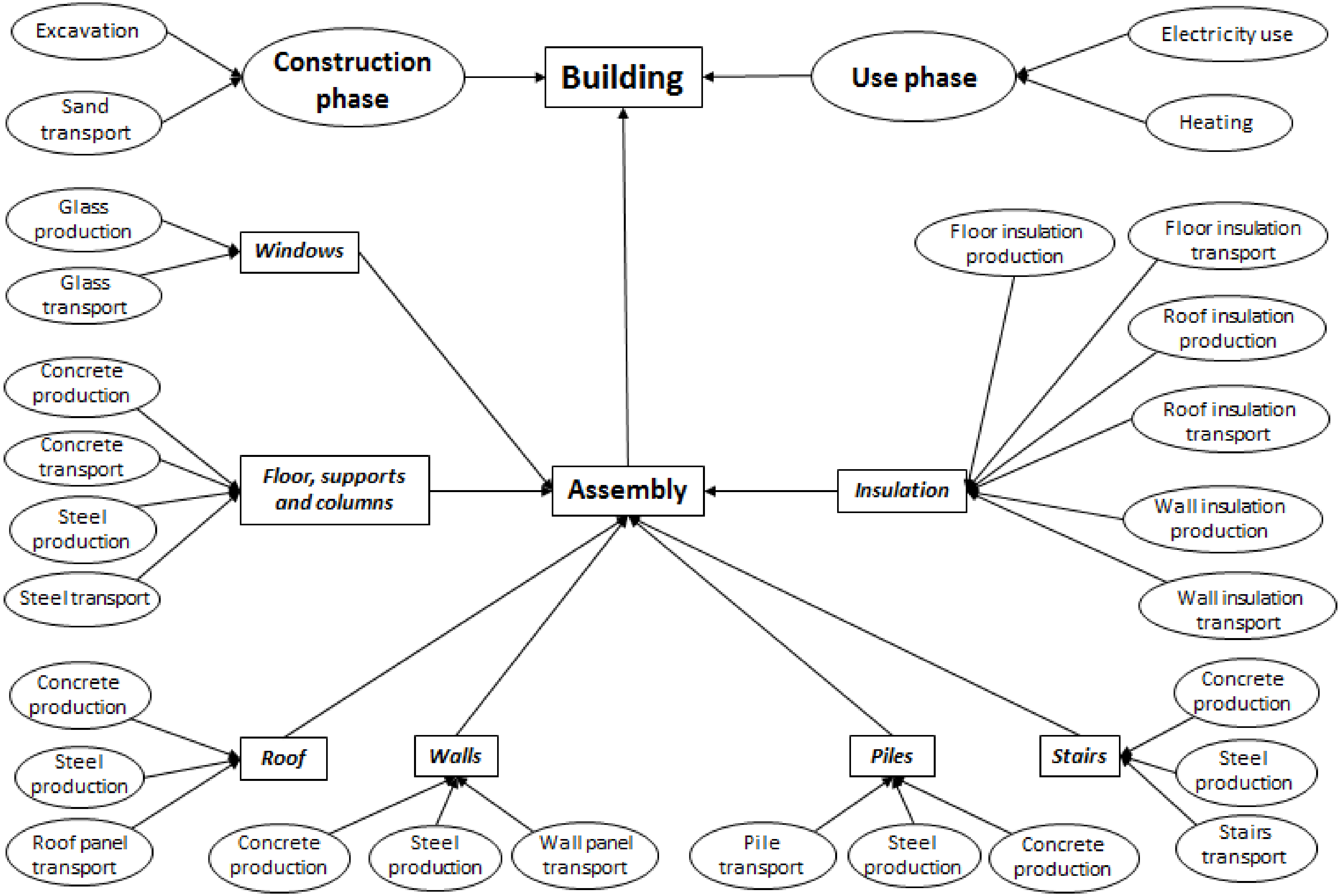


Figure 12 Diagram of the different elements examined in the LCA and the way the LCA is constructed in SimaPro. Ovals represent processes and squares represent materials/assemblies. The arrows show the direction to which the processes or subassemblies are combined.

Table 3 Overview of input data implemented in SimaPro.

	Process in SimaPro	Unit	Scenario subsurface 1	Scenario subsurface 2	Scenario subsurface 3	Scenario aboveground 1	Scenario aboveground 2	Scenario aboveground 3	Scenario aboveground 4	Scenario aboveground 5
Assembly ***Floor, supports and columns***										
Concrete	Concrete, normal {CH} |production| Conseq, U	m^3	0.332	0.332	0.332	0.221	0.332	0.166	0.221	0.221
Steel	Reinforcing steel {RER} |production| Conseq, U	kg	31.36	31.36	31.36	20.90	31.36	15.68	20.90	20.90
Concrete transport	Transport, freight, lorry >32 metric ton, EURO5 {RER}| Transport, freight, lorry >32 metric ton, EURO5 | Conseq, U	tkm	6.790	6.790	6.790	4.526	6.790	3.395	4.526	4.526
Steel transport	Transport, freight, lorry >32 metric ton, EURO5 {RER}| Transport, freight, lorry >32 metric ton, EURO5 | Conseq, U	tkm	1.762	1.762	1.762	1.175	1.762	0.881	1.175	1.175
Roof										
Concrete	Concrete, block {DE} |production| Conseq, U	kg	170.79	170.79	170.79	113.86	170.79	85.40	113.86	113.86
Steel	Reinforcing steel {RER} |production| Conseq, U	kg	0.48	0.48	0.48	0.32	0.48	0.24	0.32	0.32
Transport	Transport, freight, lorry >32 metric ton, EURO5 {RER}| Transport, freight, lorry >32 metric ton, EURO5 | Conseq, U	tkm	16.168	16.168	16.168	10.779	16.168	8.084	10.779	10.779

Walls										
Concrete	Concrete, block {DE} |production| Conseq, U	kg	270.98	270.98	270.98	180.66	270.98	135.49	180.66	180.66
Steel	Reinforcing steel {RER} |production| Conseq, U	kg	7.80	7.80	7.80	5.20	7.80	3.90	5.20	5.20
transport	Transport, freight, lorry >32 metric ton, EURO5 {RER}| Transport, freight, lorry >32 metric ton, EURO5 | Conseq, U	tkm	26.317	26.317	26.317	17.545	26.317	13.158	17.545	17.545
Piles										
Concrete	Concrete, block {DE} |production| Conseq, U	kg	506.35	506.20	506.42	726.95	743.39	718.73	726.78	727.03
Steel	Reinforcing steel {RER} |production| Conseq, U	kg	28.08	28.07	28.09	47.77	48.85	47.23	47.75	47.77
transport	Transport, freight, lorry >32 metric ton, EURO5 {RER}| Transport, freight, lorry >32 metric ton, EURO5 | Conseq, U	tkm	7.963	7.961	7.964	11.543	11.804	11.413	11.541	11.545
Stairs										
Concrete	Concrete, block {DE} |production| Conseq, U	kg	7.10	7.10	7.10					
Steel	Reinforcing steel {RER} |production| Conseq, U	kg	0.28	0.28	0.28					
transport	Transport, freight, lorry >32 metric ton, EURO5 {RER}| Transport, freight, lorry >32 metric ton, EURO5 | Conseq, U	tkm	2.273	2.273	2.273					
Railings										
Steel	Steel, chromium steel 18/8, hot rolled {RER} |production| Conseq, U	kg	0.202	0.202	0.202					
Transport	Transport, freight, light commercial vehicle {Europe without Switzerland}|processing| Conseq, U	tkm	0.019	0.019	0.019					

Windows										
Glass	Glazing, double, U<1.1 W/m2K, laminated safety glass {RER}|production|Conseq, U	m^2	0.0441	0.0441	0.0441	0.0441	0.0441	0.0441	0.0441	0.0441
Transport	Transport, freight, light commercial vehicle {Europe without Switzerland}|processing| Conseq, U	tkm	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033
Insulation										
Roof insulation (XPS)	Polystyrene, extruded {RER}|polystyrene production, extruded, CO2 blown| Conseq, U	kg	4.455	4.455	4.455	4.455	4.455	4.455	4.455	4.455
Wall insulation (Rockwool 123)	Rock wool, packed {CH}|production| Conseq, U	kg	0.759	0.0	1.044	0.759	0.759	0.759	0.0	1.044
Floor insulation (Rockwool 211 Vario)	Rock wool, packed {CH}|production| Conseq, U	kg	3.600	0.0	5.400	3.600	3.600	3.600	0.0	5.400
Transport roof insulation	Transport, freight, light commercial vehicle {Europe without Switzerland}|processing| Conseq, U	tkm	0.0089	0.0089	0.0089	0.0089	0.0089	0.0089	0.0089	0.0089
Transport walls insulation	Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| Transport, freight, lorry 7.5-16 metric ton, EURO5 | Conseq, U	tkm	0.150	0.0	0.206	0.150	0.150	0.150	0.0	0.206
Transport floor insulation	Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| Transport, freight, lorry 7.5-16 metric ton, EURO5 | Conseq, U	tkm	0.709	0.0	1.064	0.709	0.709	0.709	0.0	1.064

Use phase										
Electricity	Electricity, high voltage {NL}|market for| Conseq, U	MWh	57.712	57.712	57.712	54.643	54.643	54.643	54.643	54.643
Heat	Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler condensing modulating <100kW| Conseq, U	GJ	19.819	59.324	16.780	21.338	20.467	21.814	77.746	17.830
Construction phase										
Excavation	Excavation, hydraulic digger {RER}| processing| Conseq, U	m^3	5	5	5	1	1	1	1	1
Sand transport	Transport, freight, lorry >32 metric ton, EURO5 {RER}| Transport, freight, lorry >32 metric ton, EURO5 | Conseq, U	tkm	77.841	77.841	77.841	15.568	15.568	15.568	15.568	15.568

4. Impact assessment and interpretation

In this stage the actual assessment using the SimaPro program was performed. As explained in paragraph 2.5 the standard impact assessment methodology used in this research was the Hierarchist version of the ReCiPe midpoint methodology with the normalisation values of Europe. Using this method the results were examined. In the results scenarios subsurface 1 and aboveground 1 were the default scenarios, which were assumed most comparable to the real life situation. These scenarios contain the actual data as it was obtained from de Vette (2004), the manufacturers and other applicable data sources. The lifetime of the two buildings was in these scenarios the same and the results were inserted according to the functional unit, which was *"a net m^2 of comfortable retail floor space to obtain provisions for 100 years".* This is the case for all the results unless otherwise mentioned. Other scenarios were used to observe the effect of a change in the thickness of the insulation layers, the lifetime of the aboveground building, and a change in the factor that determined the volume of concrete and steel use of the aboveground building compared to the subsurface building. The first thing examined was the comparison between the two default scenarios subsurface 1 and aboveground 1. In addition to this, the effect of a change in the factor that determined the volume of concrete and steel use of the aboveground building compared to the subsurface building was also examined.

4.1 Comparative analysis scenario subsurface 1 vs. aboveground 1.

As explained in paragraph 2.3.2 in the aboveground 1 scenario the change in the volume of steel and concrete compared to the subsurface building was advised by expert judgement of the IOB (2014). In order to see the effect when this factor is not fully correct scenarios aboveground 2 and 3 were also added to figure 13. An overview of the different scenarios was given in table 1 of paragraph 2.3.3.

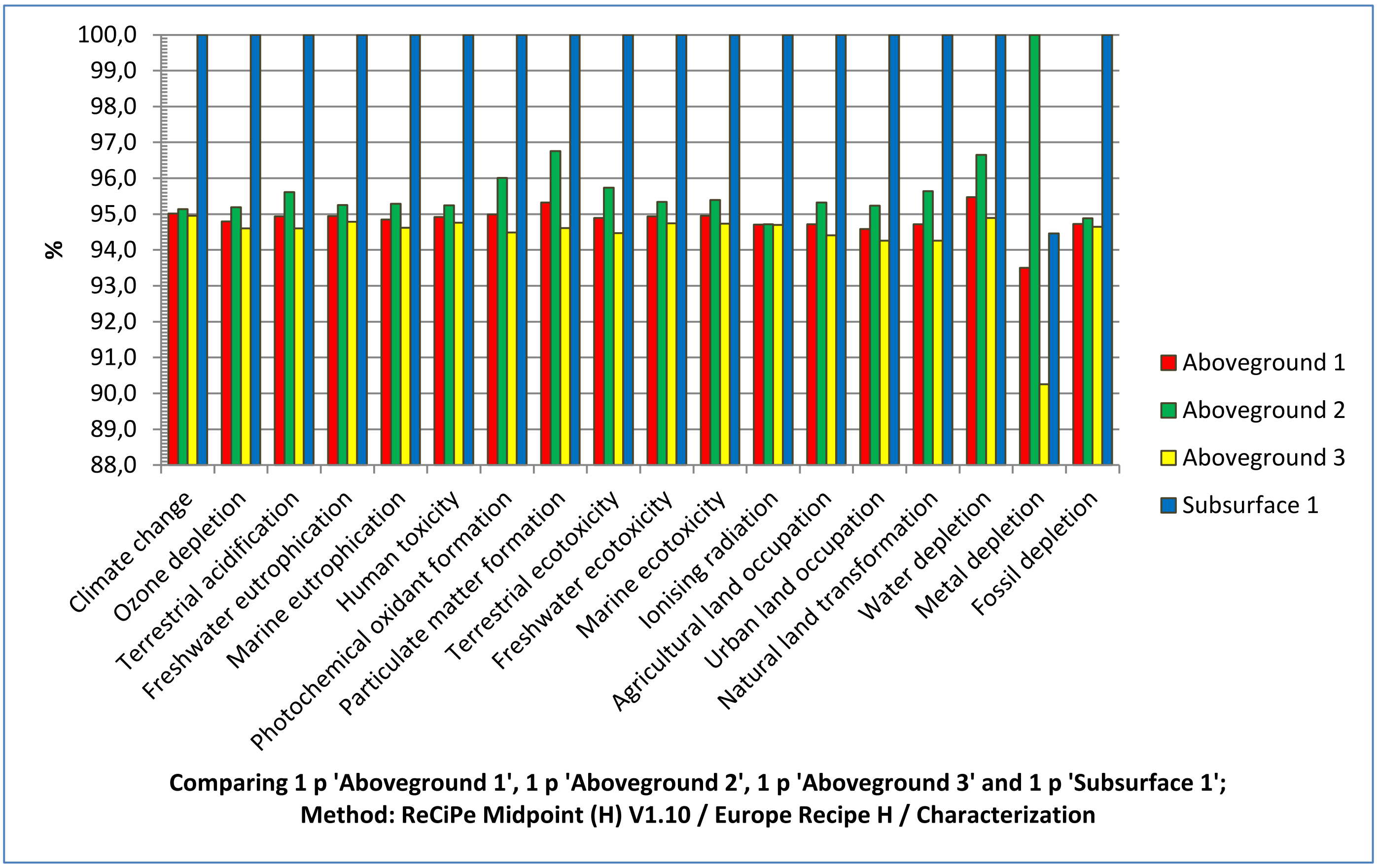


Figure 13 Characterisation results from the comparative impact analysis of the default scenarios and the scenarios with different factors for the material use of the aboveground building.

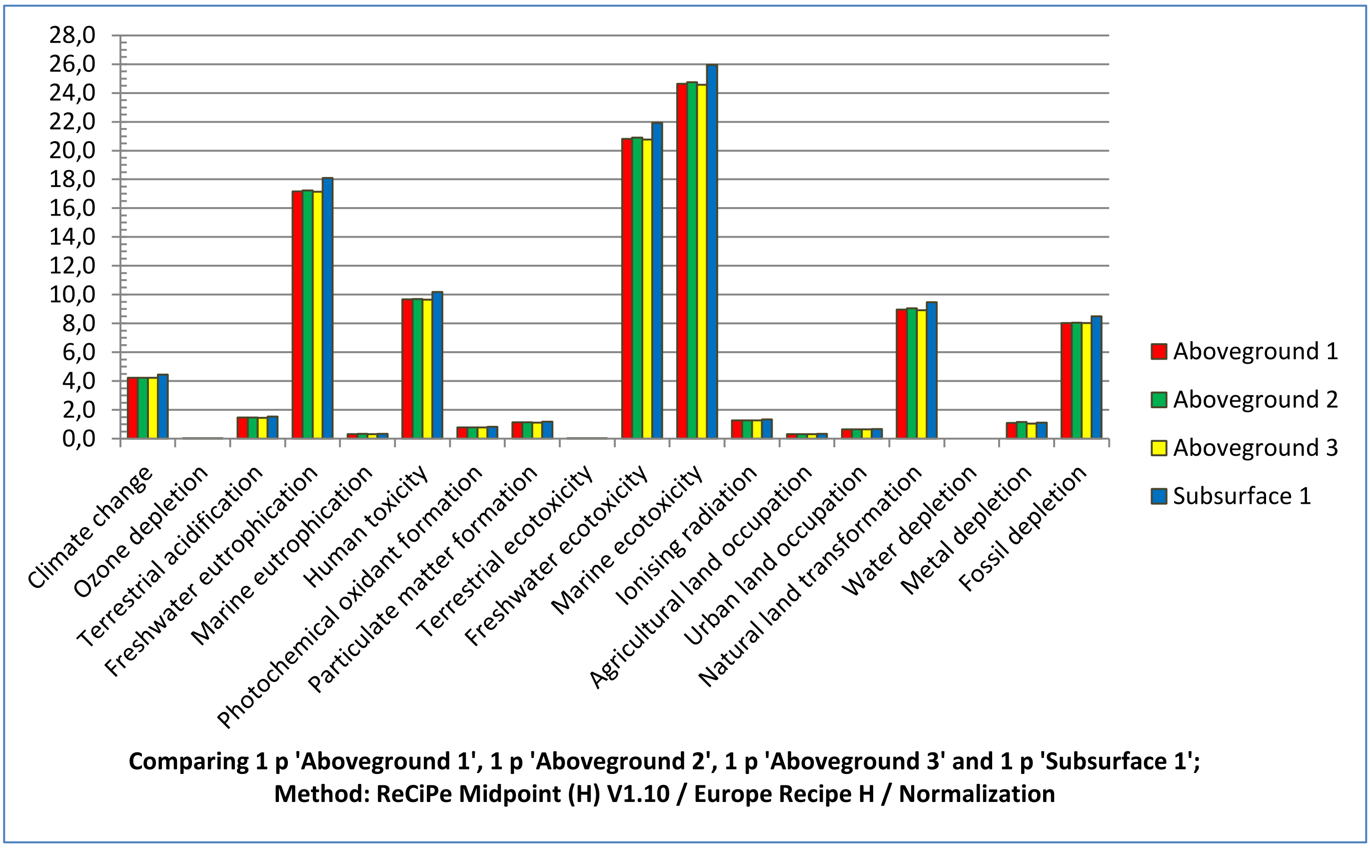


Figure 14 Normalized results from the comparative impact analysis of the default scenarios and the scenarios with different factors for the material use of the aboveground building based on the average yearly impacts of an average European citizen.

From figure 13 was observed that the main subsurface scenario (subsurface 1) scored worse on all impact categories compared to the main aboveground scenario (aboveground 1). When the “material use” factor changed this result did not change a lot. Only on metal depletion the aboveground building scored worse in the aboveground 2 scenario, in which the building uses the same “material use” factor. To observe the real effect changing from an aboveground supermarket to a subsurface supermarket could have, normalization was performed. The normalization in this research is based on the average yearly impact per impact category of the average European citizen. Its results in figure 14 showed that for metal depletion changing to a subsurface supermarket would have almost no effect, while for other impacts the change would have a more negative impact. So even if only options to reduce the metal depletion per average European citizen are examined, subsurface construction does not seem a real option. From this point of view building a subsurface supermarket seemed not profitable for the environment compared to an aboveground supermarket. Hard conclusions can, however, not be drawn from only this result. Although the full LCA shows a more negative picture for the subsurface supermarket, this does not say every part of the LCA comes out worse. If one aspect of the LCA is dominant in creating the difference, it could be possible that the subsurface supermarket comes out better if this dominant aspect is overcome. Some phases of the life cycle of a subsurface supermarket (e.g. Assembly, use phase, and construction) could thus still be positive, which could create opportunities for building in the subsurface. In order to explore these advantages it first had to be known what aspects of the life cycle played a dominant role in the difference between the two main scenarios. This was examined by performing a dominance analysis.

4.1.1 Dominance analysis scenario subsurface 1 vs aboveground 1.

Performing a dominance analysis to examine the impacts of the separate aspects of the LCA is in SimaPro only possible in the LCA of a single product. By doing this for both the aboveground 1 and subsurface 1 scenario, the opportunity arose to compare both graphs in parallel to each other, which made it possible to see what the major cause of the impacts was. This, however, would not show the elements that cause the difference. If one element had the same dominant impact in both products it had the dominant effect but it did not cause the dominant difference. For this reason the difference in indicator result between scenario subsurface 1 and aboveground 1 was examined for each impact category. The resulting differences were put in a stacked bar chart to be able to obtain a dominance analysis on the difference between the two scenarios.

From figure 15 it can be observed that the use phase then came out as the dominant cause of the difference between the subsurface 1 and aboveground 1 scenario. It was also observed that in the assembly some impact categories were more positive for the subsurface building. To get a better picture of where the negative and positive points of subsurface construction are located, the different impact characteristics had to be observed per phase by the same type of dominance analysis. Figure 16 shows that within the use phase, the difference in electricity use between scenario subsurface 1 and aboveground 1 was the deciding factor. Still it was shown in figure 15 that the subsurface supermarket also had some positive aspects.

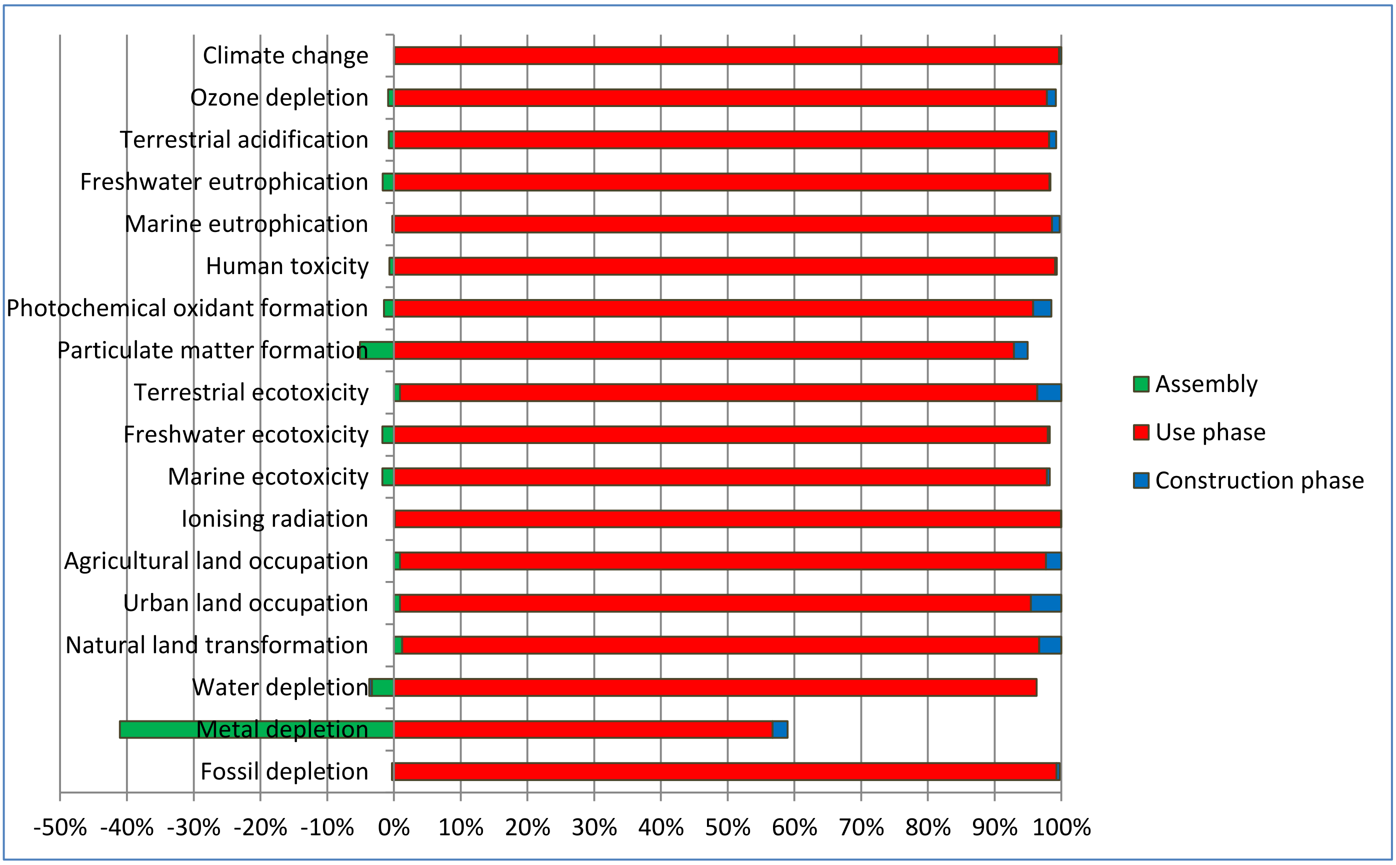


Figure 15 Comparative dominance analysis between scenario subsurface 1 and scenario aboveground 1 (positive percentage means higher impact for scenario subsurface 1).

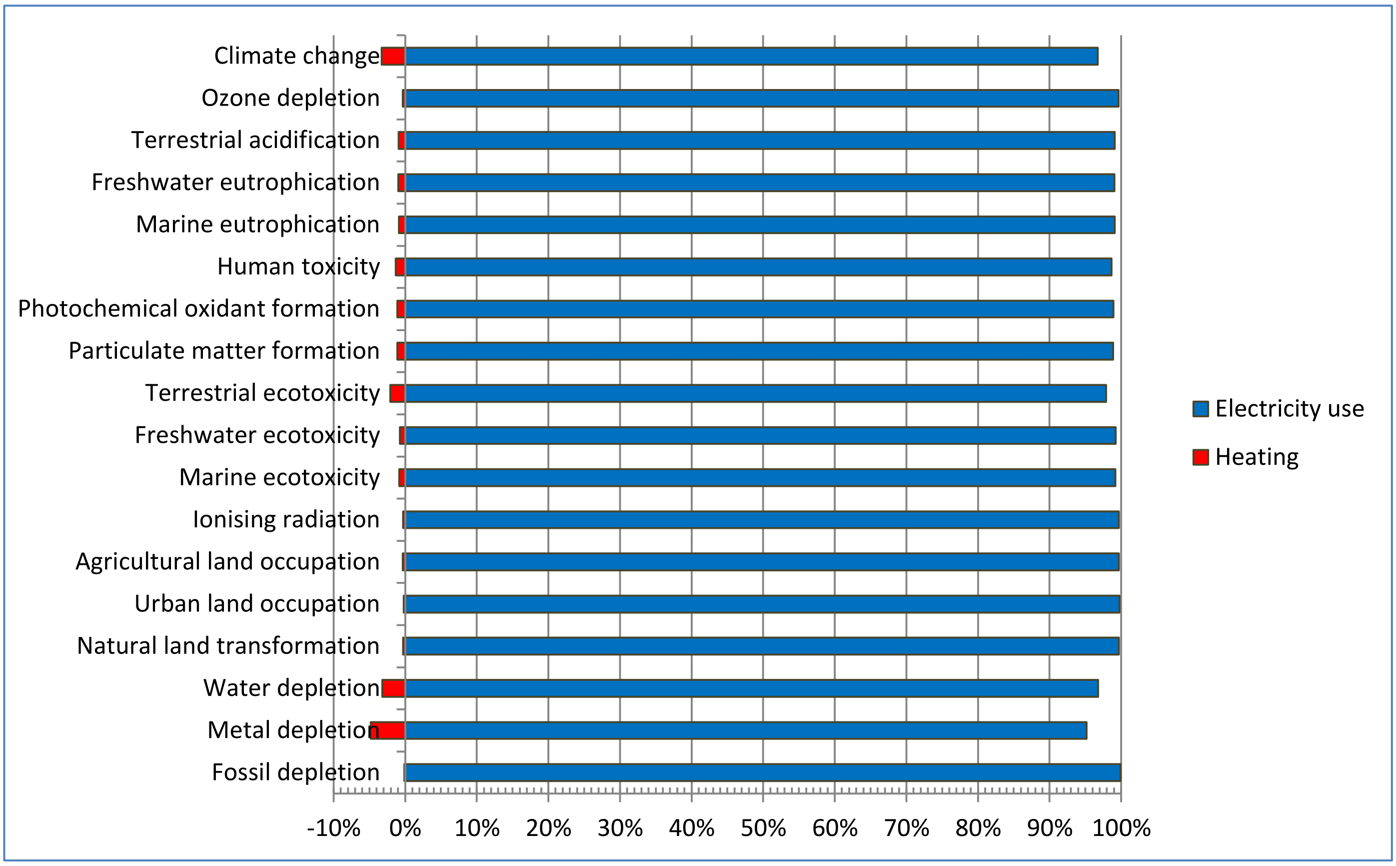


Figure 16 Comparative dominance analysis between the use phase of scenario subsurface 1 and the use phase of scenario aboveground 1 (positive percentage means higher impact for scenario subsurface 1).

Comparing the assembly of the scenarios subsurface 1 and aboveground 1 (see figure 17) showed that the assembly of the subsurface supermarket scored better on 12 of the 18 impact categories. Scenarios aboveground 2 and aboveground 3, however, also showed that this is highly dependent on how much less material can be used in the aboveground building. Looking at the normalized results of the assembly of the two main scenarios showed that the change in the average yearly impact of an average European citizen would only be very small when changing from an aboveground supermarket to a subsurface supermarket. Out of the top 5 impact categories for which the average yearly impact per average European citizen would be influenced the most, only 1 was in favour of the aboveground 1 scenario (see figure 18). When a decision is made to reduce all the environmental impacts examined in this research, no matter what the size of the reduction would become, changing to a subsurface supermarket would, based on the assembly, be an option. Furthermore, it has to be said that this change is made per net m^2 of retail floor space over a period of 100 years. The total change the building causes over a period of 100 years is thus more.

Overall, the assembly of the subsurface supermarket seems to be more positive than the assembly of the aboveground supermarket, although the normalized effect is only small. Based on the results of the assembly the subsurface supermarket could thus become a more serious option to replace the aboveground supermarket, although the normalized effect is only small. Looking in more detail at the cause of this positive effect, by using a dominance analysis (see figure 19), showed that this was only caused by the piles of the building. By performing a completeness check on the information available it was possible to explain that this positive view could even be a good assumption. The completeness check is performed in the next paragraph.

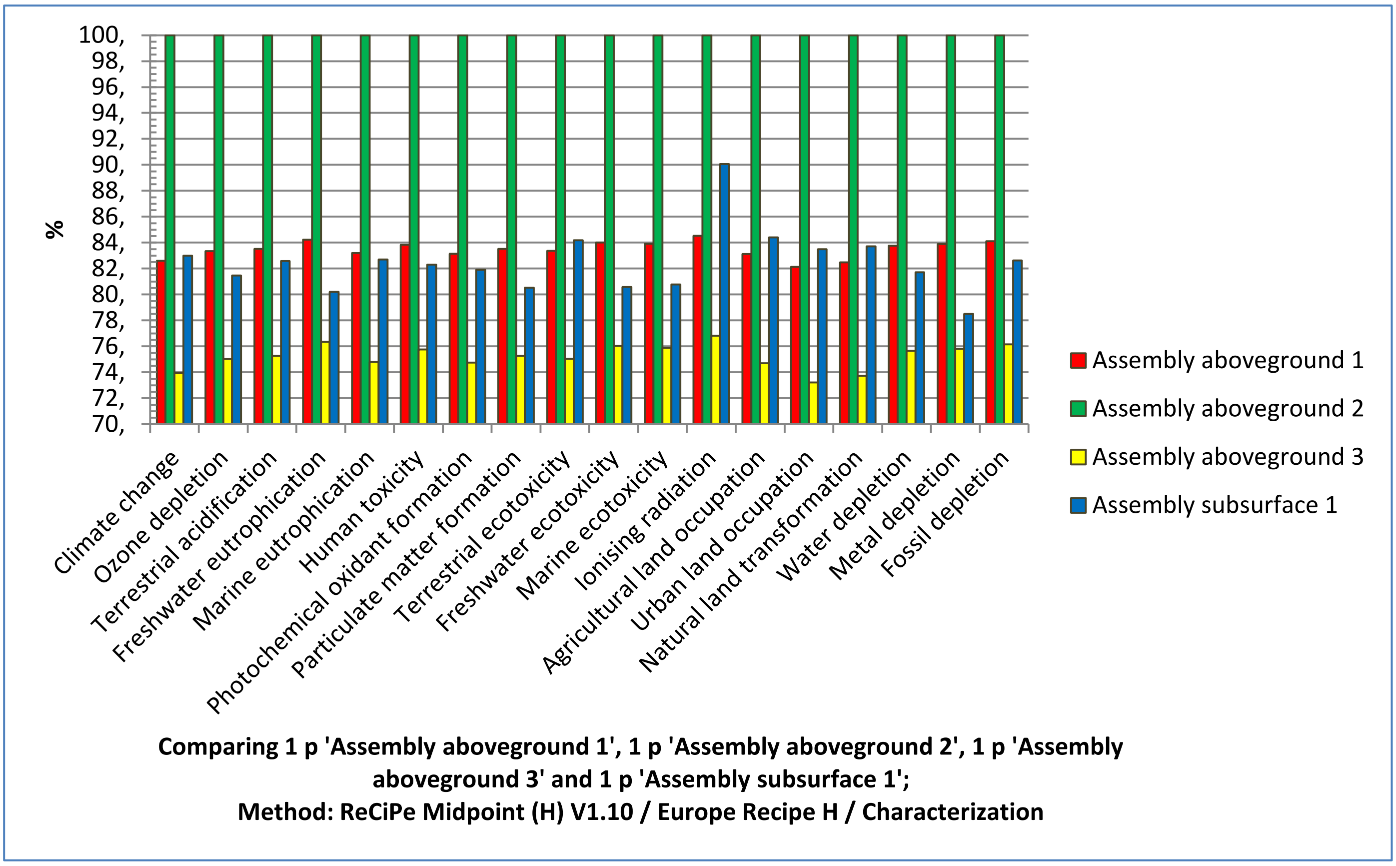


Figure 17 Characterisation results from the comparative impact analysis of the assembly of the two default scenarios and the scenarios with different factors for the material use of the aboveground building.

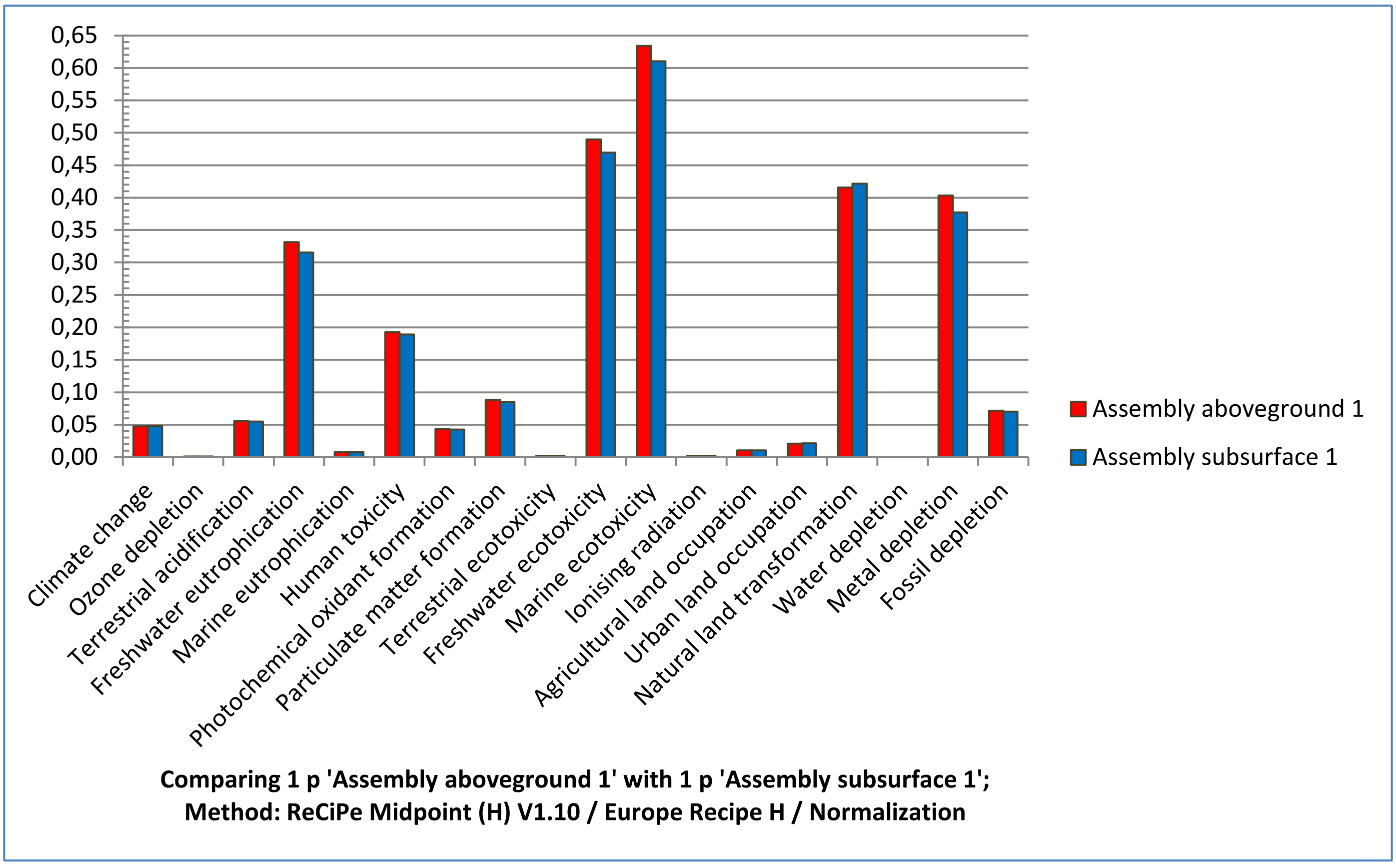


Figure 18 Normalized results from the comparative impact analysis of the assembly of the two default scenarios based on the average yearly impacts of an average European citizen.

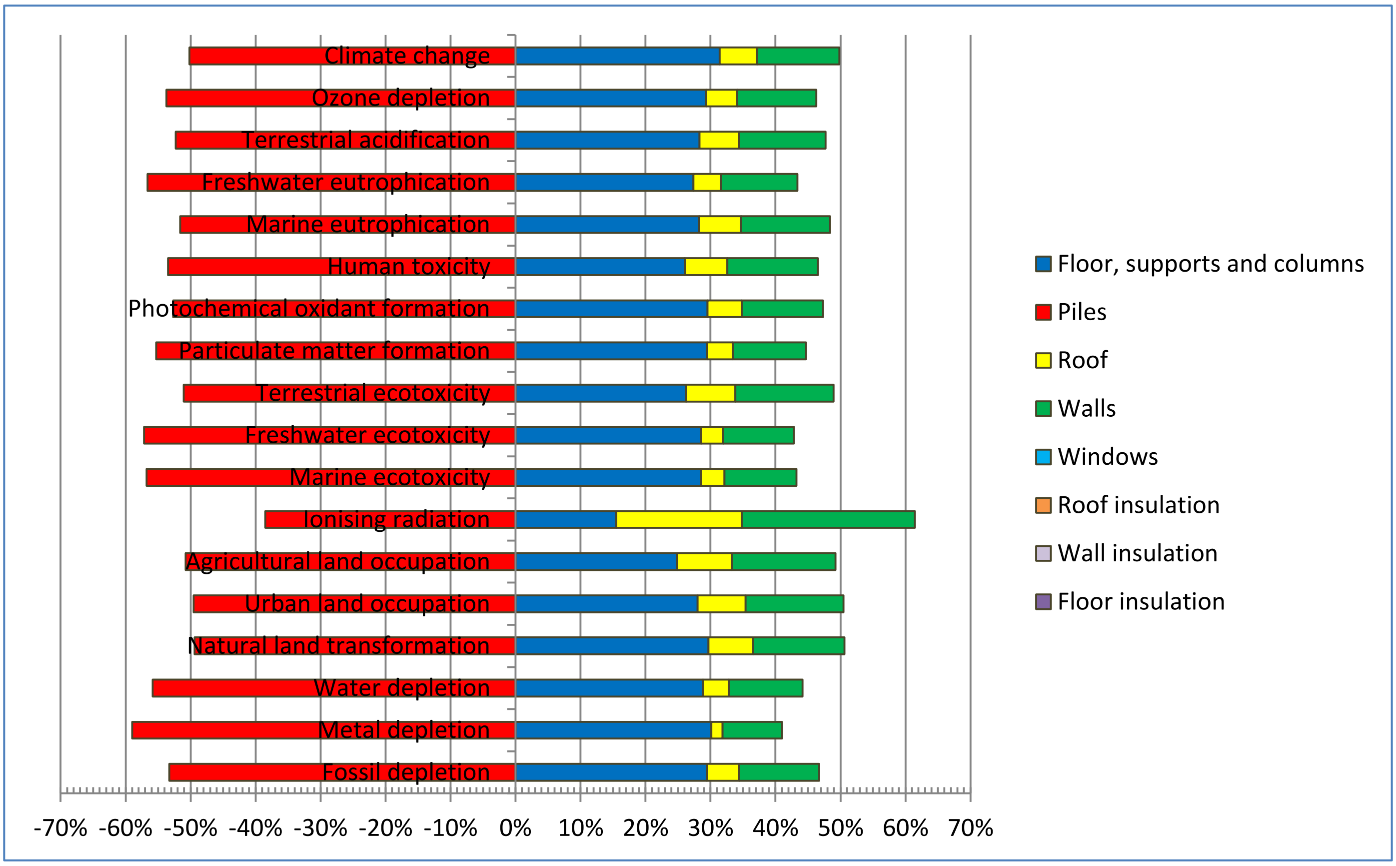


Figure 19 Comparative dominance analysis of the assembly between scenario subsurface 1 compared to aboveground 1 (positive percentage means higher impact for scenario subsurface 1).

4.2 Completeness check

As explained in the introduction, one of the main reasons for examining subsurface construction was the increasing population in combination with urbanization, which puts a pressure on land use. Direct land use is one of the aspects which were not taken into account in the LCA. A supermarket needs parking space for their customers, which takes space. In the subsurface building the parking is located on top of the building, which means customers have to get in the supermarket using an elevator. Still the area of land used is then the same as the building area. In the aboveground building the parking is located next to the supermarket, which meant no elevators were needed. Here the area of land used is the area of the building and the area of parking combined. It is also possible for an aboveground building to build a parking on top or under the building. This would mean the aboveground building would also need elevators to transport people inside and outside the supermarket. In this research the change in electricity use, which was the dominant aspect in the difference between scenario subsurface 1 and aboveground 1, was only caused by the elevators. For this reason it was also important to compare the subsurface 1 scenario with an aboveground scenario that has the same electricity use. For this scenario aboveground 8 was developed, which is the same as the aboveground 1 scenario but which has the electricity use of the subsurface 1 scenario. The resulting comparison (see figure 20) showed that the differences are only small between the subsurface and aboveground scenario. Still the subsurface building seems to score a little better. To observe how important each impact is in comparison with the average yearly impact of an average European citizen, normalization was done. The normalized results in table 4 show that with the same electricity use in none of the impact categories real differences occur in the impact compared to the average yearly impact of an average European citizen. The numbers of impact categories that were more profitable for the subsurface supermarket compared to the aboveground supermarket were also almost equal. Furthermore, in the normalized results the water depletion turns zero. This is caused by the fact that the normalization factor for water depletion was also zero. Still the characterization results showed that water depletion was in favour of the subsurface building, which makes 10 out of the 18 impacts more positive for the subsurface building. According to the normalization results this includes the four impact categories for which the supermarket has the largest share in the average yearly impact per average European citizen.

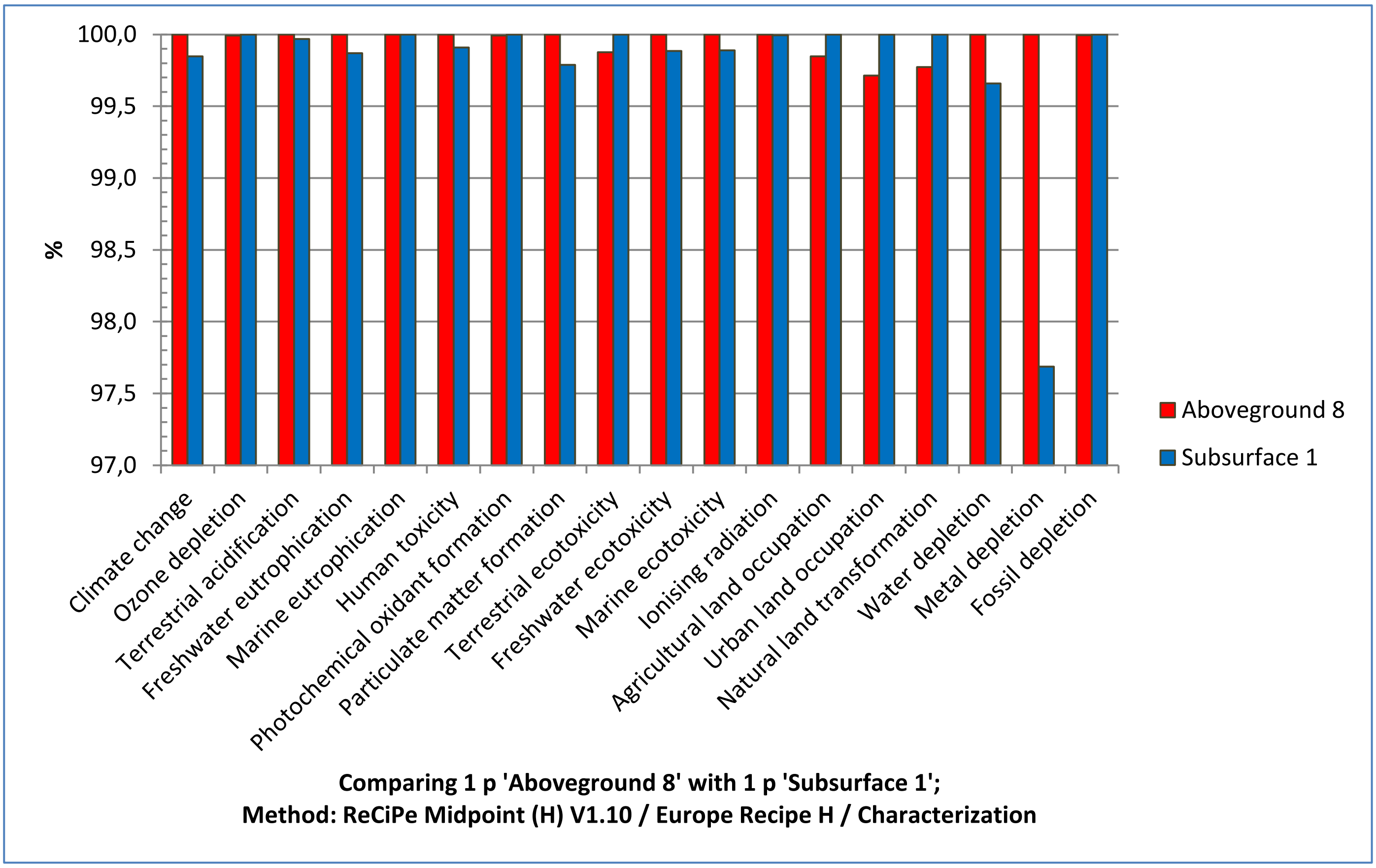


Figure 20 Characterisation results from the comparative impact analysis between scenario subsurface 1 and aboveground 8, which had the same electricity use as the subsurface building.

By checking where the differences were made, using figure 21, it was found that the energy use, which in this case was only heating, and the assembly have a more positive effect for the subsurface building, due to more excavation and sand transport. The construction phase on the other hand is more positive for the aboveground building. Opportunities related to the subsurface building are in increasing the positive effects (heating and the piles) and decreasing the negative ones (Construction, electricity use and parts of the assembly). Before real conclusions could be drawn on these results it was, however, examined how large the uncertainty is in the results. Both an uncertainty analysis and sensitivity analysis could be used to analyse this. As explained in paragraph 2.6 an uncertainty analysis based on a statistical method was, however, not possible with the data used. The uncertainty of the results was then only examined using the sensitivity analysis. This is shown in the next paragraph.

Table 4 Normalized results from the comparative impact analysis between scenario subsurface 1 and aboveground 8. A green box means the lowest impact.

Label	Aboveground 8	Subsurface 1
Climate change	4.453	🟩 4.446
Ozone depletion	🟩 0.04155	0.04156
Terrestrial acidification	1.5494	🟩 1.5489
Freshwater eutrophication	18.113	🟩 18.089
Marine eutrophication	🟩 0.3489	0.3488
Human toxicity	10.195	🟩 10.186
Photochemical oxidant formation	🟩 0.8282	0.8283
Particulate matter formation	1.193	🟩 1.190
Terrestrial ecotoxicity	🟩 0.03637	0.03642
Freshwater ecotoxicity	21.940	🟩 21.915
Marine ecotoxicity	25.972	🟩 25.943
Ionising radiation	1.3452	🟩 1.3451
Agricultural land occupation	🟩 0.3372	0.3378
Urban land occupation	🟩 0.684	0.686
Natural land transformation	🟩 9.454	9.476
Water depletion	0	0
Metal depletion	1.137	🟩 1.110
Fossil depletion	🟩 8.4891	8.4895

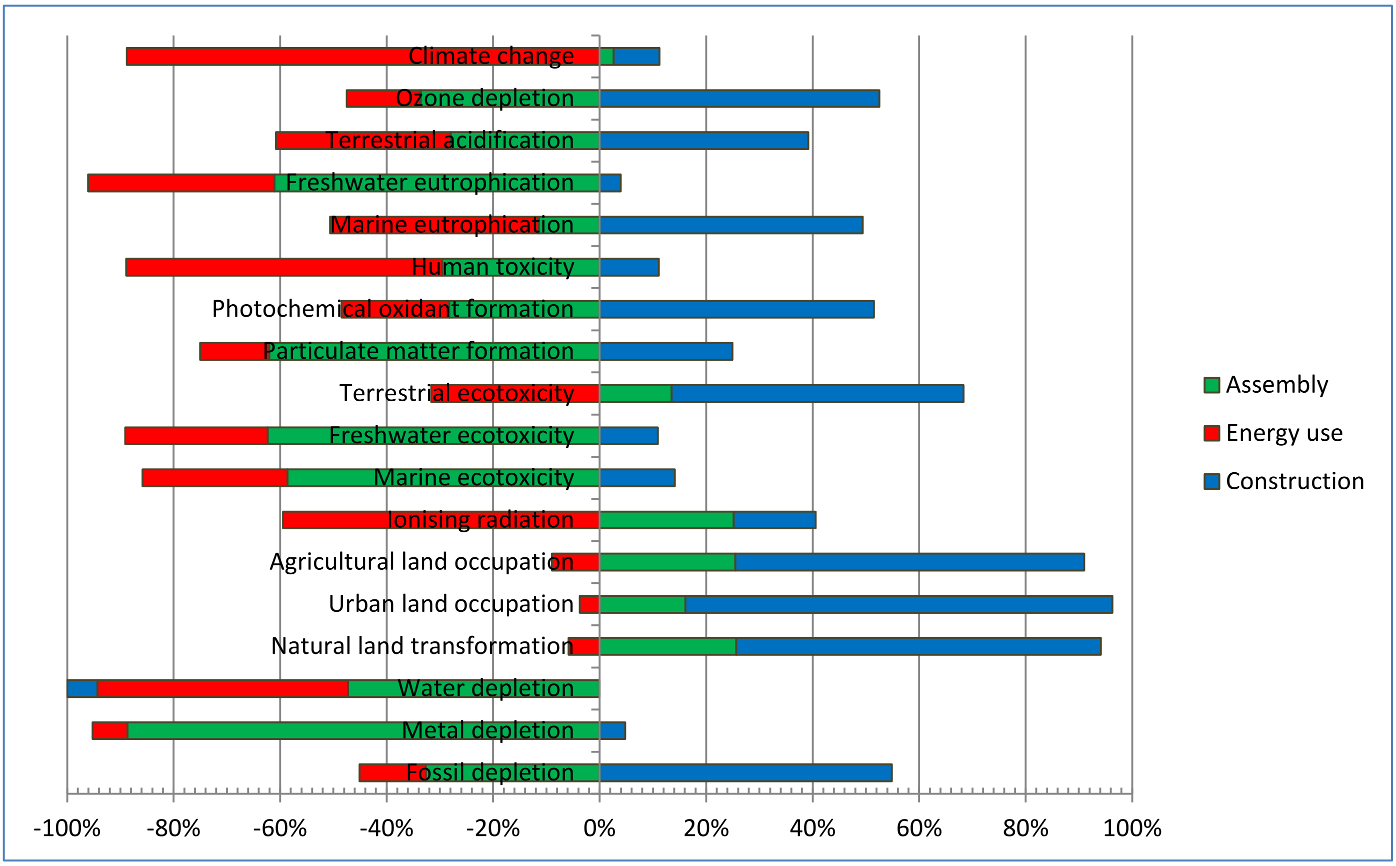


Figure 21 Comparative dominance analysis between scenario subsurface 1 and aboveground 8 (positive percentage means higher impact for scenario subsurface 1).

4.3 Sensitivity analysis

As explained before, in the sensitivity analysis changes are made on the assumptions, data used, method used etc. In this research assumptions were made about the thickness of the wall and floor insulation, and the lifetime of the building. The database used in this research was the consequential database, which is a new type of database. For this reason it was examined if changing the database had any influence on the final results. Another data element examined was the electricity mix. A standard electricity mix of the Netherlands was used as data input for the electricity consumption in the main scenarios. Because the electricity use is the dominant aspect in the difference between the aboveground and subsurface building it was important to examine if the aboveground building still had less environmental impact when a more renewable electricity production method would be applied. Next to changing the assumptions and data, the methodology is changed to see if results are different when other methods were applied. The first thing examined will, however, be the thickness of the insulation layer.

4.3.1 The insulation

Insulation has an effect on different aspects of the LCA. Using more insulation would reduce the heating needed, but it would also cause a larger material use of insulation and in response more transport. The effect of more or less insulation on the different impact characteristics is thus not linear. In this research three insulation layer thicknesses were chosen for both the aboveground and subsurface scenario to be able to observe the effect of a change in the thickness of the insulation layer.

For the subsurface building the scenarios with different insulation layers were the scenarios subsurface 1, subsurface 2 and subsurface 3. Comparing the results in figure 22 showed that using no insulation at all for the subsurface building is not an option. It is furthermore observed that changing the insulation layer did not really have a big impact on the total LCA. Still the thicker insulation layer overall seemed to have the least environmental impact. It only scored worse on natural land transformation. This natural land transformation impact means that the transformation of land is allocated to a product. Take for example mining. With each mass of a specific metal mined, a number of m^2 of existing land are converted to a mining area. The number of m^2 natural land transformation can then be allocated to the mining of a certain mass of metal.

For the aboveground building the scenarios with different insulation layers were the scenarios aboveground 1, aboveground 4 and aboveground 5. In the aboveground building the same trend was observed as in the subsurface building (see figure 23). Using no insulation at all is again not an option and having more insulation did not have a significant impact on the results. Still, having more insulation seemed to be more environmentally beneficial for almost all impacts except for the natural land transformation. Comparing the results of the subsurface with the aboveground building it was also observed that for the aboveground building changes in the insulation layer have a larger effect on the impacts. This means that in further research it could be important to explore the effect of changing insulation layers even further.

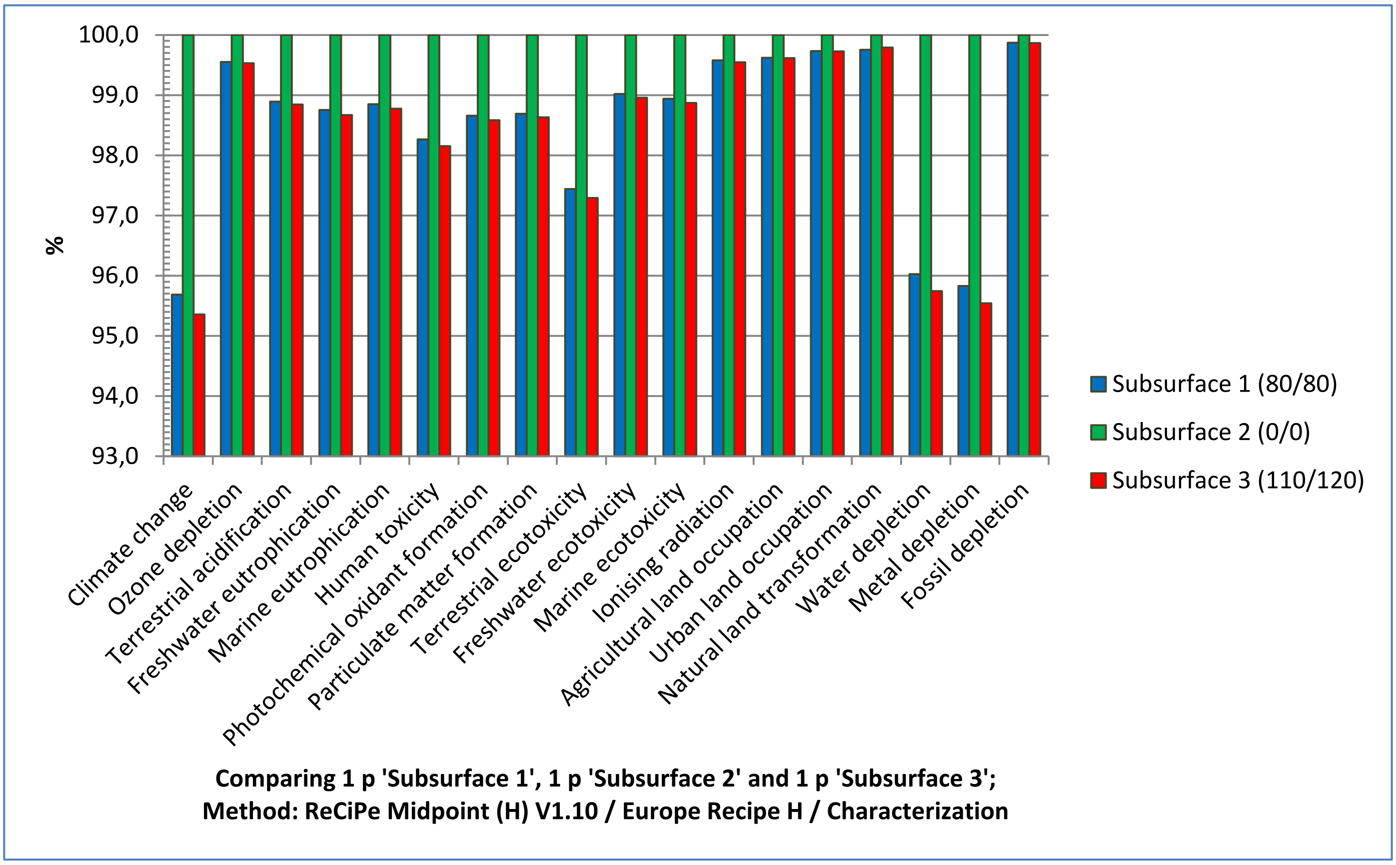


Figure 22 Characterisation results from the comparative impact analysis between the different insulation scenarios of the subsurface building, which are subsurface 1, subsurface 2, and subsurface 3.

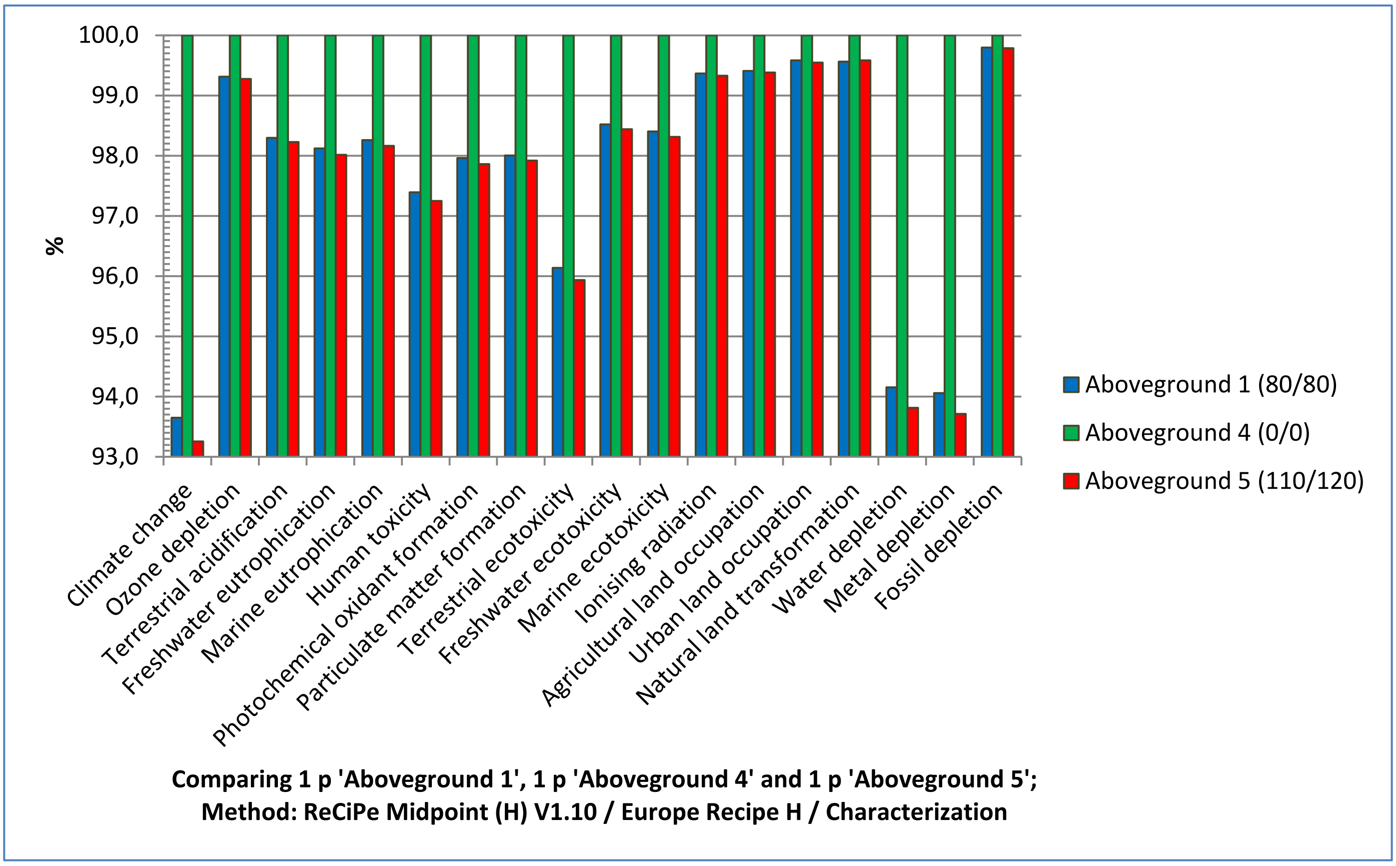


Figure 23 Characterisation results from the comparative impact analysis between the different insulation scenarios of the aboveground building, which are aboveground 1, aboveground 2, and aboveground 3.

4.3.2 The lifetime

In the subsurface the building materials were put under different conditions as the aboveground building. A difference in conditions, like for example the weather influences, UV-radiation and microbiological activity, can create a situation in which materials degrade faster in one of the two situations. This would influence the lifetime of the building. This research looks at a period of 100 years. If one building has a shorter lifetime, this would mean that a new building would need to be built or renovations are needed more often. This increases the material usage for the building with the shorter lifetime over a period of 100 years. In this research the effect of the lifetime was examined in three scenarios. In these scenarios the lifetime of the aboveground building was the same, halve or double that of the subsurface building. Scenario aboveground 1 was the scenario in which the lifetime was the same, which is 100 years. In scenario aboveground 6 the lifetime was 50 years and the amount of materials is doubled. In scenario aboveground 7 the lifetime was 200 years, so the amount of materials was halved. Although these scenarios are extreme and not very realistic, they were still used to show the effect of changing the lifetime of the materials. The energy use and construction were not changed because it was assumed the ground was already dug out and the building would just keep using the same amount of energy.

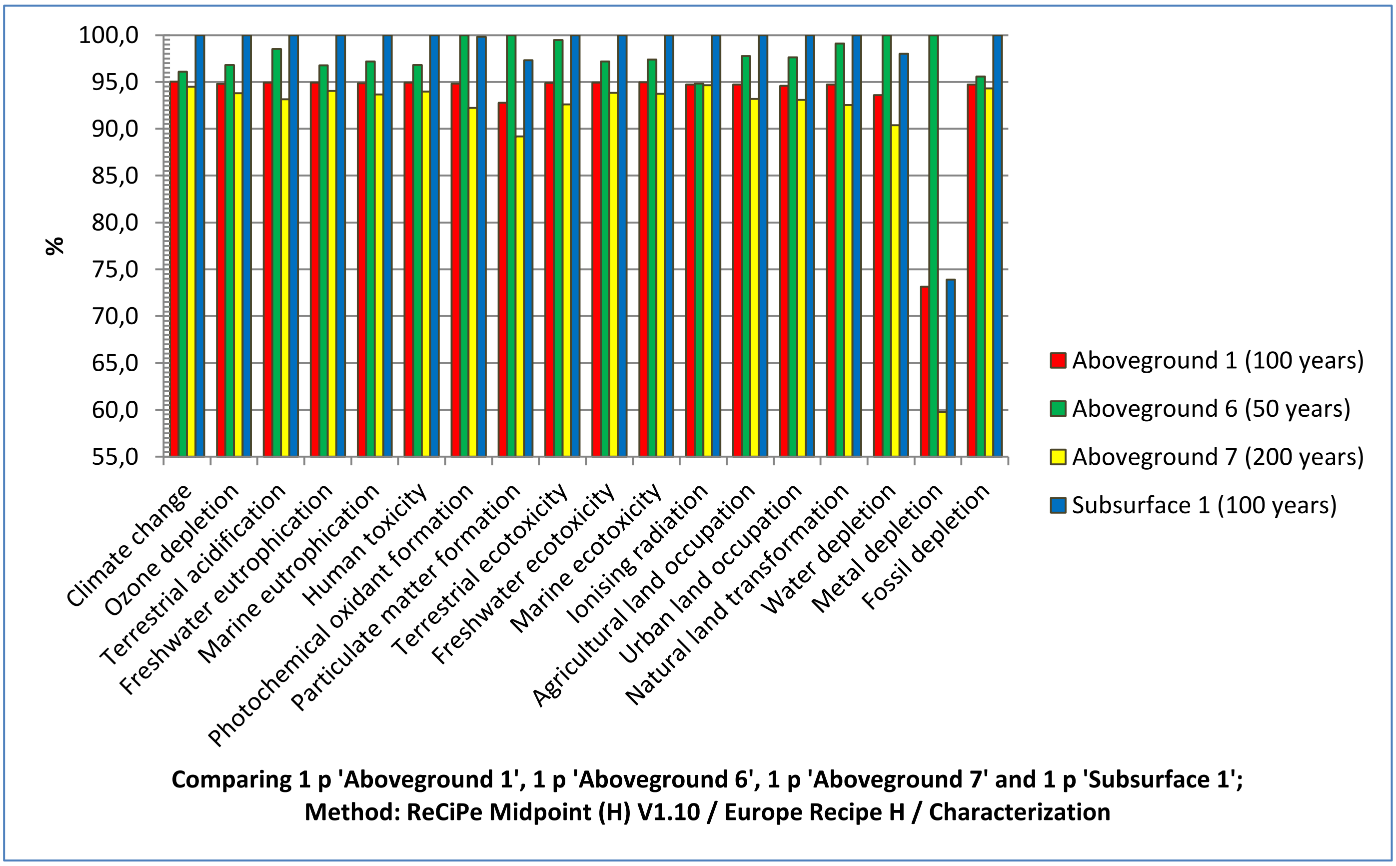


Figure 24 Characterisation results from the comparative impact analysis which compares different lifetimes for scenario aboveground 1 with scenario subsurface 1.

Comparing the life cycle of different lifetimes in figure 24 shows that if the lifetime of the aboveground building is halve that of the subsurface building, the subsurface building still only scores better on 4 impact categories. The electricity use thus is so influential in the LCA that even a much larger lifetime does not change the overall results. In order to see the effect without the electricity use the lifetime was changed the same way in scenario aboveground 8, which is scenario aboveground 1 with the electricity use of the subsurface building. This created scenarios 9 (50 years) and 10 (200 years).

Compared to scenario aboveground 8, already 10 out of the 18 impact categories were in favour of the subsurface building (see figure 20). Changing the lifetime, as observed in figure 25, showed that when the aboveground building has halve the lifetime of the subsurface building it scores worse on all impacts. However, if the lifetime of the aboveground building is double that of the subsurface building the aboveground building would score better on all impacts. This makes the lifetime an important factor for future research.

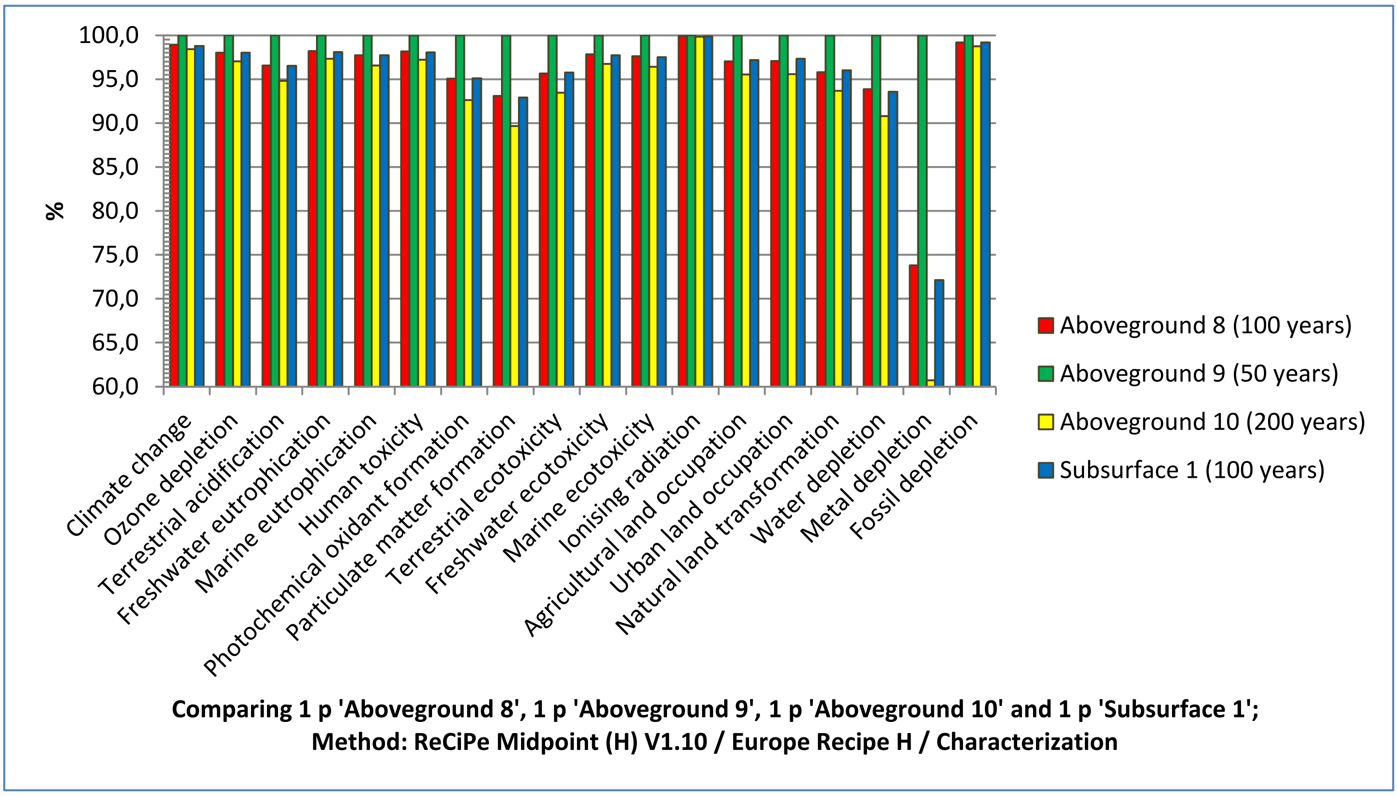


Figure 25 Characterisation results from the comparative impact analysis which compares different lifetimes for scenario aboveground 8 (subsurface electricity) with scenario subsurface 1.

4.3.3 The electricity production mix

The results of the different scenarios showed that the electricity use has a very dominant effect in the comparison between the aboveground and subsurface scenarios. In all these scenarios the electricity use of the building was produced by the high voltage electricity mix of the Netherlands. The electricity mix changes based on the type of database chosen. According to Bauer (2014) in the consequential database only unconstrained suppliers are taken into account. For electricity markets this means only processes with electricity as a reference product are taken into account. When electricity is a by-product the production is dependent on the production of the reference product. For this reason electricity produced by combined heat and power (CHP), waste and biofuels is not taken into account. Furthermore, the consequential database uses a future electricity mix based on the competitiveness of the technologies in the current market. Technologies that are not competitive will thus be phased out. New electricity producing technologies, like solar power, were also not taken into account in the consequential database if these were not seen in the current electricity mix. These new technologies would, however, also not be observed in the allocation database. The last difference between in the electricity mix in the consequential database compared to the allocation database is the import of electricity from other countries. In the consequential database imports are not taken into account (Ecoinvent Centre, 2013).

Looking closer at the data behind the electricity mix that was used in this research shows that the majority of the electricity in the mix is produced by hard coal, which is not assumed a really sustainable fuel (see table 5). Nuclear and different types of wind power have almost the same share but still much lower than the share of hard coal. Hydro has the lowest share in this mix. This electricity mix is different from the current electricity mix for the Netherlands as shown by the International Energy Agency (IEA, 2012) and the Centraal Bureau voor de Statistiek (CBS, 2014). The major difference noticed is the electricity production from natural gas, which is missing. The electricity production with natural gas from 2008 to 2012, however, showed a decrease, which means it was getting less competitive. This decreasing trend was also seen for oil. In the future mix the electricity production plants that use natural gas and oil will then be replaced by more competitive ways of electricity production.

Table 5 Electricity mix, according to SimaPro, in the "high voltage, electricity production" of the Netherlands.

Fuel	**Share in electricity mix of the Netherlands (%)**
Hard coal	72.2
Wind	14.24
Nuclear	13.24
Hydro	0.34

The final electricity mix used in this research shows that it is still relying for a large share on fossil fuels. With renewable technologies improving, these could become a bigger player in the market of the future. Changing to a fully renewable energy source could maybe give more positive results for the subsurface 1 scenario compared to the aboveground 1 scenario. For this reason the effect of using three types of renewable electricity were examined, which are hydro, offshore wind, and solar electricity (see table 6).

Table 6 Different fuel types for electricity production selected and examined in SimaPro

Fuel type	***Process used in SimaPro***
Hydro	Electricity, high voltage {NL}| electricity production, hydro, run-of-river | Conseq, U
Wind	Electricity, high voltage {NL}| electricity production, wind, 1-3MW turbine, offshore | Conseq, U
Solar	Electricity, low voltage {NL}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Conseq, U

In the comparison of the default scenarios with the electricity mix of the Netherlands, none of the impact categories was more positive for the subsurface building. Looking at the characterization results when the electricity use of the building is fully provided by hydro power (see figure 26), it was seen that the subsurface building scores better on four impacts. Furthermore, it was observed that the difference between the impacts became smaller for most impacts when using hydro power. Changing to hydropower thus did not really have a major effect.

When looking at the results from wind power (see figure 27), the subsurface building scored only better on climate change. For the other impacts the difference between the impacts did not really increase much. Changing to wind power thus did not really have a major effect. The results from solar power showed even less improvement. None of the impact categories scored more positive for the subsurface building and the difference between the impacts seemed to stay around the same. Changing to solar power thus did not really have a major effect on the comparison (see figure 28). Although some impacts became better when changing to hydro and wind power, the effects were not enough to make the subsurface building more positive. The electricity use of the subsurface building should thus be tackled from the demand side instead of the supply side.

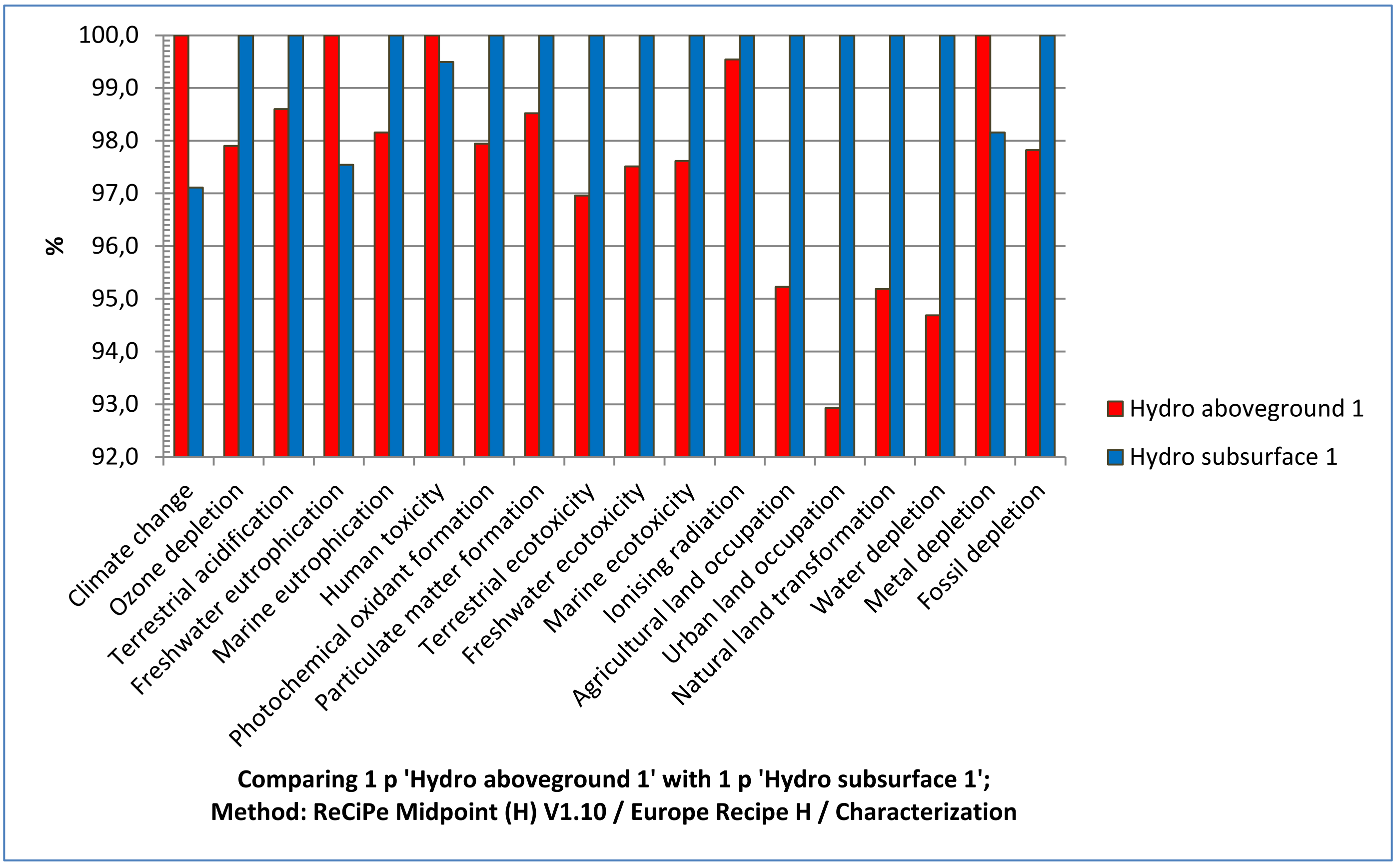


Figure 26 Characterisation results from the comparative impact analysis of the default scenarios using hydro power for electricity production.

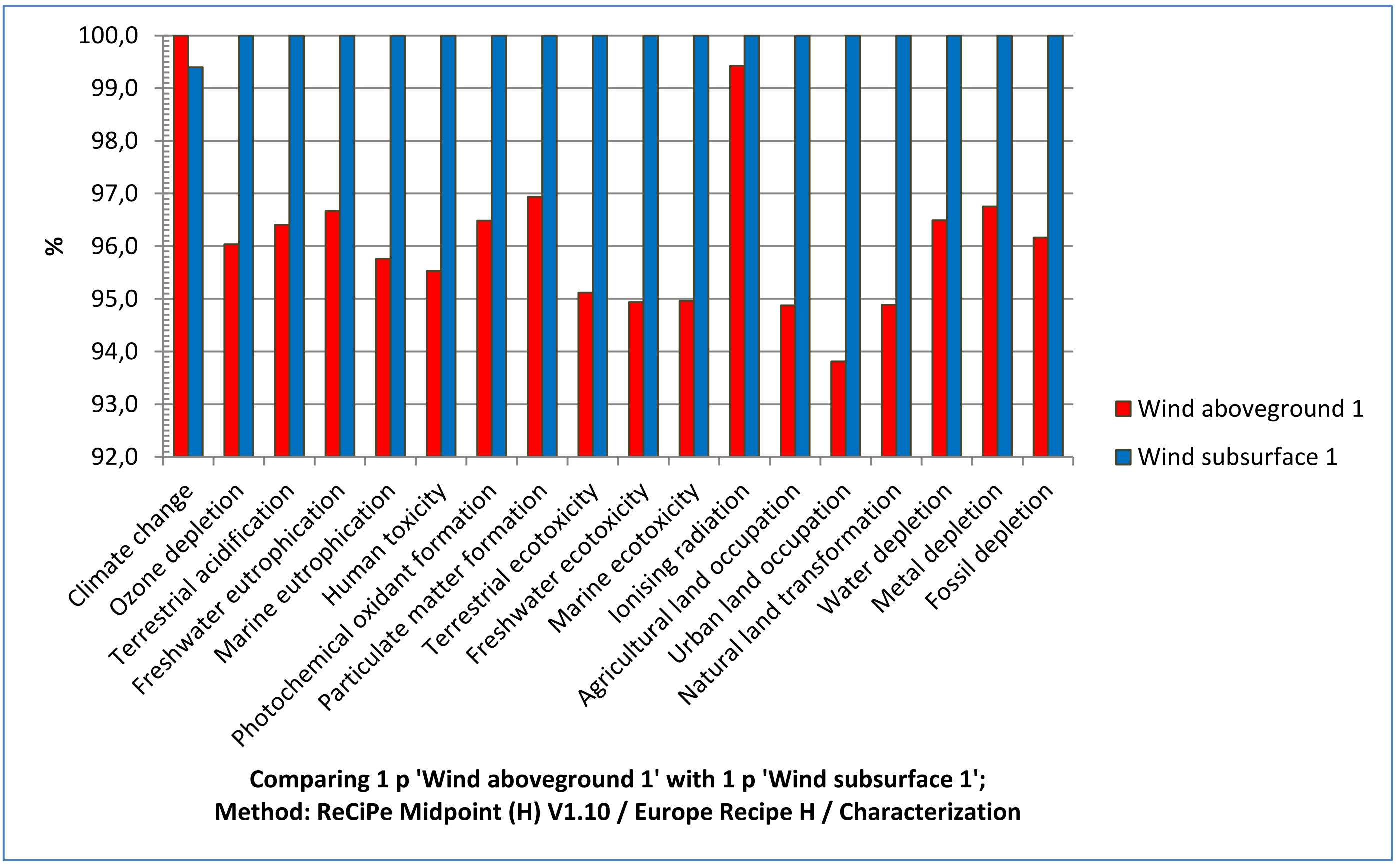


Figure 27 Characterisation results from the comparative impact analysis of the default scenarios using wind power for electricity production.

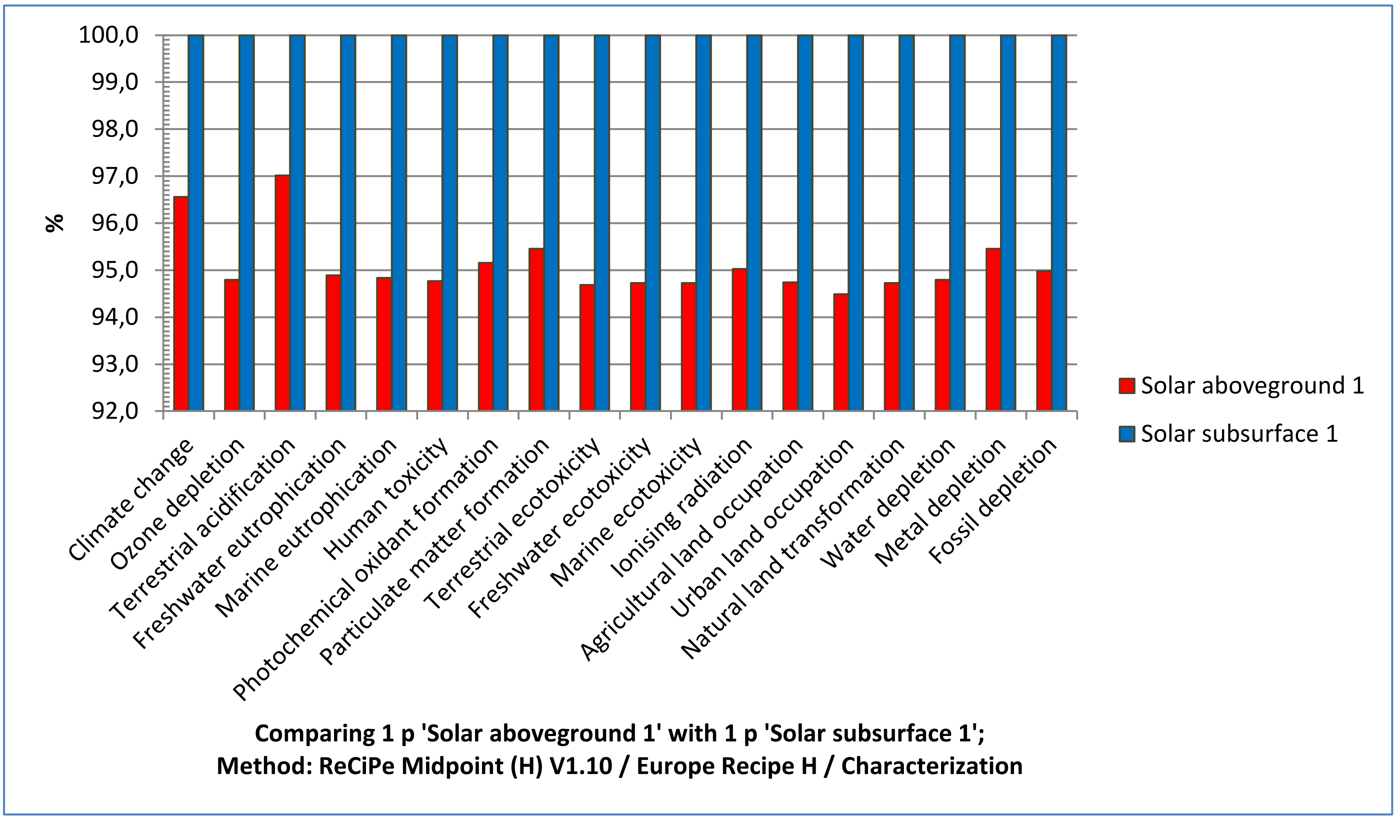


Figure 28 Characterisation results from the comparative impact analysis of the default scenarios using solar power for electricity production.

4.3.4 Choice of database

As was mentioned in paragraphs 3.4 and 4.3.3 the consequential database looks more into the future processes that are expected to dominate the markets according to present trends. Within the two databases differences could occur in the datasets that are included per proces. This could influence the results. For this reason a comparison is made between the results with the consequential database and results using the allocation database.The results examined are the full LCA and assembly comparison between the two main scenarios subsurface 1 and aboveground 1.

Comparing the characterization results from the full LCA shows that by using the allocation data (see figure 29) the final conclusion regarding the results does not change compared to using the consequential data (see figure 30). The aboveground 1 scenario still scores better on all impact categories. However, the difference in the impact per impact category is larger when using the alloaction database. The choice of database then still has an influence on the results itself.

Comparing the characterization results of the assembly of the scenarios subsurface 1 and aboveground 1 shows a different story. Using the allocation database 11 of the 18 impact categories were better for the subsurface 1 scenario (see figure 31). When using the consequential database 12 of the 18 impact categories better (see figure 32). The scenario that scores better per impact category also changes. Using the consequential database the ozone depletion, marine eutrophication and water depletion impact categories score better for the subsurface 1 scenario, where the same impact categories score better for the aboveground 1 scenario when using the allocation database. For the impact categories terrestrial ecotoxicity and agricultural land occupation the subsurface 1 scenario scores better when using the allocation database and the aboveground 1 scenario scores better when using the consequential database. This comparison between the consequential and allocation database shows that the choice of database could change the outcome of the results. The choice of the database should thus be taken with care.

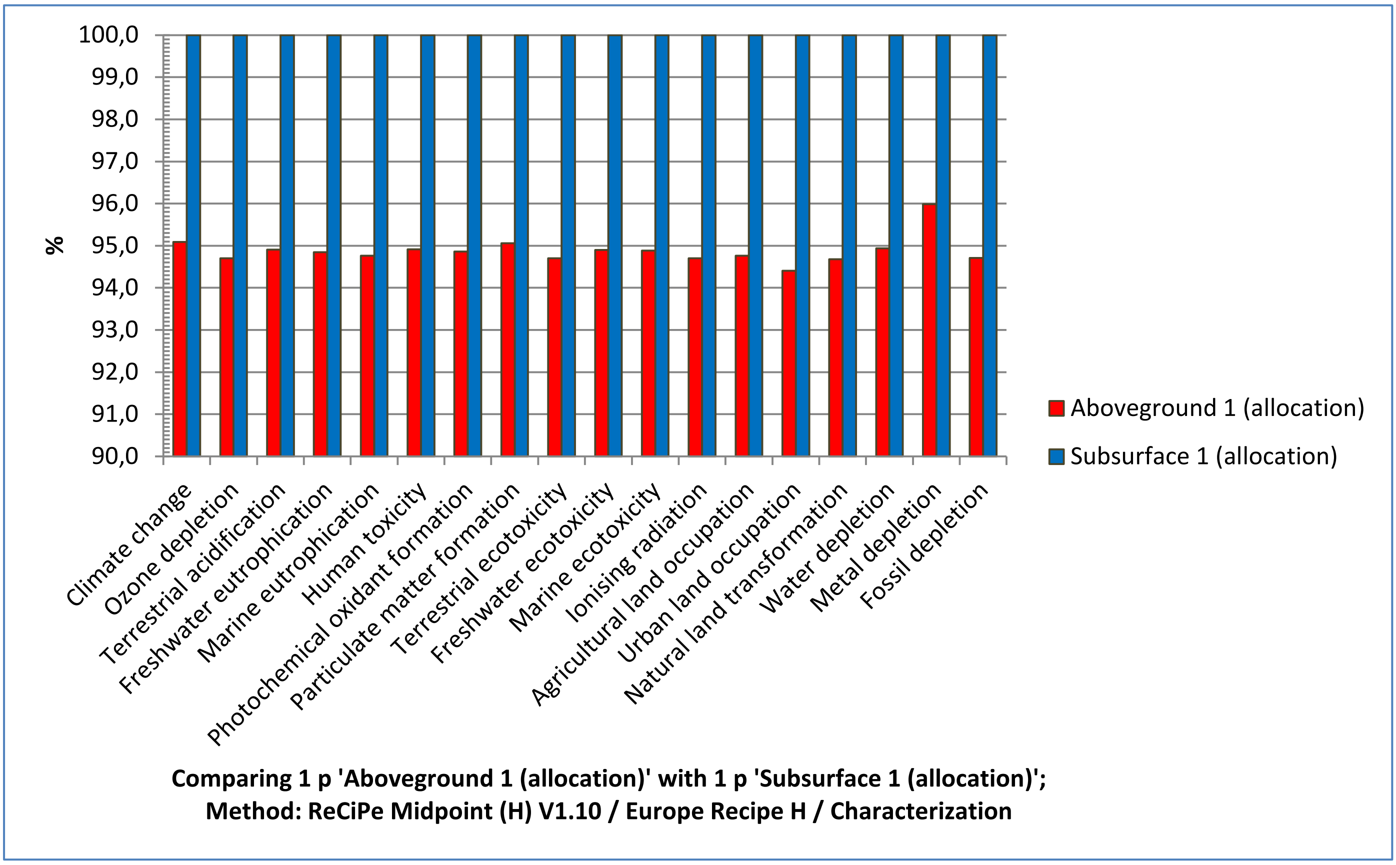


Figure 29 Characterisation results from the comparative impact analysis of the default scenarios subsurface 1 and aboveground 1 using the allocation database.

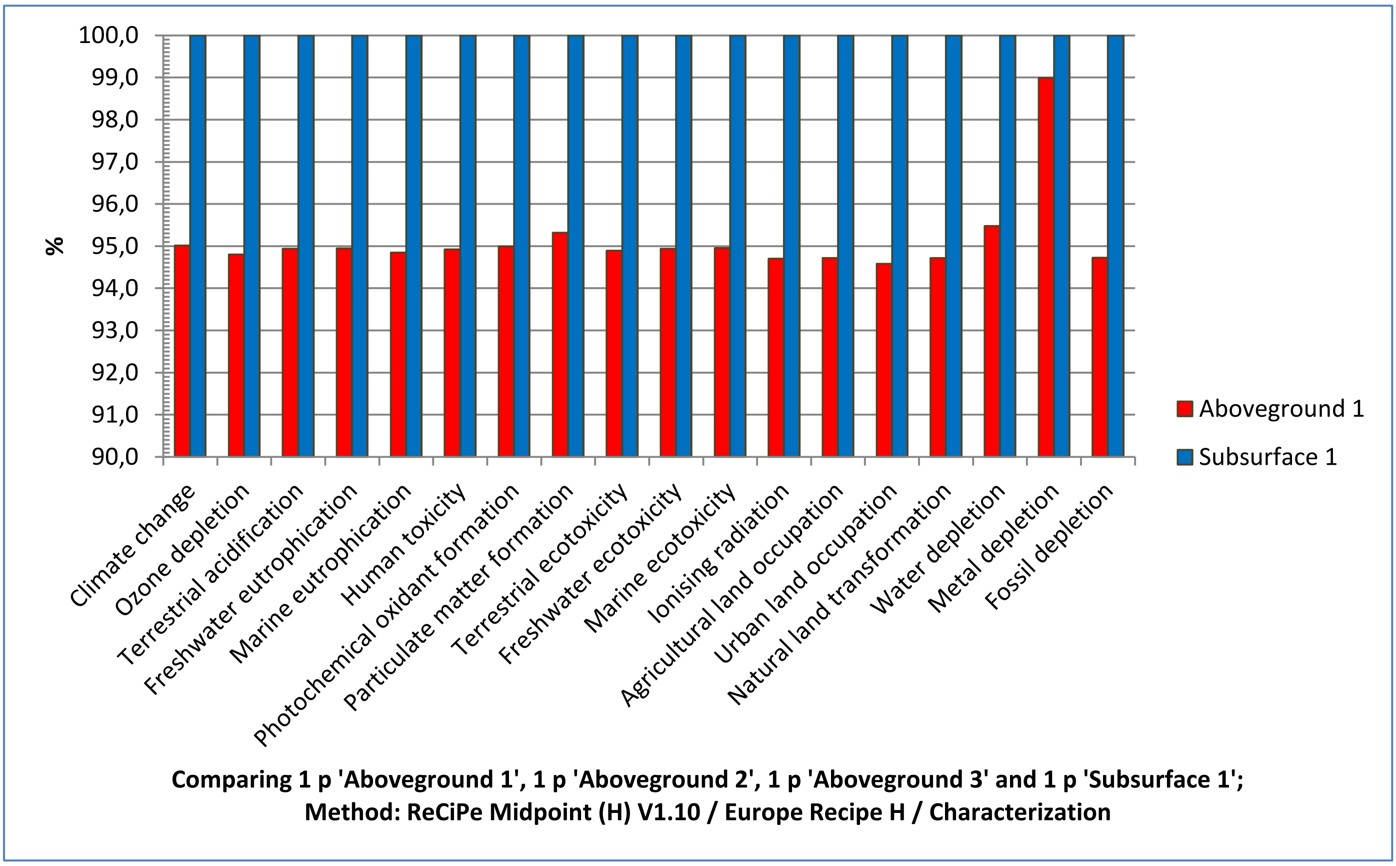
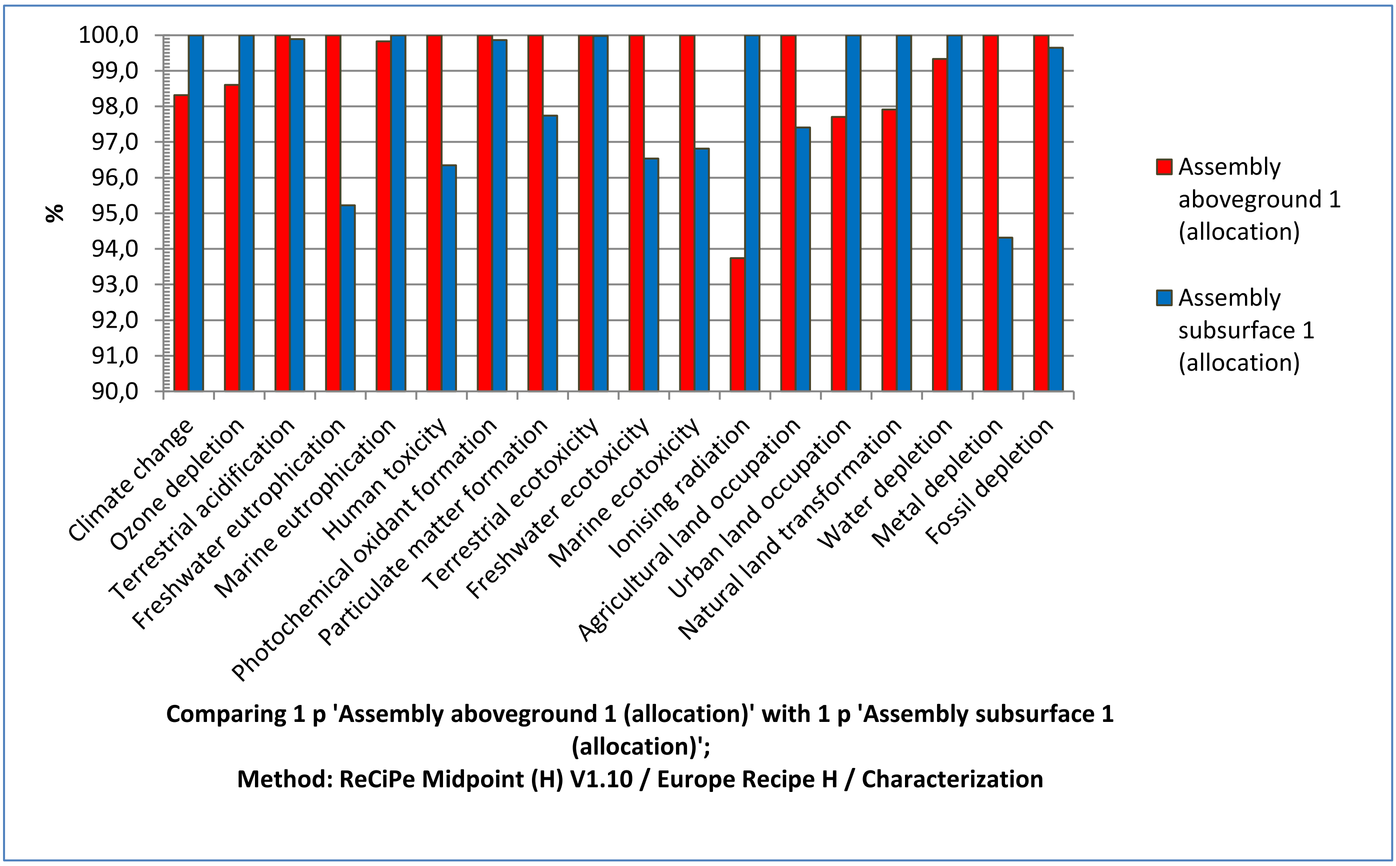
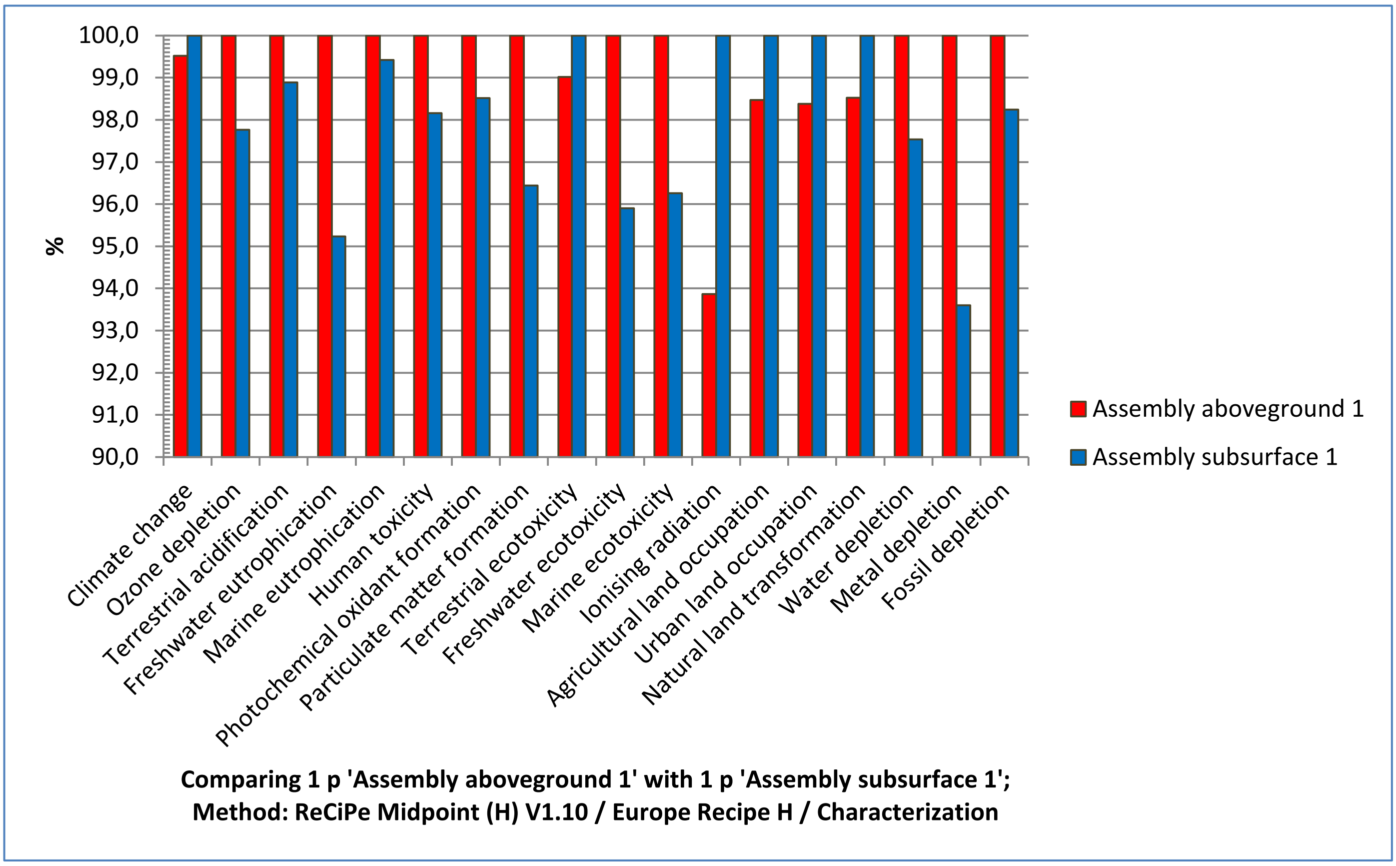


Figure 30 Characterisation results from the comparative impact analysis of the default scenarios subsurface 1 and aboveground 1 using the consequential database.



Comparing 1 p 'Assembly aboveground 1 (allocation)' with 1 p 'Assembly subsurface 1 (allocation)';
Method: ReCiPe Midpoint (H) V1.10 / Europe Recipe H / Characterization

Figure 31 Characterisation results from the comparative impact analysis of the assembly of the default scenarios subsurface 1 and aboveground 1 using the allocation database.



Comparing 1 p 'Assembly aboveground 1' with 1 p 'Assembly subsurface 1';
Method: ReCiPe Midpoint (H) V1.10 / Europe Recipe H / Characterization

Figure 32 Characterisation results from the comparative impact analysis of the assembly of the default scenarios subsurface 1 and aboveground 1 using the consequential database.

4.3.5 Cultural perspective

As explained in paragraph 2.5 the cultural perspective can play a role in the results. In ReCiPe there are three cultural perspectives, which are the hierarchist (H), individualist (I) and egalitarian (E). The comparison of the cultural perspective was examined in two ways. First the individualist and egalitarian perspectives were compared with the hierarchist perspective for the aboveground 1 and subsurface 1 scenario (see table 7). The results show the percentage difference in resulting impact. It was observed that in most impact categories the cultural perspective plays no role and no change was observed. When looking at the impact categories that were affected it was seen that the change is only large for the human toxicity, terrestrial ecotoxicity and marine ecotoxicity. The biggest difference with these impact categories is seen in the egalitarian perspective. The perspectives thus did have an influence on the results. However, looking closer at the results from the subsurface 1 and aboveground 1 scenario it was seen that the changes are almost the same for both scenarios. This meant that for the overall results a change in cultural perspective would most likely not have any influence. This was also observed in figure 33 which shows the difference in impact between subsurface 1 and aboveground 1 in the different perspectives. It can be seen that overall the impact of the subsurface 1 scenario is higher for all impact categories in each cultural perspective. The overall results would thus not have changed when another cultural perspective was chosen. But what about the results from the assembly which turned out better in most impact categories for the subsurface 1 scenario in comparison to the aboveground 1 scenario. Looking at figure 34 the assembly will be even better in the individualist scenario. The climate change impact turns from a higher impact in the subsurface 1 scenario to a lower impact. The difference in human toxicity increases in favour of the subsurface 1 scenario, but on the other hand the difference in ionising radiation increases in favour of the aboveground building. No major differences are thus observed.

Table 7 Difference in impact of the individualist and egalitarian perspectives compared to the hierarchist perspective in the aboveground 1 and subsurface 1 scenario. Red means the perspective has a bigger impact and green means the perspective has a lower impact.

	Aboveground 1		***Subsurface 1***	
Impact category	***Individualist***	***Egalitarian***	***Individualist***	***Egalitarian***
Climate change	24.25	-9.52	24.32	-9.54
Ozone depletion	0.00	0.00	0.00	0.00
Terrestrial acidification	-5.64	11.53	-5.65	11.55
Freshwater eutrophication	0.00	0.00	0.00	0.00
Marine eutrophication	0.00	0.00	0.00	0.00
Human toxicity	-96.84	4461.90	-96.81	4462.59
Photochemical oxidant formation	0.00	0.00	0.00	0.00
Particulate matter formation	0.00	0.00	0.00	0.00
Terrestrial ecotoxicity	-0.47	1151.39	-0.47	1150.59
Freshwater ecotoxicity	0.00	0.08	0.00	0.08
Marine ecotoxicity	-34.21	113598.60	-34.25	113565.48
Ionising radiation	-17.35	0.00	-17.35	0.00
Agricultural land occupation	0.00	0.00	0.00	0.00
Urban land occupation	0.00	0.00	0.00	0.00
Natural land transformation	0.00	0.00	0.00	0.00
Water depletion	0.00	0.00	0.00	0.00
Metal depletion	0.00	0.00	0.00	0.00
Fossil depletion	0.00	0.00	0.00	0.00

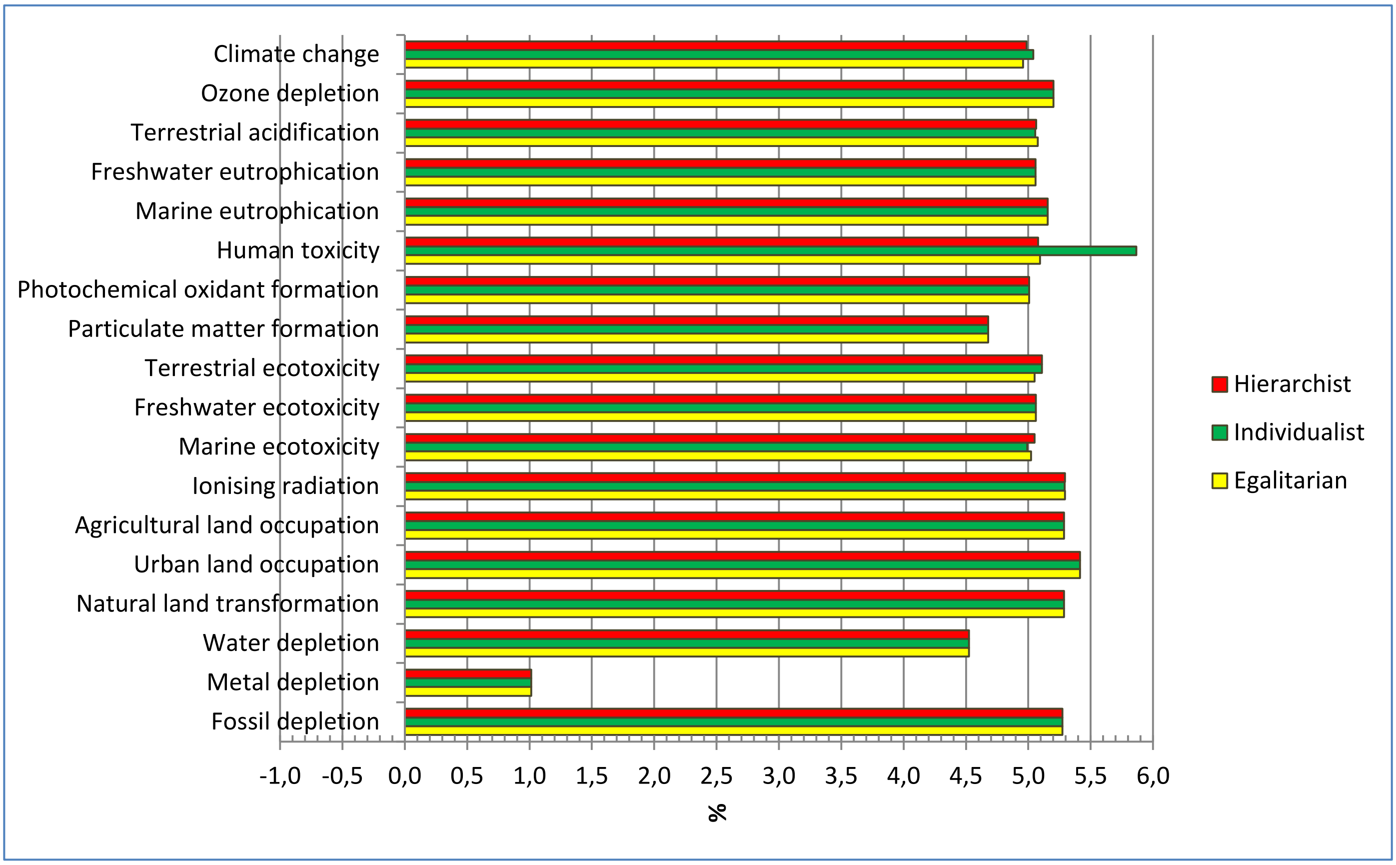


Figure 33 Comparative analysis between scenario subsurface 1 and aboveground 1 in different cultural perspectives (positive percentage means higher impact for scenario subsurface 1).

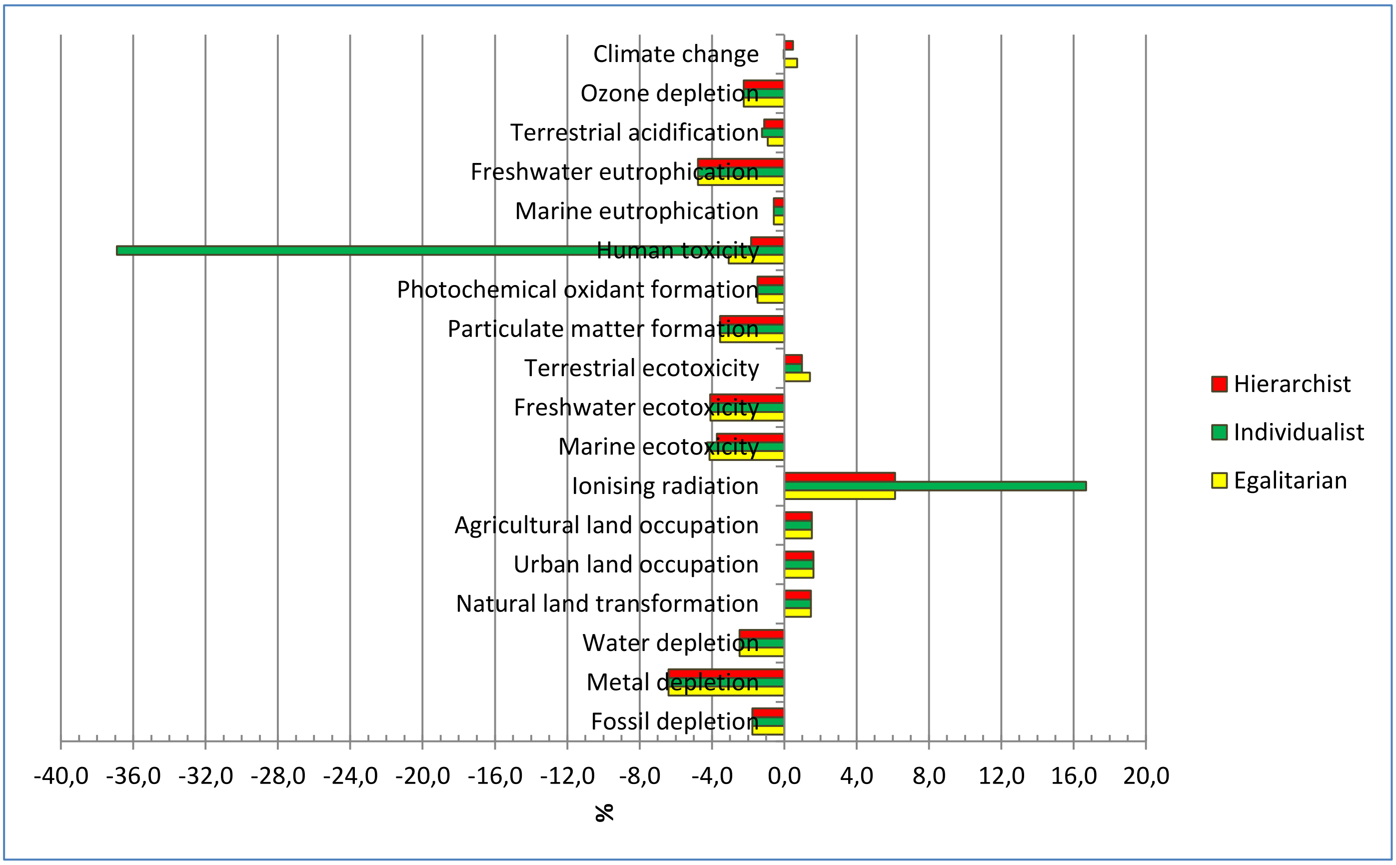


Figure 34 Comparative analysis of the assembly between scenario subsurface 1 and aboveground 1 in different cultural perspectives (positive percentage means higher impact for scenario subsurface 1).

4.3.6 Impact methodology

The main results in this research were based on the midpoint ReCiPe impact methodology. Each methodology, however, has its own impact categories and its own way of calculating the results. For this reason it had to be checked whether other methods showed other results or whether these were the same. As explained in paragraph 2.6, in this research the extra method examined was the Cumulative Energy Demand (CED) method, which only includes non-renewable energy. The reason for this was the dominant role of the electricity use in the LCA. From figure 35 was found that the aboveground 1 scenario also scored better per impact category in comparison to the subsurface 1 scenario with the CED method. This result was then logically also observed at the single point result in figure 36. From the ReCiPe results it was known that the electricity use had a major influence in these results and that the assembly was actually the more positive aspect of the subsurface building. This result was also observed with the CED method. Looking at the characterization of the assembly (see figure 37) the aboveground 1 scenario scores better on nuclear and the subsurface 1 scenario on fossil. Adding up the results in a single score, however, shows that with the CED method the assembly in the subsurface 1 scenario scores better than the aboveground 1 scenario (see figure 38). In the end no real changes in the end results were observed with the CED method compared to the ReCiPe midpoint method.

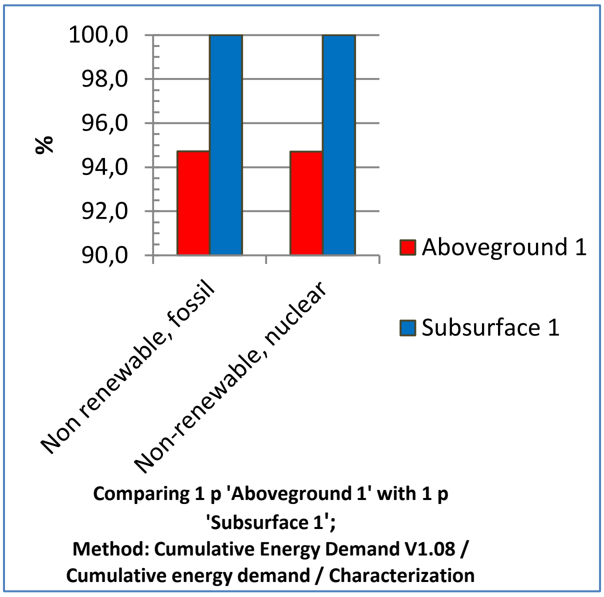


Figure 35 Characterisation results from the comparative impact analysis of scenarios aboveground 1 and subsurface 1 using the CED method.

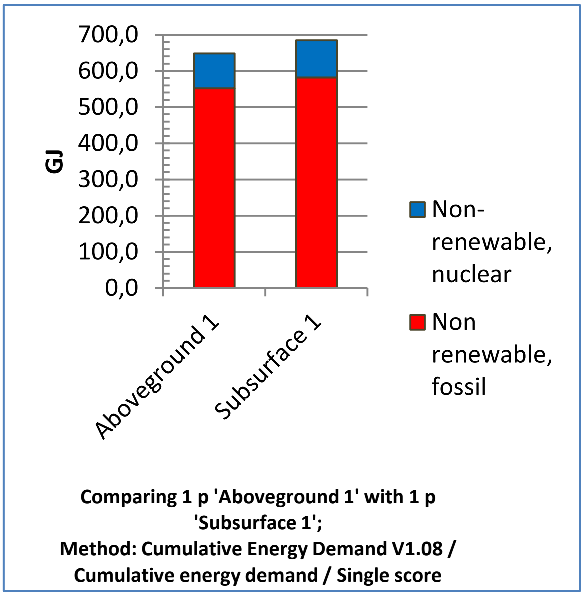


Figure 36 Single score results from the comparative impact analysis of scenarios aboveground 1 and subsurface 1 using the CED method.

The second method to which the ReCiPe midpoint method was compared is the ReCiPe endpoint method. In the endpoint method the different impact categories have a different unit to make it easy to group them. The endpoint method includes only 17 impact categories. The marine eutrophication and water depletion categories, which were present in the midpoint method, are not included. Furthermore, the climate change impact category has been separated in climate change human health and climate change ecosystems in order to prepare the category for grouping. The impact categories were then grouped together into three main categories to have a better overview of the final result. These grouped results were in this research not weighted. The results show that in the endpoint method the impact of the subsurface building was larger for all the different impact categories (see figure 39), which was also the case in the midpoint method. When grouping them together the same result would then also be observed. The assembly showed different results per impact category when using the midpoint method. This makes it useful to compare the grouped results of the assemblies of scenarios subsurface 1 and aboveground 1.

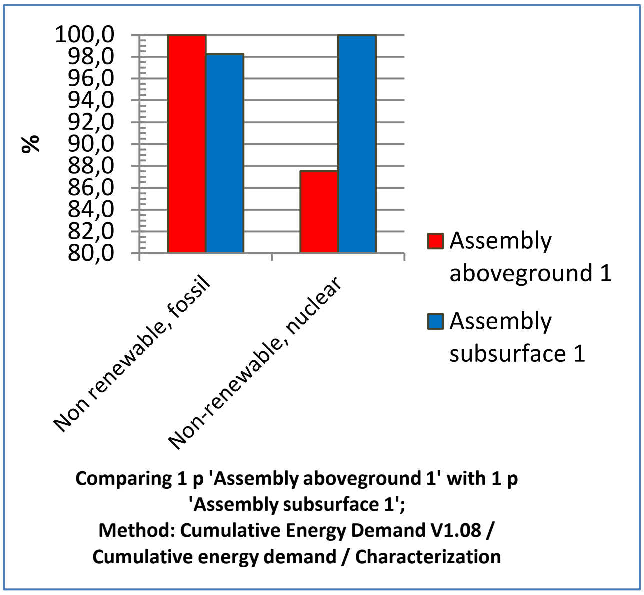


Figure 37 Characterisation results from the comparative impact analysis of the assembly of scenarios aboveground 1 and subsurface 1 using the CED method.

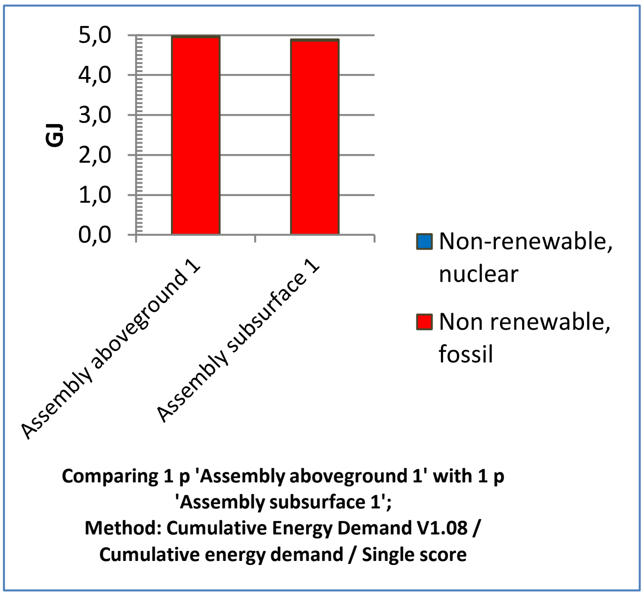


Figure 38 Single score results from the comparative impact analysis of the assembly of scenarios aboveground 1 and subsurface 1 using the CED method.

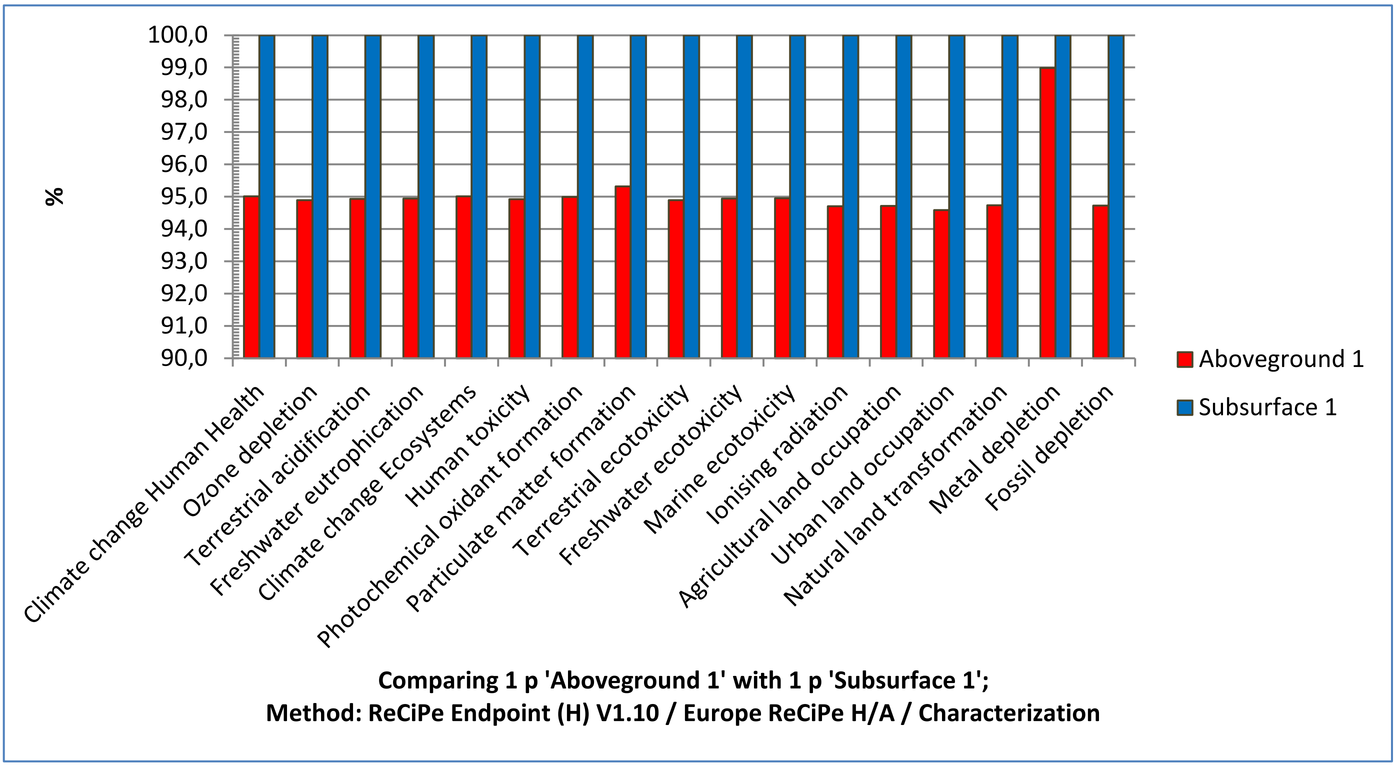


Figure 39 Characterisation results from the comparative impact analysis of scenarios aboveground 1 and subsurface 1 using the ReCiPe endpoint method.

Looking at the damage assessment of the assembly showed that the aboveground supermarket scored better on the "Ecosystem" endpoint indicator (see figure 40). The subsurface building, however, scored better on both the "Human Health" and "Resources" endpoint indicator. These results were based on percentages per endpoint category. This did not say anything about the size of the effect of changing from scenario aboveground one to scenario subsurface 1 could have. By performing a normalization based on the average yearly impact of an average European citizen the size of the effect was observed (see figure 41). The normalized results showed that the overall difference of all three endpoint categories between the assemblies of scenarios aboveground 1 and subsurface 1 is in favour of the subsurface 1 scenario. The assembly in the subsurface 1 scenario thus also scores better than the aboveground 1 scenario in the ReCiPe endpoint method.

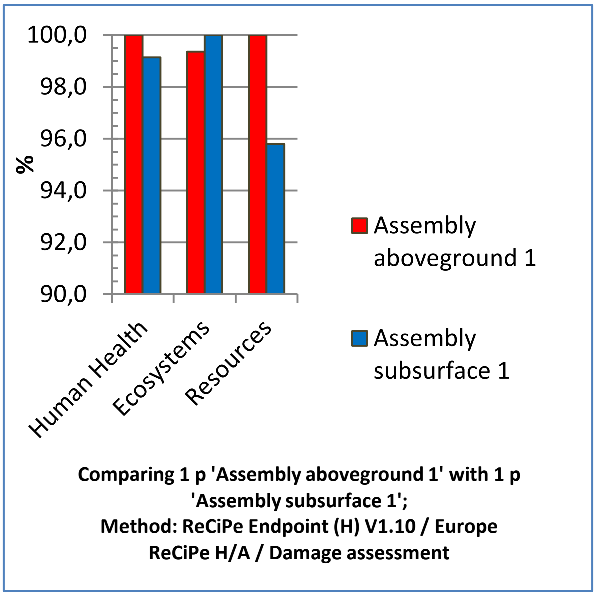


Figure 40 Damage assessment results from the comparative impact analysis of the assembly of scenarios aboveground 1 and subsurface 1 using the ReCiPe endpoint method.

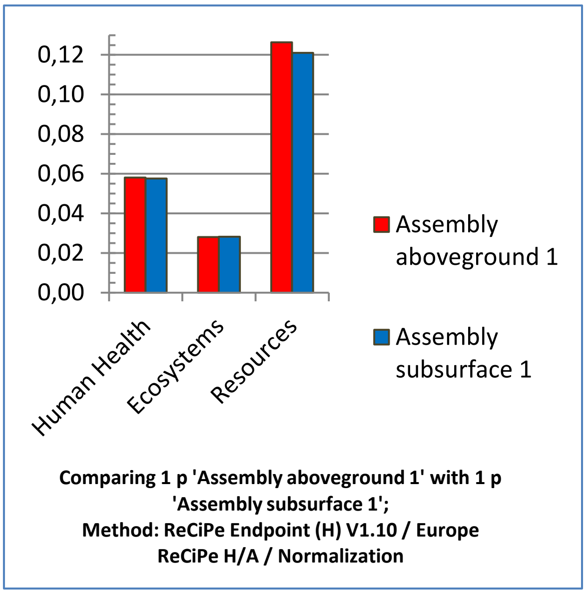


Figure 41 Normalized results from the comparative impact analysis of the assembly of scenarios aboveground 1 and subsurface 1 using the ReCiPe endpoint method.

The ReCiPe endpoint method in the end did not show real changes in results with the ReCiPe midpoint method. This was also the case with the CED method. It seemed that changing the method did not have a major impact on the results. Although not all methods were examined it can be assumed that the main conclusions that were drawn from this research would not be affected by a change in impact methodology.

5. Conclusion

The world these days faces some major challenges for the future. The increasing population size and urbanization are challenges that put pressure on the space that is available on planet earth. The available land has to be used efficiently. In a lot of cities this is done by using high rise buildings. A less explored option is building in the subsurface. It is, however, unknown if this really is a more sustainable way of building. The aim of this research was to obtain a first view on the sustainability of a subsurface building compared to an aboveground building by looking at the environmental impact. Based on legal aspects the choice was made to make a comparison between two supermarkets. The following research question was then answered within this research:

"How does a subsurface supermarket compare environmentally with an aboveground supermarket?"

To answer this research question, the LCA methodology was used to compare an existing subsurface supermarket in Brielle to a designed comparable aboveground supermarket. Results from the LCA showed that a supermarket at the surface level most likely is environmentally better than a supermarket located in the subsurface. In this comparison the electricity use played the major role in creating the difference in environmental impact. For the electricity use of the building an assumption was made about how this energy was produced, which was by the electricity mix of the Netherlands. This electricity mix could be the reason that the aboveground building scores better. The electricity mix could also be changed to a more sustainable one. The designed aboveground supermarket, however, has the same choice. Because the electricity mix of both supermarkets is kept the same changes did not occur during the sensitivity analysis. The demand side of the electricity use then is the aspect that determines the difference in impact. The difference in electricity demand was caused by the elevators that were needed in the subsurface building because the parking is not at the same level as the supermarket. The parking space a supermarket needs is one of the aspects that were not measured within the LCA. This can, however, play a major role in the comparison between the aboveground supermarket and the subsurface supermarket. If the supermarkets would apply the same parking situation, the elevators would not be needed or they would be needed by both supermarkets. This could be a game changer for the subsurface supermarket. The subsurface supermarket then shows that it has aspects which perform better than the aboveground supermarket. Because of the piles and heating the subsurface supermarket actually seems to be able to score better overall than the aboveground supermarket. This is, however, so close that no hard conclusions can be made.

Looking back at the challenge of increasing population sizes and urbanization the subsurface supermarket would most likely also not have to compete with a surface supermarket. As explained, areas have to be used more efficiently. The choice then has to be made between building higher up in the air or by building further down in the subsurface. A supermarket might not be the function for which it is efficient to place it on a different level than the surface. In supermarkets loads of goods are transported, which means elevators will be used more often than for other building functions. Translating this research, however, to other building functions then the piles will most likely still be more positive for the subsurface building. For the energy use this is uncertain because variables like climate and comfortable indoor temperatures can change per function. The electricity use for elevators will then play a smaller role or even no role at all in the comparison. Real chances for the subsurface construction then open up. For these options to also be practically available the building laws, e.g. regarding natural lighting, need to be changed. In the end subsurface construction seems to have positive factors that could give it an opportunity to become a serious option for the future. Still some issues need to be solved and further research will be needed to really make hard conclusions about the option of placing buildings in the subsurface.

6. Discussion

Based on the conclusions, this research showed that there are some opportunities for building subsurface. The results of this research were based on data obtained from a case study subsurface supermarket. Large amounts of drawings and other information, obtained from the owner of the supermarket, were examined to produce input data for the LCA. Some missing information was obtained by using assumed values, contacting experts or cutting of these parts from the system.

Limitations in time, data availability and expertise created an uncertainty in the results that came from the research. Due to these limitations the waste management was not examined within this research. It is unknown what the demolition phase in terms of the waste management of a subsurface supermarket would look like. It could be possible that less materials can be obtained back and be recycled as would be the case in the waste management of an aboveground supermarket. For a supermarket located just under the surface this would perhaps not create any major issues, but when building deeper in the subsurface this could create bigger issues. Not only was the waste management not taken into account, different aspects of the construction phase were not examined due to limitations in time and data availability.

Piling of the piles in the subsurface was one of the elements not taken into account. Although for the subsurface supermarket more sand needed to be dug up, the piles also had to be piled less deep. This is thus an aspect assumed more positive for the subsurface supermarket. Another aspect not taken into account is the energy use for the pumping of groundwater out of the construction area during the construction. The subsurface supermarket is build deeper, which means most likely more pumping was needed. The difference in environmental impact in the construction phase of a subsurface supermarket compared to an aboveground supermarket will most likely not have a large effect on its total environmental impact when the subsurface supermarket is built just below the surface. When building deeper in the subsurface more digging, sand transport, pumping and maybe other not mentioned aspects will be needed. In comparison, the aboveground supermarket would then also need to be built higher. Parts of the building then would need to be transported up in the air which also would need energy and thus cause a larger environmental impact. Environmental impacts in the construction phase thus did not play a major role in this research but they can become more important when buildings become taller.

Due to limitations in time and expertise simplified calculations were used to obtain the material usage present in the housing body of the supermarket. Help from experts in the field was obtained to learn how to read the drawings and get material usages out. This would, however, only influence the results from the floor, supports and columns. Other parts of the assembly of the supermarket were based on more accurate data or values obtained from the suppliers. These will most likely have only a small uncertainty. Because the same data is used for both supermarkets, they both apply the same uncertainty. However, a material use factor for the aboveground supermarket was used. This factor was not used on the piles, which was one of the positive aspects of the subsurface supermarket. The uncertainty in the assembly could thus become larger. This is, however, nothing compared to having used the wrong material use factor, which would even have a larger impact. Changing the material use factor has shown that no real changes are observed in the final results. Small changes caused by an uncertainty would then most definitely not cause a change in the final result. When only looking at the assembly this material use factor, and thus also the uncertainty, can play a role in the impact results of the assembly. This does not mean the conclusions about the piles are uncertain. The piles will stay positive for the subsurface supermarket and they can still make sure the subsurface supermarket comes out better. When the subsurface supermarket is placed deeper the length of the pile would decrease and so would its material use. Still there will come a point where this will not be possible anymore.

Looking further into the assembly the insulation can have an uncertainty. Insulation has an effect on assembly and the energy use. The amount of insulation used in both supermarkets was based on an assumption. In the sensitivity analysis it was shown that changing the insulation layer has an influence. It also showed that the same change between the two supermarkets seems to cause a different size of the effect in the impacts. The environmental impact of insulation is, however, not only about the amount of insulation. In a subsurface supermarket another type of insulation could be more environmentally friendly than is the case for the aboveground supermarket. This could create a different effect in the difference between the two supermarkets. To really be able to observe this effect an optimal insulation situation should be chosen. This will most likely differ per climate region. Furthermore, for the subsurface supermarket the optimal insulation could be affected by the depth of the supermarket. The combined effect of insulation type, size and depth of the supermarket is then an important aspect which has to be examined. Although the difference in impact for now looks small it is unknown what the difference in impact will be when an optimized situation is examined.

The climate not only has an effect on the heating. Materials could respond different per climate. Materials can degrade and thus break down or become less strong after a certain period of time. This material lifetime can affect the building materials differently in the subsurface compared to the aboveground. In the subsurface aspects like for example microbiological activity and groundwater could affect the materials and reduce their lifetime. In the aboveground supermarket materials could be affected by different aspects like for example rain and UV-radiation. In the sensitivity analysis was already shown that this could have a major impact on the final results of the LCA. More information or research on the effects of external influences on the lifetime of building materials is needed to get a better comparison between the subsurface and aboveground supermarket.

In this research the processes in SimaPro were used to examine the difference in environmental impact between a subsurface supermarket and an aboveground supermarket. The choice of the processes implemented in SimaPro was based as much as possible on the actual data obtained from the case study supermarket in Brielle. For the floors, supports and piles it was known that these were produced at location. Other parts of the housing body like the piles, roof, walls and stairs were produced in a factory and then transported as parts to the supermarket location. For this reason a different type of concrete was chosen for the floors, supports and piles. Based on its description it should be the correct choice. Using the same type of concrete for all different parts of the supermarket would not have been fair and would have created an even bigger uncertainty. Furthermore, for both the aboveground and subsurface supermarket the same choices were made. The real uncertainty in the results due to process choices made in SimaPro should thus be negligible.

Next to the choice of a specific process can have an influence, the type of database the processes were chosen from can have an influence. The database used in this research was the consequential database, which uses a different calculation method and looks more into the long term. The sensitivity analysis of the type of database showed that the choice of the database can be very important. The product having the least impact per impact category could change based on the database chosen. When future decisions have to be made based on these impact categories the choice of the type of database could make a difference. The main results in this research, however, did not show a difference when changing the type of database.

Next to the processes that were inserted in SimaPro and the type of database used, the choices made within the impact methodology could change the final results. Important choices made were the choice of the impact methodology, the choice of endpoint vs midpoint, and the choice of cultural perspective. The sensitivity analysis showed that the final results did not change based on choices within the impact methodology. For this research this thus was no real uncertainty.

According to this research building in the subsurface seems to have opportunities that could make it a viable option to increase subsurface construction for the future. However, the supermarkets examined in this research were most likely not built fully efficient. Looking at the developments in the building sector buildings become more and more efficient in using for example natural lighting. This study has shown that the use phase was the major aspect that created the difference between aboveground and subsurface construction. It is then unsure whether subsurface construction can compete with optimized aboveground buildings. New technologies might then be needed to provide a subsurface building with the necessary lighting, ventilation etc.

Also other aspects could be important for building subsurface. People might be hesitant to be in the subsurface. These and other social aspects are not included in LCA. Not only people can be affected by buildings. Other parts of the ecosystem (animals, vegetation etc.) can also be influenced. This also includes the direct land use change, because when more land is used less land is available for all sorts of vegetation. These are also not included in LCA, because there are more local impacts. The LCA only looks at impacts that are global. The local impacts can, however, also be environmental impacts that prove to be very important in the decision to build aboveground or subsurface. This means LCA alone is not enough to decide whether subsurface construction will be more environmental friendly than aboveground construction. It can, however, be questioned if other methods take into account changes or impacts in the subsurface. Most known methodologies only take into account impacts above the surface. When building subsurface the subsurface impacts or changes can also be very important.

7. Recommendations

From the points in the discussion it seems that still some information is missing that could be useful to determine if building subsurface is more environmentally friendly than building aboveground. The depth of the building and the climate at which it is placed could become very important in that case. In a study by van Dronkelaar et al. (2014) the heat loss at different depths and climates was already examined. The depth and climate, however, have an influence on many more aspects of the building, which combined can give different results. It can be examined how the environmental impacts change when changing the depth of the building. It should then also be taken into account that when building deeper, windows will not be useful anymore and have to be replaced. This can also have an influence on the amount of artificial lighting. As explained within this research a supermarket is normally not build very efficient regarding natural lighting, which means going deeper in the subsurface should not affect the amount or artificial lighting needed.

Still it could also be examined how the environmental impact of a subsurface building would compare to an aboveground building which is built efficiently regarding natural lighting. The electricity use for elevators would then most likely become the determining factor again. To get a good observation it should be assumed the subsurface building is still connected to the surface. It then becomes a multi-storey building. For the aboveground a building should be assumed with the same amount of storeys. Both buildings can then be optimized, not only for natural lighting but also for example for insulation, to obtain a fair comparison. This way also subsurface construction and high rise construction can be compared. This would also represent a better view of the possibilities of the future because the aim for the future is to build buildings as optimized as possible.

Next to the different depths the climates also play a role. Subsurface construction might not be suitable for each climate zone. In this research the climate of the Netherlands was examined. In further research the same study can be conducted using different climate conditions by choosing different locations. By changing the location not only the climate would change. Soil characteristics will also change, which can influence results. In addition the lifetime of building materials in different types of climates and soils can be studied. In this research was seen that the lifetime of the building materials can create totally different results when changed. More information about how the lifetime of materials in the subsurface compares to the lifetime of materials aboveground is then needed. This is a study more related to material science.

Further studies can also be focussed on the parts of the life cycle that were less explored in this research. This includes looking deeper in the construction and demolition of subsurface buildings compared to aboveground buildings to see how the environmental impacts compare. Here the depth and climate can again play a role and thus be taken into account.

Looking deeper in the environmental impacts using LCA might not even be the only option. In the discussion was mentioned that LCA only looks at global impacts which are long term. Other impacts that could create opportunities but also create threats, like e.g. social impacts and local impacts, are not included in LCA. To also examine these other impacts different methods can be used like a social impact LCA or an environmental impact assessment. Combining the results of this LCA with results from a social and local perspective should then give more insight in the opportunities for subsurface construction. It could, however, even be possible that some impacts cannot be measured with any of the other methods available. This especially can be the case regarding subsurface impacts and changes. If no method is available, research should focus on developing a new method or expanding existing methods to ensure all impacts are examined before hard conclusions are taken.

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Appendix A. Scenarios used in the research

Table 8 Layer thicknesses of different parts of the building envelope in different scenarios.

		Subsurface scenarios			**Aboveground scenarios**				
		S1	***S2***	***S3***	***A1***	***A2***	***A3***	***A4***	***A5***
	Factor subsurface vs aboveground	1	1	1	1.5	1	2	1.5	1.5
Roof	Concrete thickness (mm)	74.26	74.26	74.26	49.51	74.26	37.13	49.51	49.51
	Steel thickness (mm)	0.061	0.061	0.061	0.041	0.061	0.031	0.041	0.041
	Insulation thickness (mm)	135	135	135	135	135	135	135	135
	Total thickness (mm)	209.32	209.32	209.32	184.55	209.32	172.16	184.55	184.55
Walls	Concrete thickness (mm)	285.57	285.57	285.57	190.38	285.57	142.79	190.38	190.38
	Steel thickness (mm)	2.42	2.42	2.42	1.615	2.423	1.211	1.615	1.615
	Insulation thickness (mm)	80	0	110	80	80	80	0	110
	Total thickness (mm)	368.00	288.00	398.00	272.00	368.00	224.00	192.00	302.00
Floor	Concrete thickness (mm)	296.98	296.98	296.98	197.99	296.98	148.49	197.99	197.99
	Steel thickness (mm)	3.02	3.02	3.02	2.011	3.016	1.508	2.011	2.011
	Insulation thickness (mm)	80	0	120	80	80	80	0	120
	Total thickness (mm)	380.00	300.00	420.00	280.00	380.00	230.00	200.00	320.00
	Stairs taken into account	Yes	Yes	Yes	No	No	No	No	No
	Elevators taken into account	Yes	Yes	Yes	No	No	No	No	No

Appendix B. Material use calculations

A building exists of many different elements which combined form the building. As explained earlier, in this research the housing body's material use was one of the elements to be examined. In case of the subsurface building the housing body taken into account existed of the floor, columns, roof, walls, insulation, stairs, railings, piles and the windows. For the aboveground building the same housing body was used but without the stairs and railings. Furthermore, the aboveground building used a different amount of material due to different forces that act on the building. The material use was examined part by part.

Appendix B.1 The floor and columns

The floor and columns were examined together in this research. The reason for this was that at the places of the columns a support is located which makes the floor thicker. In this support the amount of reinforcement is bigger. Instead of pointing this extra steel and concrete to one of the two parts, the choice was made to just add them together. Next to supports at the places where columns are, there are even more supports located at places where the piles are. These supports were all included in one bigger part which was called the floor, supports and columns. The floor, supports and columns were all made out of steel reinforced concrete.

The volume of concrete and steel in the floor, supports and columns was examined using the drawings obtained from de Vette (2004). The total volume of concrete for floor, columns and supports was calculated by adding up the extra concrete volume used for the columns and piles to the total floor volume. This volume, however, represents the volume of the whole part, which thus includes the volume of steel used for reinforcement. The volume steel was subtracted from the total volume of the part to obtain the volume of concrete. In order to calculate the volume of concrete, the volume of steel was thus first needed.

For the amount of steel in the floor an area of 25 m^2 floor was examined because the supports are 5 m apart and they thus cover an area of 25 m^2. This area was assumed to be representative for the whole building. Using drawing IOB D12W and IOB D13W (de Vette, 2004) it was observed that the main reinforcement is Ø12 mm steel and that there are two nets used above each other for which the wires are 150 mm apart in both directions. The length of a wire in an area of 25 m^2 in both the length and the width direction is 5 m. With a wire each 150 mm there are 33.3 wires in both the length and width direction per net. Each wire having a length of 5 m, this gave a total wire length of 166.67 m per direction per net. With two nets present, the total length of wire in the same direction was 333.3 m. Using the diameter of the wire, which was 12 mm, the volume of steel per direction was calculated to be 0.0377 m^3. Adding up the steel of both directions gave a volume of steel of 0.0754 m^3 in 25 m^2 of building or 0.003 m^3 steel per m^2 floor. Using the building lengths and widths from IOB DO2, IOB D12 and IOB D13 (de Vette, 2004) the total area of the floor was calculated by splitting the total area in six subareas. In figure 8 in paragraph 2.3.1 the total examined area is shown with the green lines and the examined subareas are shown with the red lines. The outside of the outer walls was taken for the measurement. Combining all subareas gave a total floor area of 2695.6 m^2. The total amount of steel in the floor would then be 8.1 m^3. The density of steel was assumed to be 7800 $kg*m^{-3}$ (Soortelijkgewicht.com, 2014; The Engineering Toolbox, 2014c), giving a steel mass of 63412 kg or 63.4 tonne.

The steel in the supports was harder to obtain. This was calculated using drawings IOB D14 DRSN 10 and DRSN 28 (de Vette, 2004). The supports have a sloped part which causes the length of the wires to change per wire. Here the slope was used to calculate the length of each wire separately in both directions. The supports differ between the piles with and without a column on it, which causes a difference in the distance between the wires of each type of column. The wires are, furthermore, not starting at the end of the support. It was measured that the distance from the side of the support to the steel in the support is 75 mm. This assumption was used for all supports. Next to wires going in the width and length direction of the building, there are also wires in the supports that go up. These were measured using a ruler and multiplied by the scale of the drawing. There is not only an amount of extra steel in the support, but some of the Ø12 steel, which was assumed to be there, is also replaced by the extra steel. To obtain the total volume of extra steel in the supports, the volumes of the wires in different directions were added up and the replaced volume of steel was subtracted from this volume. This was done for both types of support, which gave an extra volume of steel of 0.0288 m^3 per support without column and an extra volume of steel of 0.0368 m^3 for the supports with a column. From drawing IOB D02 (de Vette, 2004) it was seen that there are 54 supports without a column and 20 with a column. The extra volume of steel then became 1.56 m^3 for the supports without columns and 0.74 m^3 for the supports with columns.

Looking at the columns, there are two types of columns, which are □400 mm and Ø245 mm. To calculate the amount of steel and concrete drawing IOB D18 (de Vette, 2004) was used. The □400 has some shackles which go round the steel in the column. These are 45 mm deep in the column. The column is 400 mm by 400 mm meaning the shackles have a length of 310 on each side giving a total length of 1240 mm. At one side of the shackle there is, however, a little extra steel, which was measured using a ruler to be 280 mm. The total length of each shackle then is 1520 mm or 1.52 m. These shackles are located every 250 mm over a length of 3750 mm. This means there are 15 shackles in each column giving a total wire length of 22.8 m for the shackles. The column itself has eight wires going down the column. Using a ruler these were measured to be 4.42 m, each with a diameter of 20 mm. On the bottom there are eight wires that are used for extra reinforcement, which are Ø16 mm. These, with a ruler, measured a length of 1.73 m. The shackles are made of Ø8 mm steel giving a volume of steel of 0.0011 m^3. The wires at the top and bottom gave a volume of steel of 0.0111 m^3 and 0.0028 m^3 respectively. The total volume of steel in the column of □400 mm thus is 0.015 m^3.

The column of Ø245 has a layer of steel covering the outside, and steel at the inside at the top and at the bottom. Using a ruler the top wires measured 1.24 m per wire and the bottom ones measured 1.35 m per wire. At the top there are eight wires and at the bottom five giving a total steel length of 9.9 m and 6.8 m respectively. Both top and bottom wires are 16 mm in diameter giving a volume of 0.002 m^3 and 0.0014 m^3 respectively. The diameter of the column is 244.5 mm which gave a circumference of 0.768 m. The column is 4 m long and the steel has a thickness of 0.0063 m giving a volume of steel of 0.0194 m^3. The total volume of steel in the column of Ø245 thus is 0.0227 m^3. There are 20 columns of □400 mm and 5 columns of Ø245 mm in the building. This gave a total steel volume of 0.3 m^3 for the □400 column and 0.11 m^3 for the Ø245 column. Adding up the steel in the columns, the supports and the floor gave a volume of 10.84 m^3 of steel for the floor, supports and columns. For the steel use in the different aboveground scenarios the volume of steel was divided by the corresponding factor of that scenario. Using the density of steel the mass of steel was calculated for all scenarios (see table 9).

For the volume of concrete, the steel volume was subtracted from the volume of the parts. The volume of the parts was thus still needed. As said the floor area was calculated to be 2695.6 m^2. From drawing IOB DO4 (de Vette, 2004) was found that the thickness of the floor is 0.3 m giving a total volume of the floor of 808.7 m^3. The supports have a sloped part and a straight part. The sloped part has an area of 1.351 m^2 and the straight part an area of 0.9 m^2 giving a total area of 2.251 m^2 for the support. In drawing IOB D04 was found that the support has an extra 0.5 m thickness, which gave a volume of 1.126 m^3 per support. There are 74 supports, making a total volume of 83.3 m^3 for all supports.

The columns of □400 mm have a length of 0.4 m, a width of 0.4 m and a height of 3.75 m. This gave a volume for the column of □400 mm of 0.6 m^3 per column. There are 20 columns of □400 mm in the building giving a total volume for column □400 mm of 12.00 m^3. The column of Ø245 mm has a diameter of 0.2445 m and a height of 4 m giving a volume of 0.19 m^3 per column. There are 5 columns of Ø245 mm in the building giving a total volume for column Ø245 mm of 0.94 m^3. The columns together then have a volume of 12.94 m^3.

The volume of the floor, supports and columns together was 904.9 m^3 of which 10.84 m^3 is steel and thus 894.1 m^3 is concrete. For the concrete use in the different aboveground scenarios this volume of concrete was divided by the corresponding factor (1, 1.5 or 2) of that scenario. The floor, supports and columns were not prefabricated but produced at location, which meant their input in SimaPro was m^3. Still the volume of concrete has to be transformed to a mass, which was used in the transportation section. The density of concrete differs a lot depending on the composition. In this research it was assumed to be 2300 kg*m^{-3} (Elert, 2001; The Engineering Toolbox, 2014a) and used to calculate the mass of concrete. Table 9 shows the mass of steel and the volume and mass of concrete calculated for the different scenarios.

Table 9 Materials used in the floor, supports and columns.

Scenario	*Volume of concrete (m^3)*	*Mass concrete (tonne)*	*Mass steel (tonne)*
Subsurface 1,2,3	894.1	2056.4	84.52
Aboveground 1,4,5	596.1	1370.9	56.35
Aboveground 2	894.1	2056.4	84.52
Aboveground 3	447.0	1028.2	42.26

Appendix B.2 The roof and walls

The roof and walls are both made of precast reinforced concrete panels, which were produced by Atlas Bouwtechnisch Adviesburo (2014). For these panels it was too difficult to calculate the steel use in the panels based on the drawings. For this reason Atlas Bouwtechnisch Adviesburo (2014) was contacted for the material use in the panels. An overview of the concrete and steel use in the roof was send by Atlas Bouwtechnisch Adviesburo (2014) and used in this research. According to Atlas Bouwtechnisch Adviesburo (2014) the roof has an area of 2512.52 m^2 in which 429.12 tonnes of concrete was used and 1202.11 kg of steel. The mass of concrete and steel per square meter then are 170.79 kg*m^{-2} and 0.478 kg*m^{-2} respectively. In this research the roof was assumed fully closed and it was thus assumed it has an area equal to the floor area, which was 2695.6 m^2. The roof of the building would then exist of 460.39 tonne of concrete and 1289.71 kg of steel. For the mass of concrete and steel used in the roof of the aboveground scenarios these amounts of concrete and steel were divided by the corresponding factor of that scenario. The mass of concrete and steel used in the roof in each scenario are shown in table 10.

Table 10 Materials used in the roof.

Scenario	*Mass concrete (tonne)*	*Mass steel (tonne)*
Subsurface 1,2,3	460.4	1.29
Aboveground 1,4,5	306.9	0.86
Aboveground 2	460.4	1.29
Aboveground 3	230.2	0.64

The walls of the subsurface building exist of 730.47 tonne of concrete and 21.01 tonne of steel. For the mass of concrete and steel used in the walls of the aboveground scenarios these amounts of concrete and steel were divided by the corresponding factor (1, 1.5 or 2) of that scenario. The mass of concrete and steel used in the roof in each scenario are shown in table 11.

Table 11 Materials used in the walls.

Scenario	*Mass concrete (tonne)*	*Mass steel (tonne)*
Subsurface 1,2,3	730.5	21.01
Aboveground 1,4,5	487.0	14.01
Aboveground 2	730.5	21.01
Aboveground 3	365.2	10.51

Appendix B.3 Stairs

The stairs were made of precast reinforced concrete by Steenhuis beton BV (2014). The mass of each type of stairs was known. The part of concrete and steel in this mass was, however, not known and too difficult to determine. For this reason Steenhuis beton BV (2014) was contacted for the material use in the different stairs. An overview of the concrete and steel use in the different stairs was send by Steenhuis beton BV (2014) and used in this research. According to Steenhuis beton BV (2014) the stairs have a density of 2400 kg*m^{-3} in which 90 kg of steel is present per m^3. Multiplying the mass of each type of stairs with the amount of that type of stairs gave the total mass of that specific type of stairs. Adding all stairs together then gave a total mass for the stairs of 19.89 tonne. To obtain the mass of concrete and steel the total mass is changed to a volume using the density. This gave a volume of 8.29 m^3 for the stairs. This volume was multiplied with the mass of steel present per volume of stairs to get the mass of steel in the stairs, which was 745.9 kg. With the mass of steel known the mass of concrete could easily be calculated by subtracting the mass of steel from the mass of the stairs. This gave a concrete mass of 19144.1 kg (see table 12). This mass of steel and concrete for the stairs was only applied to the subsurface scenarios. The aboveground building does not have stairs, which meant in none of the aboveground scenarios there is a material usage from stairs.

Table 12 Mass of concrete and steel used in the stairs.

Type of stairs	*Mass (tonne)*	*Amount*	*Total mass (tonne)*
T-1	0.9	1	0.90
T-2	1.1	2	2.20
T-3	1.2	1	1.20
T-4	2.3	1	2.30
T-5	1.5	1	1.50
T-6	1.7	1	1.70
BO-1	3.19	1	3.19
BO-2	1.75	1	1.75
BO-3	2.28	1	2.28
BO-4	0.51	1	0.51
PL-1	2.36	1	2.36
		Total mass stairs (tonne) =	19.89
		Total volume (m^3) =	8.29
		Total mass steel (kg) =	745.9
		Total mass concrete (kg) =	19144.1

Appendix B.4 Railings

The railings were produced by Biemans Constructie Rijen B.V. Drawings Biemans 30930-001 to 30930-007, Biemans 31105-001 and Biemans 31192-001 (de Vette, 2004) were used to calculate the volume and mass of RVS 304 that was used in the railings. The drawings are separated by stairs 5+6, stairs 3+4, railing at escalator and railing at double stairs. All these elements exist of brands ("Merk" on drawing) which are parts of a railing that can be used multiple times to create a railing. The railing carrier is for example a brand which can be used more often to create a full railing. Each brand has different shapes and sizes on it for which the volume of RVS has to be calculated separately. Between drawings brand numbers can occur multiple times. Brand numbers are thus specific for each drawing.

For stairs 5+6 drawings Biemans 30930-001, 30930-003, 30930-005 and 30930-006 (de Vette, 2004) were used. Using the sizes given in the drawings, all volumes of all different parts of each brand were calculated. The volumes of RVS per brand for stairs 5+6 are shown in table 13. For brand 023 the length of the upper and lower beam of the frame was not given and thus estimated by measuring with a ruler. From table 13 can be found that for stairs 5+6 the total volume of RVS 304 is 28.25 dm^3 or 0.028 m^3.

Table 13 Volumes of RVS used per brand (Merk) for stairs 5+6.

Name	*Material type*	*Volume (dm^3)*	*Amount*	*Total volume (dm^3)*
Merk 001	RVS 304	1.038	4	4.153
Merk 002	RVS 304	0.063	15	0.938
Merk 003	RVS 304	0.414	1	0.414
Merk 015	RVS 304	3.295	1	3.295
Merk 020	RVS 304	2.756	1	2.756
Merk 021	RVS 304	4.822	1	4.822
Merk 022	RVS 304	4.819	1	4.819
Merk 023	RVS 304	3.356	1	3.356
Merk 024	RVS 304	0.591	2	1.181
Merk 025	RVS 304	0.645	1	0.645
Merk 026	RVS 304	0.653	2	1.305
Merk 027	RVS 304	0.063	9	0.563
			Total volume (dm^3) =	28.25

For stairs 3+4 drawing Biemans 30930-002 was used. The volumes of RVS per brand for stairs 3+4 are shown in table 14. It can be found that for stairs 3+4 the total volume of RVS 304 is 5.93 dm^3 or 0.006 m^3.

Table 14 Volumes of RVS used per brand (Merk) for stairs 3+4.

Name	*Material type*	*Volume (dm^3)*	*Amount*	*Total volume (dm^3)*
Merk 010	RVS 304	0.65	2	1.29
Merk 011	RVS 304	0.22	2	0.44
Merk 012	RVS 304	1.47	2	2.95
Merk 013	RVS 304	0.06	20	1.25
			Total volume (dm^3) =	5.93

For the railing at the escalator drawing Biemans 30930-004 and 31105-001 were used. The volumes of RVS per brand for the railing at the escalator are shown in table 15. It can be found that for the railing at the escalator the total volume of RVS 304 is 10.86 dm^3 or 0.011 m^3.

Table 15 Volumes of RVS used per brand (Merk) for railing at the escalator.

Name	*Material type*	*Volume (dm^3)*	*Amount*	*Total volume (dm^3)*
Merk 001	RVS 304	2.62	1	2.62
Merk 002	RVS 304	2.54	1	2.54
Merk 016	RVS 304	2.85	2	5.70
			Total volume (dm^3) =	10.86

For the railing at the double stairs drawing Biemans 31192-001 was used. The volumes of RVS per brand for the railing at the double stairs are shown in table 16. It can be found that for the railing at the double stairs the total volume of RVS 304 is 23.93 dm^3 or 0.024 m^3.

Table 16 Volumes of RVS used per brand (Merk) for railing at the double stairs.

Name	*Material type*	*Volume (dm^3)*	*Amount*	*Total volume (dm^3)*
Merk 001	RVS 304	8.38	1	8.38
Merk 002	RVS 304	8.17	1	8.17
Merk 003	RVS 304	0.92	8	7.39
			Total volume (dm^3) =	23.93

RVS 304 is a stainless steel grade which has around 18% chromium and 8% nickel (Euro Inox, 2014; Stainless Structurals, 2013). The density of RVS 304 is around 7900 $kg*m^{-3}$ (Euro Inox, 2014; Stainless Structurals, 2013), which was used to calculate the mass of each location measured. With all locations counted together the total mass of RVS 304 for railings was calculated to be 544.9 kg (See table 17). In the aboveground building there are no railings because there are no stairs or elevators which need railings. The material use for railings was thus not applied to the aboveground building but only to the subsurface building.

Table 17 RVS 304 usage at different locations of the subsurface building.

Location	*Material type*	*Volume (m^3)*	*Mass RVS (kg)*
Stairs 5 + 6	RVS 304	0.028	223.16
Stairs 3 + 4	RVS 304	0.006	46.88
Railing at escelator	RVS 304	0.011	85.81
Railing at double stairs	RVS 304	0.024	189.08
	Total volume (m^3) =	0.069	544.92

Appendix B.5 Piles

Piles are part of the foundation of the building and they are used to support the building. In drawing IOB D11 (de Vette, 2004) a table is implemented which shows the different types of piles that are applied in the subsurface building (see table 18). Each type of pile has a different length, dimension and maximum load. With this information the volume of the subsurface piles was calculated. In order to obtain the amount of steel and concrete more information was needed about the reinforcement in the piles.

Table 18 Information about the piles that are located in the subsurface supermarket.

Type	Dimension (mm)	amount	Pile level relative to NAP[3] (m)	Length (m)	Cut-off level relative to NAP[3] (m)	P max (kN) calculation value	P min (kN) calculation value
A	□320	222	27.00	22.5	4.96	1100	-360
B	□350	6	27.00	22.5	4.96	1100	-360
C	□320	7	27.00	22.0	5.71	1100	-360
D	□320	4	27.00	22.0	5.46	1100	-360
E	□320	56	27.00	23.0	4.61	1100	-360
F	□320	4	27.00	25.5	2.11	524	-
G	□320	4	27.00	27.5	0.17	730	-350
H	□320	3	27.00	25.0	2.39	730	-350
I	□320	17	27.00	27.0	Var.	730	-350
J	□320	1	27.00	23.0	4.46	730	-350
K	□320	2	26.00	22.0	4.61	1100	-360

The amount of reinforcement in the piles was calculated using information from Martens beton b.v. (2014) about reinforcement in piles. The reinforcement was calculated for each type of pile separately. As an example the reinforcement was calculated for the piles which were used the most in the building, which are the type A piles in table 18. These piles have a dimension of □320 mm and are 22.5 m long. According to Martens beton b.v. (2014) the concrete cover on top of the spiral in a pile is 30 mm. The pile has a width of 320 mm on all sides, so the width of the spiral is 260 mm on all sides and the total length per winding is 1040 mm. Each pile has 16 windings, which means the total length of the spiral is 16640 mm per pile (see formula 2). The spiral has a diameter of 5 mm, which gave an area of 19.63 mm^2 (see formula 3). The volume of steel for the spiral then is 326,726 mm^3 or 0.0003m^3 (see formula 4).

Formula 2 Total length of the spiral in the piles with a dimension of □320 mm.

$$\begin{aligned}&Spiral\ width = Width\ pile - 2 * concrete\ cover = 320 - 2 * 30 = 260\ mm\\&Length\ per\ winding = Spiral\ width * sides\ per\ winding = 260 * 4 = 1040\ mm\\&Total\ length\ spiral = Length\ per\ winding * windings = 1040 * 16 = 16640\ mm\end{aligned}$$

Formula 3 Area of the spiral in the piles with a dimension of □320 mm.

$$Area\ spiral = 0.25 * \pi * D^2 = 0.25 * \pi * 5^2 = 19.63\ mm^2$$

Formula 4 Volume of the spiral in the piles with a dimension of □320 mm.

$$\begin{aligned}&V_{Spiral} = Area\ spiral * Total\ length\ spiral = 19.63 * 16640 = 326{,}726\ mm^3\\&= 0.0003\ m^3\end{aligned}$$

Formula 5 Formula for the calculation of the area of the main reinforcement needed in piles.

$$Aa = 0.525 * \left(0.35 + j + \frac{0{,}02 * L}{b}\right) * \frac{b^2}{100}$$

Legend:

Aa = Area of minimal needed reinforcement (mm)
b = Width of the pile (mm)
L = Length of the pile (mm)
j = $\frac{L-3000}{40000}$

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[3] NAP is the Normaal Amsterdams Peil or Amsterdam Ordnance Datum.

For the main reinforcement in the piles formula 5 from Martens beton b.v. (2014) is used. Filling in this formula has shown that the area of minimal reinforcement needed is 1206.24 mm^2. The area of the reinforcement is separated over 4 strings. Each string then had an area of 301.56 mm^2, which corresponded to a diameter of 19.6 mm (see Formula 6 to Formula 8).

Formula 6 Total area of main reinforcement needed in the piles with a dimension of ☐320 mm and a length of 22.5 m.

$$Aa = \ 0.525 * \left(0.35 + \frac{L - 3000}{40000} + \frac{0{,}02 * L}{b}\right) * \frac{b^2}{100}$$
$$= 0.525 * \left(0.35 + \frac{22500 - 3000}{40000} + \frac{0{,}02 * 22500}{320}\right) * \frac{320^2}{100} = 1206.24\, mm^2$$

Formula 7 Area of main reinforcement needed per string in the piles with a dimension of ☐320 mm and a length of 22.5 m.

$$Area\ per\ string = \frac{Aa}{4} = \frac{1206.24}{4} = 301.56\, mm^2$$

Formula 8 Minimal string diameter needed in the piles with a dimension of ☐320 mm and a length of 22.5 m.

$$Diameter\ of\ string = \sqrt{\frac{Area\ per\ string}{0.25 * \pi}} = \sqrt{\frac{301.56}{0.25 * \pi}} = 19.6\, mm$$

String diameters have sizes that are full numbers which increase in size by 2 (Ø8, Ø10, Ø12, etc.). For this pile 4 strings with a diameter of 20 were then used as reinforcement. This gave an area per string of 314.16 mm^2 and an area of steel for main reinforcement of 1256.6mm^2. The concrete cover at the top and bottom of the pile is 30mm, which gave a total length of the string in the pile of 22440 m. The volume of steel for the main reinforcement then became 0.0282m^3 (see formula 9 to formula 11). With both the volume of steel in the main reinforcement and spiral known, the total volume of steel per pile was calculated to be 0.0285m^3 (see formula 12). The total volume of steel was then calculated by multiplying the steel per pile with the amount of piles, which gave a volume of 6.33 m^3 (see formula 13).

Formula 9 Area of steel used for main reinforcement in the piles with a dimension of ☐320 mm and a length of 22.5 m.

$$Area\ per\ string = 0.25 * \pi * D^2 = 0.25 * \pi * 20^2 = 314.16\, mm^2$$
$$Area\ steel_{main\ reinforcement} = Area\ per\ string * strings = 314.16 * 4 = 1256.6\, mm^2$$

Formula 10 String length of main reinforcement used in the piles with a dimension of ☐320 mm and a length of 22.5 m.

$$String\ length = Length\ pile - 2 * concrete\ cover = 22500 - 2 * 30 = 22440\, mm$$

Formula 11 Volume of steel used for main reinforcement in the piles with a dimension of ☐320 mm and a length of 22.5 m.

$$V_{Steel\ for\ main\ reinforcement} = Area\ steel_{main\ reinforcement} * length\ pile = 1256.6 * 22440$$
$$= 28{,}198{,}936\, mm^3 = \ 0.0282\, m^3$$

Formula 12 Total volume of steel used per pile with a dimension of ☐320 mm and a length of 22.5 m.

$$V_{Steel\ pile} = \ V_{Steel\ for\ main\ reinforcement} + V_{Spiral} = 0.0282 + 0.0003 = 0.0285\, m^3$$

Formula 13 Total volume of steel used in all piles of type A.

$$V_{Steel\ piles\ type\ A} = \ V_{Steel\ pile} * amount\ of\ piles = 0.0285 * 222 = 6.33\, m^3$$

To obtain the amount of concrete in the piles, the volume of the piles was calculated. For the type A pile the volume of the pile was calculated to be 1.81 m^3 (see formula 14 and formula 15). With a steel volume of 0.0285 m^3 the concrete volume in the pile was 1.78 m^3 per pile (see formula 16). The total volume of concrete for all type A piles together then was 395.4 m^3 (see formula 17). Doing this for all the different types of piles gave a total steel volume of 9.70 m^3 and a total concrete volume of 593.4 m^3 for all piles in the subsurface building (see table 19).

Formula 14 Area of the pile with a dimension of □320 mm and a length of 22.5 m.

$$Area_{Pile} = 0.25 * \pi * D^2 = 0.25 * \pi * 0.320^2 = 0.08mm^2$$

Formula 15 Volume of the pile with a dimension of □320 mm and a length of 22.5 m.

$$V_{pile} = Area_{Pile} * Total\ length_{Pile} = 22.5 * 0.08 = 1.810m^3$$

Formula 16 Volume of concrete used per pile with a dimension of □320 mm and a length of 22.5 m.

$$V_{concrete\ pile} = V_{pile} - V_{Steel\ pile} = 1.810 + 0.0285 = 1.78m^3$$

Formula 17 Volume of concrete used in all piles of type A.

$$V_{concrete\ piles\ type\ A} = V_{concrete\ pile} * amount\ of\ piles = 1.78 * 222 = 395.4m^3$$

Table 19 Material usage in the piles of the subsurface building in scenario subsurface 1 (reference scenario).

Type	*Dimension (mm)*	*amount*	*Length (m)*	*Volume per pile (m^3)*	*Volume steel per pile (m^3)*	*Volume concrete per pile (m^3)*	*Volume steel (m^3)*	*Volume concrete (m^3)*
A	□320	222	22.5	1.810	0.029	1.78	6.33	395.4
B	□350	6	22.5	2.165	0.034	2.13	0.21	12.8
C	□320	7	22.0	1.769	0.028	1.74	0.20	12.2
D	□320	4	22.0	1.769	0.028	1.74	0.11	7.0
E	□320	56	23.0	1.850	0.029	1.82	1.63	102.0
F	□320	4	25.5	2.051	0.039	2.01	0.16	8.0
G	□320	4	27.5	2.212	0.042	2.17	0.17	8.7
H	□320	3	25.0	2.011	0.038	1.97	0.11	5.9
I	□320	17	27.0	2.171	0.041	2.13	0.70	36.2
J	□320	1	23.0	1.850	0.029	1.82	0.03	1.8
K	□320	2	22.0	1.769	0.028	1.74	0.06	3.5
					Total Volume (m^3) =		9.70	593.4

For the piles that support the aboveground building, the piles of the subsurface building could not be multiplied by factors to obtain the amount of materials used in the aboveground building. Here the burden on the piles was the factor that played a role. The burden on the piles depends on the forces that act on the building. In both buildings the weight of the building acted as a force, which meant the subsurface piles changed too depending on the scenario examined. In the subsurface building Archimedes force also plays a role. This is not the case in the aboveground building. Archimedes force has a positive effect on the burden of the piles, which meant the piles needed to be able to carry less weight when Archimedes force is present. Archimedes force was not present in the aboveground building, meaning a larger burden on the piles and thus an increase in the depth of the piles or a change in the amount of piles. According to an expert from Deltares, putting the piles deeper was not practical because this would increase the chance of piles breaking (Stoevelaar, 2014). Changing the amount of piles then was the best option. For a difference in material usage for the piles, Archimedes principle was applied. Using the forces that act on the piles of the subsurface building in the reference scenario, the amount of piles in the other scenarios was calculated.

As said before, the subsurface supermarket has many different types of piles that are applied in the building, each with a different length, dimension and maximum load. The piles located under the building all have a dimension of □320 mm, which means 320 mm width and 320 mm length, and have a maximum load of 1100 kN. They only differ a little in length. It was assumed that in an aboveground building each type of pile needed to be able to withstand the same force as the same type of subsurface pile. The depth of the piles thus stayed the same, which meant the length of the piles changed in accordance to the height difference between the subsurface and aboveground building. The subsurface supermarket is located at a depth of 5 m. An aboveground supermarket would have a foundation at a depth of 1 m. The difference in height between the two buildings thus was 4 m, which meant all piles in the aboveground building increased 4m in length compared to the piles in the subsurface building. The other piles in the subsurface building were assumed the same in the aboveground building. These piles are not carrying the building itself but the surroundings, so they did not play a role in the difference between building aboveground or subsurface. Furthermore, these piles were only 9% of the total amount of piles used in the construction of the building, making it only a small part of the total. To create a good picture of the material use in the building these piles were still taken into account in the same volumes as the subsurface ones. The pile types changed were thus A, B, C, D, E, and K.

The aboveground building is build less deep, which meant Archimedes force is lower and thus the piles also need to carry this lost upward force. This upward force can be calculated using the subsurface building. The majority of piles under the subsurface building are paired in groups of three. The distance between two pair of piles is 5 m. This meant that each pair of piles carries 25 m^2 of building area and each pile carries 8.3 m^2 of building area. As explained before, the difference in height between the subsurface and aboveground building is 4 m. The extra upward Archimedes force is created by the water in the soil. This meant the density used to calculate the upward force was the density of water, which is 1000kg/m^3. Using formula 18 it was calculated that the extra upward force that the piles of the aboveground building would need to resist is 39 kN/m^2. The total extra force per pile in the aboveground building then became 327 kN (see formula 19). This extra force was not present in the additional subsurface scenarios.

Formula 18 Extra upward force per building area due to a pile length increase of the aboveground building.

$$F_{A\,Length,\;\;per\,building\,area} = \rho * g * V = \rho * g * A * h$$

$$\rightarrow \frac{F_A}{A} = \rho * g * h = 1000 * 9.81 * 4 \; = 39240\frac{N}{m^2} = 39.24kN/m^2$$

Formula 19 Extra upward force per pile due to a pile length increase of the aboveground building.

$$F_{A\,Length,\;\;on\,pile} = \;39.24 * A = 39.24 * 8.3 = 327kN$$

The second force acting on the building is its mass. As mentioned earlier the mass of the reinforced housing body changed depending on the examined scenario. Both the amount of reinforced concrete and insulation were changed per scenario in this research. Furthermore, the aboveground scenarios did not have stairs or railings. All these changes changed the mass of the building per scenario. The mass of the housing body of both the subsurface and aboveground building were thus calculated using the scenarios and the results from appendix B.1 to B.4 and B.6. The difference in mass between the buildings was then also known. In scenario aboveground 1, with factor 1.5, it was calculated that the aboveground building is 1.14*10^6 kg or 1138 tonne lighter in mass. Calculating the force, using formula 20, then gives a force reduction of 11168 kN for the entire building. The total floor area of the aboveground building is 2696m^2, which gave a force reduction of 4.14 kN/m^2 or 34.52 kN per pile (see formula 21 and formula 22).

Formula 20 Force reduction for the aboveground 1 building due to a mass reduction of the housing body.

$$F_{A\,Weight,\;\;on\,building} \;= \rho * g * V = m * g = 1.14 * 10^6 * 9.81 = 1.12 * 10^7 N = 11168.3\;kN$$

Formula 21 Force reduction per building area due to a mass reduction of the housing body of the aboveground 1 building.

$$F_{A\,Weigth,\ \ per\ building\ area} = \frac{F_{A\,Weight,\ \ on\ building}}{A} = \frac{11168.3}{2696} = 4.14\ \frac{kN}{m^2}$$

Formula 22 Force reduction per pile due to a mass reduction of the housing body of the aboveground 1 building.

$$F_{A\,Weight,\ \ on\ pile} = 4.14 * A = 4.14 * 8.3 = 34.53\ kN$$

The changes in forces were used to calculate the maximum load of the piles of the aboveground building. From formula 23 can be seen this gave a force of 1392 kN per pile. The amount of piles with a maximum load of 1100 kN in scenario subsurface 1 then changed with a factor 1.27 to get the amount of piles in scenario aboveground 1 (see formula 24). Multiplying this factor with the amount of the different types of piles of 1100 kN in the subsurface 1 scenario gives the amount of the different types of piles of 1100 kN in the aboveground 1 scenario. It was known only whole piles exist. Still the piles were not rounded up to whole piles because for two half piles one whole pile could be placed instead of two piles, which would be obtained if rounded up. Taking not rounded values then gave a better estimation of the actual material use.

Formula 23 Maximum load of the piles of the aboveground building.

$$F_{piles\ aboveground} = F_{piles\ subsurface} + F_{A\,Length,\ \ on\ pile} - F_{A\,Weight,\ \ on\ pile}$$
$$= 1100 + 327 - 34.53 = 1392.5\ kN$$

Formula 24 Factor showing the difference in amount of piles used for the aboveground 1 building compared to the subsurface 1 building.

$$Extra\ piles\ factor = \frac{Maximum\ load_{piles\ aboveground\ 1}}{Maximum\ load_{piles\ subsurface\ 1}} = \frac{1392.5\ kN}{1100\ kN} = 1.27$$

With the amount and size of the piles known the actual material use in each type of pile per scenario of the aboveground building was again determined using the information from Martens beton b.v. (2014). Adding the steel and concrete volumes of all types of piles together for each scenario gave the amount of concrete and steel used for the piles in all the different scenarios (see table 20 to table 26). Multiplying the volume of concrete and steel with their corresponding densities of 2300 kg*m^{-3} (Elert, 2001; The Engineering Toolbox, 2014a) and 7800 kg*m^{-3} (Soortelijkgewicht.com, 2014; The Engineering Toolbox, 2014c) gave the mass of concrete and steel used. The mass of concrete and steel used for the piles in the different scenarios is shown in table 27.

Table 20 Material usage in the piles of the subsurface building in scenario subsurface 2.

Type	Dimension (mm)	Length (m)	Volume per pile (m^3)	Volume steel per pile (m^3)	Volume concrete per pile (m^3)	Amount of piles	Volume steel (m^3)	Volume concrete (m^3)
A	□320	22.5	1.810	0.029	1.78	221.9	6.33	395.3
B	□350	22.5	2.165	0.034	2.13	6.0	0.21	12.8
C	□320	22.0	1.769	0.028	1.74	7.0	0.20	12.2
D	□320	22.0	1.769	0.028	1.74	4.0	0.11	7.0
E	□320	23.0	1.850	0.029	1.82	56.0	1.63	101.9
F	□320	25.5	2.051	0.039	2.01	4.0	0.16	8.0
G	□320	27.5	2.212	0.042	2.17	4.0	0.17	8.7
H	□320	25.0	2.011	0.038	1.97	3.0	0.11	5.9
I	□320	27.0	2.171	0.041	2.13	17.0	0.70	36.2
J	□320	23.0	1.850	0.029	1.82	1.0	0.03	1.8
K	□320	22.0	1.769	0.028	1.74	2.0	0.06	3.5
					Total Volume (m^3) =		9.70	593.3

Table 21 Material usage in the piles of the subsurface building in scenario subsurface 3.

Type	***Dimension (mm)***	***Length (m)***	***Volume per pile (m^3)***	***Volume steel per pile (m^3)***	***Volume concrete per pile (m^3)***	***Amount of piles***	***Volume steel (m^3)***	***Volume concrete (m^3)***
A	□320	22.5	1.810	0.029	1.78	222.0	6.33	395.5
B	□350	22.5	2.165	0.034	2.13	6.0	0.21	12.8
C	□320	22.0	1.769	0.028	1.74	7.0	0.20	12.2
D	□320	22.0	1.769	0.028	1.74	4.0	0.11	7.0
E	□320	23.0	1.850	0.029	1.82	56.0	1.63	102.0
F	□320	25.5	2.051	0.039	2.01	4.0	0.16	8.0
G	□320	27.5	2.212	0.042	2.17	4.0	0.17	8.7
H	□320	25.0	2.011	0.038	1.97	3.0	0.11	5.9
I	□320	27.0	2.171	0.041	2.13	17.0	0.70	36.2
J	□320	23.0	1.850	0.029	1.82	1.0	0.03	1.8
K	□320	22.0	1.769	0.028	1.74	2.0	0.06	3.5
					Total Volume (m^3) =		9.71	593.5

Table 22 Material usage in the piles of the aboveground building in scenario aboveground 1.

Type	***Dimension (mm)***	***Length (m)***	***Volume per pile (m^3)***	***Volume steel per pile (m^3)***	***Volume concrete per pile (m^3)***	***Amount of piles***	***Volume steel (m^3)***	***Volume concrete (m^3)***
A	□320	26.5	2.131	0.041	2.09	281.0	11.39	587.5
B	□350	26.5	2.550	0.048	2.50	7.6	0.37	19.0
C	□320	26.0	2.091	0.040	2.05	8.9	0.35	18.2
D	□320	26.0	2.091	0.040	2.05	5.1	0.20	10.4
E	□320	27.0	2.171	0.041	2.13	71	2.93	151.0
F	□320	25.5	2.051	0.039	2.01	4.0	0.16	8.0
G	□320	27.5	2.212	0.042	2.17	4.0	0.17	8.7
H	□320	25.0	2.011	0.038	1.97	3.0	0.11	5.9
I	□320	27.0	2.171	0.041	2.13	17.0	0.70	36.2
J	□320	23.0	1.850	0.029	1.82	1.0	0.03	1.8
K	□320	26.0	2.091	0.040	2.05	2.5	0.10	5.2
					Total Volume (m^3) =		16.51	852.0

Table 23 Material usage in the piles of the aboveground building in scenario aboveground 2.

Type	***Dimension (mm)***	***Length (m)***	***Volume per pile (m^3)***	***Volume steel per pile (m^3)***	***Volume concrete per pile (m^3)***	***Amount of piles***	***Volume steel (m^3)***	***Volume concrete (m^3)***
A	□320	26.5	2.131	0.041	2.09	287.9	11.67	601.9
B	□350	26.5	2.550	0.048	2.50	7.8	0.38	19.5
C	□320	26.0	2.091	0.040	2.05	9.1	0.36	18.6
D	□320	26.0	2.091	0.040	2.05	5.2	0.21	10.6
E	□320	27.0	2.171	0.041	2.13	72.6	3.00	154.7
F	□320	25.5	2.051	0.039	2.01	4.0	0.16	8.0
G	□320	27.5	2.212	0.042	2.17	4.0	0.17	8.7
H	□320	25.0	2.011	0.038	1.97	3.0	0.11	5.9
I	□320	27.0	2.171	0.041	2.13	17.0	0.70	36.2
J	□320	23.0	1.850	0.029	1.82	1.0	0.03	1.8
K	□320	26.0	2.091	0.040	2.05	2.6	0.10	5.3
					Total Volume (m^3) =		16.88	871.3

Table 24 Material usage in the piles of the aboveground building in scenario aboveground 3.

Type	*Dimension (mm)*	*Length (m)*	*Volume per pile (m^3)*	*Volume steel per pile (m^3)*	*Volume concrete per pile (m^3)*	*Amount of piles*	*Volume steel (m^3)*	*Volume concrete (m^3)*
A	□320	26.5	2.131	0.041	2.09	277.6	11.25	580.4
B	□350	26.5	2.550	0.048	2.50	7.5	0.36	18.8
C	□320	26.0	2.091	0.040	2.05	8.8	0.35	18.0
D	□320	26.0	2.091	0.040	2.05	5.0	0.20	10.3
E	□320	27.0	2.171	0.041	2.13	70.0	2.89	149.2
F	□320	25.5	2.051	0.039	2.01	4.0	0.16	8.0
G	□320	27.5	2.212	0.042	2.17	4.0	0.17	8.7
H	□320	25.0	2.011	0.038	1.97	3.0	0.11	5.9
I	□320	27.0	2.171	0.041	2.13	17.0	0.70	36.2
J	□320	23.0	1.850	0.029	1.82	1.0	0.03	1.8
K	□320	26.0	2.091	0.040	2.05	2.5	0.10	5.1
					Total Volume (m^3) =		16.32	842.4

Table 25 Material usage in the piles of the aboveground building in scenario aboveground 4.

Type	*Dimension (mm)*	*Length (m)*	*Volume per pile (m^3)*	*Volume steel per pile (m^3)*	*Volume concrete per pile (m^3)*	*Amount of piles*	*Volume steel (m^3)*	*Volume concrete (m^3)*
A	□320	26.5	2.131	0.041	2.09	281.0	11.39	587.4
B	□350	26.5	2.550	0.048	2.50	7.6	0.37	19.0
C	□320	26.0	2.091	0.040	2.05	8.9	0.35	18.2
D	□320	26.0	2.091	0.040	2.05	5.1	0.20	10.4
E	□320	27.0	2.171	0.041	2.13	70.9	2.93	151.0
F	□320	25.5	2.051	0.039	2.01	4.0	0.16	8.0
G	□320	27.5	2.212	0.042	2.17	4.0	0.17	8.7
H	□320	25.0	2.011	0.038	1.97	3.0	0.11	5.9
I	□320	27.0	2.171	0.041	2.13	17.0	0.70	36.2
J	□320	23.0	1.850	0.029	1.82	1.0	0.03	1.8
K	□320	26.0	2.091	0.040	2.05	2.5	0.10	5.2
					Total Volume (m^3) =		16.50	851.8

Table 26 Material usage in the piles of the aboveground building in scenario aboveground 5.

Type	*Dimension (mm)*	*Length (m)*	*Volume per pile (m^3)*	*Volume steel per pile (m^3)*	*Volume concrete per pile (m^3)*	*Amount of piles*	*Volume steel (m^3)*	*Volume concrete (m^3)*
A	□320	26.5	2.131	0.041	2.09	281.1	11.39	587.6
B	□350	26.5	2.550	0.048	2.50	7.6	0.37	19.0
C	□320	26.0	2.091	0.040	2.05	8.9	0.35	18.2
D	□320	26.0	2.091	0.040	2.05	5.1	0.20	10.4
E	□320	27.0	2.171	0.041	2.13	70.9	2.93	151.0
F	□320	25.5	2.051	0.039	2.01	4.0	0.16	8.0
G	□320	27.5	2.212	0.042	2.17	4.0	0.17	8.7
H	□320	25.0	2.011	0.038	1.97	3.0	0.11	5.9
I	□320	27.0	2.171	0.041	2.13	17.0	0.70	36.2
J	□320	23.0	1.850	0.029	1.82	1.0	0.03	1.8
K	□320	26.0	2.091	0.040	2.05	2.5	0.10	5.2
					Total Volume (m^3) =		16.51	852.1

Table 27 Materials used in the piles in the different scenarios.

Scenario	*Volume concrete (m^3)*	*Volume steel (m^3)*	*Mass concrete (tonne)*	*Mass steel (tonne)*
Subsurface 1	593.4	9.70	1364.9	75.70
Subsurface 2	593.3	9.70	1364.5	75.68
Subsurface 3	593.5	9.71	1365.1	75.71
Aboveground 1	852.0	16.51	1959.6	128.76
Aboveground 2	871.3	16.88	2003.9	131.67
Aboveground 3	842.4	16.32	1937.4	127.30
Aboveground 4	851.8	16.50	1959.1	128.73
Aboveground 5	852.1	16.51	1959.8	128.77

Appendix B.6 Insulation

Insulation is applied to the roof, walls and floor. As explained in paragraph 2.3.3, extruded polystyrene (XPS) with a thickness of 135 mm was used for roof insulation. For the walls and floor Rockwool 123 and Rockwool 211 Vario respectively were assumed to be used as insulation. Furthermore, it was explained that the XPS has a density of 33 kg*m^{-3}, Rockwool 123 of 23 kg*m^{-3} and Rockwool 211 Vario of 45 kg*m^{-3}. As explained earlier, the roof and floor have an area of 2695.6 m^2. The volume of XPS roof insulation then was 363.9 m^3 with a mass of 12008.9 kg or 12.0 tonne. The Rockwool 211 Vario floor insulation then had a volume of 215.6 m^3 for a thickness of 80 mm and a volume of 323.5 m^3 for a thickness of 120 mm. Using the density of Rockwool 211 Vario this gave a mass of 9.70 tonne for a thickness of 80 mm and a mass of 14.56 tonne for a thickness of 120 mm. The walls have an area of 1112.13 m^2. The Rockwool 123 wall insulation then had a volume of 89.0 m^3 for a thickness of 80 mm and a volume of 122.3 m^3 for a thickness of 110 mm. Using the density of Rockwool 123 this gave a mass of 2.05 tonne for a thickness of 80 mm and a mass of 2.81 tonne for a thickness of 110 mm. The mass of all types of insulation and in each scenario are shown in table 28.

Table 28 Insulation use in the building

Scenario	*Mass XPS (tonne)*	*Mass Rockwool 123 (tonne)*	*Mass Rockwool 211 Vario (tonne)*
Subsurface 1	12.0	2.05	9.70
Subsurface 2	12.0	0	0
Subsurface 3	12.0	2.81	14.56
Aboveground 1	12.0	2.05	9.70
Aboveground 2	12.0	2.05	9.70
Aboveground 3	12.0	2.05	9.70
Aboveground 4	12.0	0	0
Aboveground 5	12.0	2.81	14.56

Appendix B.7 Windows

The windows of the subsurface supermarket are double glazing laminated safety glass with brand name “SGG Parsol Groen Securit”, which were provided by van den Heuvel glas (de Vette, 2004). Drawings 794|01, 794A01, 794A02, 794A03, 794A05, 794A06, 794A07, 794A09, 794A10, and detail drawings 794D01 to 794D35 of van den Heuvel glas (de Vette, 2004) show all the different windows that are located in the subsurface building. As explained before, the part of the building which is located above the roof of the supermarket was not taken into account. In this part a lot of windows are located. The drawings used in this research were drawings 794A02, 794A07, 794A10 and its corresponding detail drawings (de Vette, 2004).

All windows in the building are numbered. Windows with the same number are exactly the same in size. In this research the windows located at the facade “Thoelaverweg” (numbers 107 to 146 and 170 to 172) and the facade “Entreetrap” (numbers 174 to 197 and 409) were taken into account. For windows 146 and 409 only the bottom part, which is located under the roof of the building, was taken into account. The part above the roof plays no role in the actual structure of the building and serves just a decorative purpose. The areas of each window were calculated using geometry and trigonometry (e.g. Pythagorean Theorem). The areas per window number are given in table 29 and table 30. The total area of windows taken into account in the aboveground and subsurface building is shown in table 31. In SimaPro only the areas were needed, but for the transport of the windows the mass of the windows also needed to be known. According to the detailed drawings D20 and D23 the thickness of the glass is 10 mm. The density of common glass was assumed to be 2600 kg*m^{-3} (The Engineering Toolbox, 2014b). Using the density and thickness of the glass, the volume and mass of the glass were calculated. These are shown table 32.

Table 29 Area used for each window number part 1.

Position window	Amount of windows	Area per window (m^2)	Area of window (m^2)
107	1	1.24	1.24
108	1	1.64	1.64
109	1	0.75	0.75
110	17	1.27	21.64
111	1	1.15	1.15
112	1	1.55	1.55
113	1	0.56	0.56
114	1	0.57	0.57
115	1	0.57	0.57
116	1	0.58	0.58
117	1	0.58	0.58
118	1	0.59	0.59
119	1	0.59	0.59
120	1	0.60	0.60
121	1	0.61	0.61
122	1	0.62	0.62
124	1	0.77	0.77
125	1	1.38	1.38
126	1	1.78	1.78
127	1	0.87	0.87
128	12	1.28	15.37
129	1	1.26	1.26
130	1	1.66	1.66
131	1	0.75	0.75
132	10	1.28	12.81
133	1	1.14	1.14
134	1	1.54	1.54
135	1	0.63	0.63
136	1	1.01	1.01
139	2	1.28	2.56
140	1	0.66	0.66
141	1	1.00	1.00
142	1	1.24	1.24
143	1	0.24	0.24
144	1	0.51	0.51
145	1	0.04	0.04
146 bottom	1	0.84	0.84

Table 30 Area used for each window number part 2.

Position window	Amount of windows	Area per window (m^2)	Area of window (m^2)
170	1	1.28	1.28
171	1	0.14	0.14
172	1	0.64	0.64
174	1	0.41	0.41
175	1	0.56	0.56
176	1	0.68	0.68
177	1	0.80	0.80
178	1	0.91	0.91
179	1	1.03	1.03
180	1	1.26	1.26
181	2	1.38	2.76
182	1	0.47	0.47
183	1	1.31	1.31
184	7	1.37	9.62
185	1	0.22	0.22
186	1	1.16	1.16
187	1	0.16	0.16
188	1	1.10	1.10
189	1	1.39	1.39
190	1	1.41	1.41
191	1	1.10	1.10
192	2	1.38	2.76
193	1	1.41	1.41
194	1	0.83	0.83
195	1	1.41	1.41
196	1	0.55	0.55
197	1	1.36	1.36
409 bottom	1	0.23	0.23

Table 31 Total area of windows per facade and for the total building examined in this research.

	Area of window subsurface (m^2)	Area of window aboveground (m^2)
Facade thoelaverweg	83.943	83.943
Facade Entreetrap	34.90	34.902
Total windows	118.846	118.846

Table 32 Volume and mass of glass used for the subsurface and aboveground building.

Scenario	*Volume glass (m^3)*	*Mass glass (kg)*	*Mass glass (tonne)*
Subsurface 1,2,3	1.188	3090.0	3.09
Aboveground 1,2,3,4,5	1.188	3090.0	3.09

Appendix B.8 Total material use

To implement all the material data from appendix B.1 to B.7 in SimaPro it still had to be related to the functional unit, which was *“a net m^2 of comfortable retail floor space to obtain provisions for 100 years”*. The material data was already calculated for 100 years. The area used was, however, the building area. To obtain the results per net m^2 of comfortable retail floor space all material data had to be divided by the net floor area, which was 2695.6 m^2. In table 33 to table 40 a good overview of the material usage per type of material and per scenario is given. These were implemented in SimaPro.

Table 33 Material usage in scenario subsurface 1.

Part	Volume concrete (m^3)	Mass concrete (kg)	Mass steel FEB500 (kg)	Mass steel RVS (kg)	Area of glass (m^2)	Mass XPS (kg)	Mass Rockwool 123 (kg)	Mass Rockwool 211 Vario (kg)
Floor, supports and columns	0.332	762.87	31.36	-	-	-	-	-
Roof	0.074	170.79	0.48	-	-	-	-	-
Walls	0.118	270.98	7.80	-	-	-	-	-
Piles	0.220	506.35	28.08	-	-	-	-	-
Stairs	-	7.10	0.28	-	-	-	-	-
Railings	-	-	-	0.202	-	-	-	-
Windows	-	-	-	-	0.044	-	-	-
Insulation	-	-	-	-	-	4.46	0.759	3.60
Total	0.744	1718.09	67.99	0.202	0.044	4.46	0.76	3.60

Table 34 Material usage in scenario subsurface 2.

Part	Volume concrete (m^3)	Mass concrete (kg)	Mass steel FEB500 (kg)	Mass steel RVS (kg)	Area of glass (m^2)	Mass XPS (kg)	Mass Rockwool 123 (kg)	Mass Rockwool 211 Vario (kg)
Floor, supports and columns	0.332	762.87	31.36	-	-	-	-	-
Roof	0.074	170.79	0.48	-	-	-	-	-
Walls	0.118	270.98	7.80	-	-	-	-	-
Piles	0.220	506.20	28.07	-	-	-	-	-
Stairs	-	7.10	0.28	-	-	-	-	-
Railings	-	-	-	0.202	-	-	-	-
Windows	-	-	-	-	0.044	-	-	-
Insulation	-	-	-	-	-	4.46	0.00	0.00
Total	0.744	1717.95	67.98	0.202	0.044	4.46	0.00	0.00

Table 35 Material usage in scenario subsurface 3.

Part	Volume concrete (m^3)	Mass concrete (kg)	Mass steel FEB500 (kg)	Mass steel RVS (kg)	Area of glass (m^2)	Mass XPS (kg)	Mass Rockwool 123 (kg)	Mass Rockwool 211 Vario (kg)
Floor, supports and columns	0.332	762.87	31.36	-	-	-	-	-
Roof	0.074	170.79	0.48	-	-	-	-	-
Walls	0.118	270.98	7.80	-	-	-	-	-
Piles	0.220	506.42	28.09	-	-	-	-	-
Stairs	-	7.10	0.28	-	-	-	-	-
Railings	-	-	-	0.202	-	-	-	-
Windows	-	-	-	-	0.044	-	-	-
Insulation	-	-	-	-	-	4.455	1.044	5.400
Total	0.744	1718.16	67.99	0.202	0.044	4.46	1.04	5.40

Table 36 Material usage in scenario aboveground 1.

Part	Volume concrete (m^3)	Mass concrete (kg)	Mass steel FEB500 (kg)	Mass steel RVS (kg)	Area of glass (m^2)	Mass XPS (kg)	Mass Rockwool 123 (kg)	Mass Rockwool 211 Vario (kg)
Floor, supports and columns	0.221	508.58	20.90	-	-	-	-	-
Roof	0.050	113.86	0.32	-	-	-	-	-
Walls	0.079	180.66	5.20	-	-	-	-	-
Piles	0.316	726.95	47.77	-	-	-	-	-
Stairs	-	-	-	-	-	-	-	-
Railings	-	-	-	-	-	-	-	-
Windows	-	-	-	-	0.044	-	-	-
Insulation	-	-	-	-	-	4.46	0.76	3.60
Total	0.665	1530.05	74.19	0.000	0.044	4.46	0.76	3.60

Table 37 Material usage in scenario aboveground 2.

Part	Volume concrete (m^3)	Mass concrete (kg)	Mass steel FEB500 (kg)	Mass steel RVS (kg)	Area of glass (m^2)	Mass XPS (kg)	Mass Rockwool 123 (kg)	Mass Rockwool 211 Vario (kg)
Floor, supports and columns	0.332	762.87	31.36	-	-	-	-	-
Roof	0.074	170.79	0.48	-	-	-	-	-
Walls	0.118	270.98	7.80	-	-	-	-	-
Piles	0.323	743.39	48.85	-	-	-	-	-
Stairs	-	-	-	-	-	-	-	-
Railings	-	-	-	-	-	-	-	-
Windows	-	-	-	-	0.044	-	-	-
Insulation	-	-	-	-	-	4.46	0.76	3.60
Total	0.847	1948.04	88.48	0.000	0.044	4.46	0.76	3.60

Table 38 Material usage in scenario aboveground 3.

Part	Volume concrete (m^3)	Mass concrete (kg)	Mass steel FEB500 (kg)	Mass steel RVS (kg)	Area of glass (m^2)	Mass XPS (kg)	Mass Rockwool 123 (kg)	Mass Rockwool 211 Vario (kg)
Floor, supports and columns	0.166	381.43	15.68	-	-	-	-	-
Roof	0.037	85.40	0.24	-	-	-	-	-
Walls	0.059	135.49	3.90	-	-	-	-	-
Piles	0.312	718.73	47.23	-	-	-	-	-
Stairs	-	-	-	-	-	-	-	-
Railings	-	-	-	-	-	-	-	-
Windows	-	-	-	-	0.044	-	-	-
Insulation	-	-	-	-	-	4.46	0.76	3.60
Total	0.574	1321.05	67.04	0.000	0.044	4.46	0.76	3.60

Table 39 Material usage in scenario aboveground 4.

Part	Volume concrete (m^3)	Mass concrete (kg)	Mass steel FEB500 (kg)	Mass steel RVS (kg)	Area of glass (m^2)	Mass XPS (kg)	Mass Rockwool 123 (kg)	Mass Rockwool 211 Vario (kg)
Floor, supports and columns	0.221	508.58	20.90	-	-	-	-	-
Roof	0.050	113.86	0.32	-	-	-	-	-
Walls	0.079	180.66	5.20	-	-	-	-	-
Piles	0.316	726.78	47.75	-	-	-	-	-
Stairs	-	-	-	-	-	-	-	-
Railings	-	-	-	-	-	-	-	-
Windows	-	-	-	-	0.044	-	-	-
Insulation	-	-	-	-	-	4.46	0.00	0.00
Total	0.665	1529.87	74.18	0.000	0.044	4.46	0.00	0.00

Table 40 Material usage in scenario aboveground 5.

Part	Volume concrete (m^3)	Mass concrete (kg)	Mass steel FEB500 (kg)	Mass steel RVS (kg)	Area of glass (m^2)	Mass XPS (kg)	Mass Rockwool 123 (kg)	Mass Rockwool 211 Vario (kg)
Floor, supports and columns	0.221	508.58	20.90	-	-	-	-	-
Roof	0.050	113.86	0.32	-	-	-	-	-
Walls	0.079	180.66	5.20	-	-	-	-	-
Piles	0.316	727.03	47.77	-	-	-	-	-
Stairs	-	-	-	-	-	-	-	-
Railings	-	-	-	-	-	-	-	-
Windows	-	-	-	-	0.044	-	-	-
Insulation	-	-	-	-	-	4.46	1.04	5.40
Total	0.665	1530.13	74.19	0.000	0.044	4.46	1.04	5.40

Appendix C. Operational energy use of the building

In the use phase of the LCA the operational energy use was an important aspect which can differ between the subsurface and aboveground building. In this phase the results show a difference between a subsurface and an aboveground supermarket without differences due to the usage of the buildings. For this the functional unit, which was *"a net m^2 of comfortable retail floor space to obtain provisions for 100 years"*, was important. When both buildings have the same comfortable retail floor space per net m^2, climate settings in the building will not influence the results. Creating a comfortable retail floor space per net m^2 then only depends on the energy use of the building. In this research the same supermarket was assumed to be build aboveground, which meant both buildings were fully comparable in function, amount of people in the building and tasks performed in the building. Furthermore, both buildings then applied exactly the same comfortable retail floor space characteristics per net m^2. Creating this comfortable floor space then depended on the energy use of the buildings.

The energy use of a building can be in the form of heat or electricity. These energies, however, enter the building in a different form, namely as electricity and natural gas. The energy use of a building is thus separated in electricity consumption and natural gas consumption. According to EPA (2008b) and EIA (2003) most electricity consumption of a supermarket comes from refrigeration followed by lighting, and Heating, Ventilation and Air Conditioning (HVAC) (see figure 42). The EIA separates the HVAC data further which gives 3% for space heating, 7% for cooling and 3% for ventilation. The majority of the natural gas consumption of a supermarket is used for space heating. The rest is used for water heating, cooking and other applications (see figure 43). This shows that the actual amount of electricity and natural gas consumption largely depends on the size, design and interior (refrigerators, lighting, air-conditioning etc.) of the building. In this research only changing elements were taken into account, which included heating and cooling, and other extra electricity uses. The first thing examined was the heating and cooling of the building.

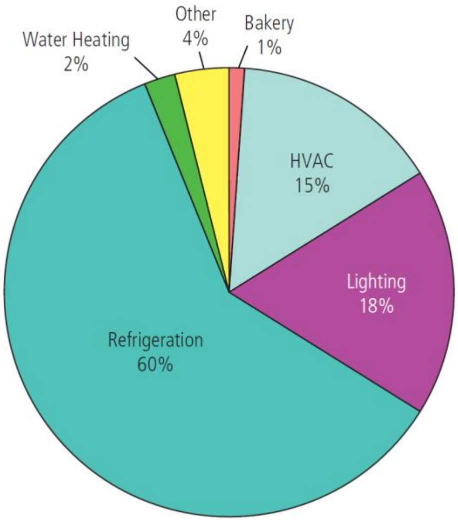


Figure 42 Electricity consumption in a supermarket by end use (EPA, 2008b).

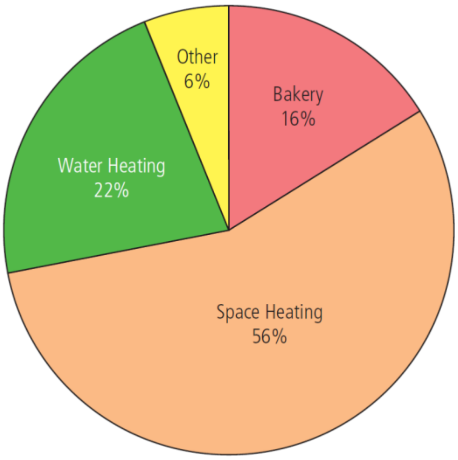


Figure 43 Natural gas consumption in a supermarket by end use (EPA, 2008b).

Appendix C.1 Heating and cooling

The amount of heating and cooling needed depends on the temperature inside the building. When the temperature exceeds a certain level, heating or cooling is needed. In the United Kingdom (UK) supermarkets are obligated to have an indoor temperature of 19 to 21°C in winter and 21 to 23°C in summer (Garstenveld, 2013). In this research 20°C and 22°C were used as the boundary for respectively heating and cooling. Because the temperature in the building was assumed stable, the amount of heating or cooling actually depended only on the change in temperature which is caused by heat exchange with the outside of the building. According to Blok (2007) the heat flow through a wall can be calculated using formula 25. Because the temperature changes during the year, the formula could not be used in this way. Therefor the degree days were used. These were explained and calculated in appendix D and the results are shown in table 41.

Formula 25 Formula for the heat flow through a wall.

$$Q = \frac{\lambda}{d} * \Delta T * A = k * \Delta T * A$$

Legenda:

Q = The heat flow through the wall (W).
ΔT = The temperature difference across the wall (K).
d = The thickness of the wall (m)
λ = The thermal conductivity ($W*m^{-1}*K^{-1}$)
k = The heat transmission coefficient = λ/d ($W*m^{-2}*K^{-1}$)
A = The surface area of the wall (m^2)

Table 41 HDD and CDD used for different parts of the building.

	Used for	*Depth (m)*	*HDD (°C)*	*CDD (°C)*
Aboveground air	Subsurface: roof +windows Aboveground: Walls + roof + windows	-	3389.0	0.0
Subsurface depth 1	Subsurface: Walls Aboveground: Not used	2.5	2760.7	0.0
Subsurface depth 2	Subsurface: Floor Aboveground: Not used	5	2760.5	0.0
Subsurface depth 3	Subsurface: Not used Aboveground: Floor	1	2763.1	0.0

With the Cooling Degree Days (CDD) or Heating Degree Days (HDD) in place of the ΔT, the annual heat loss through the walls of the building was calculated per side of the housing body using formula 25. The CDD was here important for air-conditioning and the HDD for heating. The k value in formula 25 is the total heat transmission coefficient of all layers in the wall combined. The total heat transmission coefficient of the different layers was calculated using formula 26. By using formula 26, only heat transfer within the wall would be taken into account. Outside the walls heat is also transferred through radiation and convection. At normal temperatures radiation is not important making convection the only thing taken into account. Convection can take place inside and outside the wall giving two extra heat transfer coefficients $k_{c,i}$ and $k_{c,o}$. Convection is the heat transfer by the movement of a fluid or gas (Blok, 2007). For a building this is mostly the heat transfer by the wind. In the subsurface scenarios the outside coefficient was only taken into account for the roof and windows because only these are connected to the air. The formula for the total heat transfer coefficients was then changed to obtain two new formulas for the total heat transfer coefficient (see formula 27). According to Blok (2007) the heat transfer coefficient for convection ranges from 6 – 30 $W*m^{-2}*K^{-1}$. In this research a value of 8 is used for $k_{c,i}$ and $k_{c,o}$.

Formula 26 Formula to calculate the heat transmission coefficient of a multilayer wall.

$$k_{total} = \frac{1}{\frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3}}$$

Formula 27 Total heat transmission coefficient of a multilayer wall, including convective heat transfer, for the aboveground building (left) and the subsurface building (right).

$$k_{total} = \frac{1}{\frac{1}{k_{c,i}} + \frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3} + \frac{1}{k_{c,o}}} \qquad k_{total} = \frac{1}{\frac{1}{k_{c,i}} + \frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3}}$$

Heat losses due to ventilation, normally also should have been taken into account. In this research this was not taken into account, because these days ventilation systems with a heat recovery system are available, which are especially profitable in places which would need large amounts of cooling (Home Innovation Research Labs, 2001). These systems are quite efficient meaning the small amount of extra energy, which is used to recover the heat, can be neglected. Because the temperature inside the building is kept stable and ventilation is neglected, the heat entering the supermarket through the walls is the heat that has to be compromised by air conditioning. The other way around, the heat exiting the supermarket is the heat loss that has to be compromised by heating. For the aboveground building all surfaces of the building envelope are in contact with the air except for the floor, which is connected to the soil. In the subsurface multiple surfaces of the building envelope are connected to the soil at different depths. In the soil, temperatures are different from the aboveground temperature, which meant the amount of degree days changed.

The degree days for the different parts of the building envelope of both buildings were shown in table 41. Next to the amount of degree days each surface area is connected with, information about the surface areas themselves also needed to be known. This included the areas of each surface, and the thickness and thermal conductivity of its layers. These were shown in paragraph 2.3.3 and in table 8 in appendix A. Using this information the additional heat from the environment, which needs to be cooled by air-conditioning, and the heat loss of the supermarket, which needs to be heated up by a boiler, were calculated for each scenario. In this research the functional unit looks at a period of 100 years. The heating and cooling then also had to be calculated over a period of 100 years. Table 42 and table 43 show the resulting additional heat and heat loss.

Table 42 Additional heat entering the building from the environment.

		Yearly additional heat roof (MJ)	Yearly additional heat walls (MJ)	Yearly additional heat floor (MJ)	Yearly additional heat window (MJ)	Yearly additional heat building (MJ)	Additional heat building over building lifetime (MJ)
Subsurface scenarios	Subsurface 1	0.00	0.00	0.00	0.00	0.00	0.00
	Subsurface 2	0.00	0.00	0.00	0.00	0.00	0.00
	Subsurface 3	0.00	0.00	0.00	0.00	0.00	0.00
Aboveground scenarios	Aboveground 1	0.00	0.00	0.00	0.00	0.00	0.00
	Aboveground 2	0.00	0.00	0.00	0.00	0.00	0.00
	Aboveground 3	0.00	0.00	0.00	0.00	0.00	0.00
	Aboveground 4	0.00	0.00	0.00	0.00	0.00	0.00
	Aboveground 5	0.00	0.00	0.00	0.00	0.00	0.00

Table 43 Heat loss of the building.

		Yearly heat loss roof (GJ)	Yearly heat loss walls (GJ)	Yearly heat loss floor (GJ)	Yearly heat loss window (GJ)	Yearly heat loss building (GJ)	Heat loss building over building lifetime (TJ)
Subsurface scenarios	Subsurface 1	190.9	100.3	213.0	30.0	534.2	53.4
	Subsurface 2	190.9	411.7	966.6	30.0	1599.1	159.9
	Subsurface 3	190.9	78.1	153.3	30.0	452.3	45.2
Aboveground scenarios	Aboveground 1	193.0	125.4	226.8	30.0	575.2	57.5
	Aboveground 2	190.9	117.6	213.2	30.0	551.7	55.2
	Aboveground 3	194.0	129.8	234.2	30.0	588.0	58.8
	Aboveground 4	193.0	546.1	1326.6	30.0	2095.7	209.6
	Aboveground 5	193.0	97.3	160.3	30.0	480.6	48.1

Appendix C.2 Electricity use

Next to heat the electricity use of both buildings was examined. In order to compare the difference in electricity use due to building subsurface, it was important to keep the interior per unit of size the same. As said, refrigeration plays a huge role in the electricity use of a supermarket. If the amount of refrigerators per unit of size would differ this would have a large effect on the electricity use. Also, having different refrigerator models could have a large influence. In this research the size of the buildings was the same, because the aboveground building was constructed by only making changes to the characteristics that were caused by building aboveground. The amount and type of refrigerators thus also stayed the same, which meant the electricity use and heat release of the refrigerators had no influence on the difference between the subsurface and aboveground building. The electricity use for lighting also did not differ between the aboveground and subsurface building. As mentioned before, supermarkets were not obligated to have a certain amount of natural light, which meant there were almost no windows and almost all light was coming from artificial lighting. Both buildings were the same, so the amount of artificial lighting was exactly the same. Next to lighting and refrigeration the interior of the subsurface and aboveground building was almost fully the same. The only differences between the two buildings were the elevators and the air-conditioning. In order to get subsurface with carts, people need to use an elevator. This is different from aboveground where people can enter the supermarket without using elevators. The elevators in the subsurface building have an extra electricity use which was taken into account by subtracting their electricity use from the total electricity use of the subsurface building to create an electricity use for the aboveground building. Before this could be done the electricity use for each type of elevator was estimated, starting with the elevator for people.

The elevator that is used for people is the Evolution Flexible BC61 from ThyssenKrupp (de Vette, 2004). It has a nominal load capacity of 1000 kg and it is suited for around 13 people. The motor has a power of 9.2 kW but the manufacturers test results show a performance of 5.5 kW which was used in this research. ThyssenKrupp (de Vette, 2004) made a calculation which shows the average waiting time and average transit time. The transit time is the average time it takes the elevator to go down or up. This time, which is 19.6 seconds, was used for the time the elevator operates per usage. The electricity use of the elevator was thus 107,800 J per use (see formula 28). For the amount of times it is used per day no values were obtained. Because the supermarket also has moving walks it was assumed these are used most often by all the people and the normal elevator is used only 5 times a day. The supermarket is opened every day of the year, so the elevator was assumed to be used 1825 times a year. The electricity use of the elevator then was 54.65 kWh or 0.055 MWh (see formula 29). This was probably an overestimation of its use but it still had to be seen if this result has a large effect in the total research. Next the electricity use for transporting down the goods was examined.

Formula 28 Electricity use of the elevator for people per usage.

$$Electricity_{use}\ (J) = Power\ (W) * time\ (s) = Power\ \left(\frac{J}{s}\right) * time\ (s) = 5500 * 19.6 = 107{,}800J$$

Formula 29 Yearly electricity use of the elevator for people.

$$Electricity\ use_{year}(J) = Electricity_{use}\ (J) * uses * days = 107{,}800 * 5 * 365 = 196{,}735{,}000J$$

$$Electricity\ use_{year}(kWh) = \frac{Electricity\ use_{year}(J)}{3.6{*}10^6} = \frac{196{,}735{,}000}{3.6{*}10^6} = 54.65kWh$$

The elevator that is used for goods is the A-1500 from Elsto Boekholt Dynatec (EBD) (de Vette, 2004). It has a maximum weight capacity of 1500 kg and it operates at a speed of 0.12 $m*s^{-1}$ using a motor that has a power of 4 kW. In the building the goods need to be transported over a distance of 4.55 m meaning it takes 37.9 seconds on average for the elevator to go up or down (see formula 30). Every time the elevator is used it uses 151,667 J of electricity (see formula 31). Every day products will be brought down the elevator to the supermarket or waste materials will be send up to be taken from the supermarket. According to drawing 03 from the EBD the cage of the elevator is 1400x2500 mm in size (de Vette, 2004). The roll cages are assumed to be 70x80 mm in size (Jumbo supermarkten B.V., 2013), which means that at least three and maybe even four roll cages fit in one elevator. This is a lot of products. For this research it was assumed the elevator is used efficiently and it is going up twice a day and down twice a day, which meant it is used four times a day on average. The supermarket is opened every day of the year, so the elevator is used 1460 times a year giving a yearly electricity use of 61.51 kWh or 0.062 MWh (see formula 32). The next and final elevator examined was the moving walk which is used to transport the people to and from the supermarket.

Formula 30 Average time it takes the elevator for goods to go up or down.

$$Time\ (s) = \frac{distance(m)}{speed(m/s)} = \frac{4.55}{0.12} = 37.9s$$

Formula 31 Electricity use of the elevator for goods per usage.

$$Electricity_{use}\ (J) = Power\ (W) * time\ (s) = Power\ \left(\frac{J}{s}\right) * time\ (s) = 4000 * 37.9 = 151{,}667J$$

Formula 32 Yearly electricity use of the elevator for goods.

$$Electricity\ use_{year}(J) = Electricity_{use}\ (J) * uses * days = 151.667 * 4 * 365 = 221{,}433{,}333J$$

$$Electricity\ use_{year}(kWh) = \frac{Electricity\ use_{year}(J)}{3.6{*}10^6} = \frac{221{,}433{,}333}{3.6{*}10^6} = 61.51kWh$$

In the case study two Orinoco model FS983 moving walks from ThyssenKrupp were installed (de Vette, 2004). The motor of the moving walks has a power of 9.0 kW and it is assumed to be operating during the full opening hours. Opening hours for the supermarket were different day by day but the supermarket was opened 81 hours a week. It was assumed the moving walks are started up half an hour before opening and shut of half an hour after closing. This assumption is made because employees are already in the building earlier to prepare for the day and they will leave later due to works that still have to be performed. In total 7 hours a week are thus added to the operational time of the moving walks, which made a total operational time of 88 hours a week. This corresponds to 12.6 hours a day or 4589 hours a year, which gave a yearly electricity use of

41,297,142 Wh or 41,297 kWh (see formula 33). Because the supermarket has two moving walks the total yearly electricity use for the moving walks is 82,594 kWh or 82.6 MWh.

Formula 33 Yearly electricity use of the moving walk.

$$Electricity\ use_{year} = Power * hours\ per\ day * days = 9000 * 12.6 * 365 = 41{,}297{,}142Wh$$
$$= 41{,}297kWh$$

Next to the elevators the air-conditioning could also differ between the subsurface and aboveground building. The electricity use for air-conditioning is dependent on the heat in the building. This was explained in the heat section in appendix C.1. The air-conditioning was taken into account in the electricity use by subtracting the electricity use of subsurface scenario 1 (main scenario) from the total electricity use. The electricity use for air-conditioning of the specific scenario was then added to this calculated electricity use to obtain the total electricity use in that scenario. By subtracting the electricity use of the elevators for the aboveground scenarios, the total electricity use in all scenarios was calculated. In table 42 in appendix C.1 was observed that for none of the scenarios there was an additional energy use to the building from the environment for which cooling was needed. The only electricity use change observed in this research was then the electricity use of the elevators.

To be able to calculate the electricity use of the building in the different scenarios, the yearly electricity use of the supermarket needed to be known. According to an electricity bill of December 2013, which was obtained from de Vette (2014), the electricity use of the supermarket was around 129.64 MWh for that month. In this research it is assumed that this is the average monthly electricity use of the supermarket. The yearly electricity use would then be 1555.68 MWh. By correcting this electricity use, using the methods described above, the yearly electricity use of the supermarket in the different scenarios was calculated. In the LCA the functional unit looks at a period of 100 years. The electricity use then also had to be calculated over a period of 100 years. Table 44 shows the resulting electricity uses.

Table 44 Electricity use of the aboveground and subsurface building in different scenarios.

		Yearly Electricity use reduction elevator for goods (MWh)	Yearly Electricity use reduction elevator for people (MWh)	Yearly Electricity use reduction moving walk (MWh)	Yearly Electricity use air-conditioning (MWh)	Yearly Electricity use building (MWh)	Electricity use building over building lifetime (MWh)
Subsurface scenarios	Subsurface 1	0.0	0.0	0.0	0.0	1555.68	155568
	Subsurface 2	0.0	0.0	0.0	0.0	1555.68	155568
	Subsurface 3	0.0	0.0	0.0	0.0	1555.68	155568
Aboveground scenarios	Aboveground 1	0.062	0.055	82.59	0.0	1472.97	147297
	Aboveground 2	0.062	0.055	82.59	0.0	1472.97	147297
	Aboveground 3	0.062	0.055	82.59	0.0	1472.97	147297
	Aboveground 4	0.062	0.055	82.59	0.0	1472.97	147297
	Aboveground 5	0.062	0.055	82.59	0.0	1472.97	147297

Appendix D. Degree days calculation

In order to be able to calculate the energy use for heating and cooling, the temperature of the surroundings was needed. Temperatures at the surface are measured by organizations, which meant data was obtained for this. The subsurface temperatures were not measured and could thus not directly be found. Furthermore, the temperatures in the subsurface are different from the aboveground temperature meaning the aboveground temperatures could not have been used for the subsurface building. With the help of a mathematical model it was, however, possible to predict the subsurface temperature at different depths and times (Al-Temeemi & Harris, 2001). In this model, soil characteristics are used to incorporate the heat transfer through different types of soil. These soil characteristics differ per location, which was also the case for the aboveground temperatures. This made it possible to make predictions for different climates. A calculation derived by Labs is used by Al-Temeemi and Harris (2001), Mazarron and Canas (2008), Moustafa et al. (1981), and van Dronkelaar et al. (2014) to predict the subsurface temperatures (see formula 34).

Formula 34 Formula for estimating the subsurface temperature as a function of depth and day of the year.

$$T_{(x,t)} = T_m - A_s * e^{-x*\sqrt{\pi/(365.25*\alpha)}} * \cos[\frac{2\pi}{365.25} * (t - t_0 - \frac{x}{2} * \sqrt{\frac{365.25}{\pi * \alpha}})]$$

Legenda:

$T_{(x,t)}$ = The subsurface temperature at a depth x (in m) and time t (in days) in degree Celsius (°C).

T_m = The average surface ground temperature in degree Celsius (°C).

A_s = The annual temperature amplitude at the surface (x = 0) in degree Celsius (°C).

e = The Euler's number, which is a constant.

x = The subsurface depth in meters (m).

t = The time of the year in days, where t = 0 at midnight of December 31st (days).

t_0 = The phase constant, which is the day of minimum surface temperature in days (days).

α = The thermal diffusivity of the soil in m^2 per day (m^2/day).

According to Watson and Labs (Al-Temeemi & Harris, 2001) the average surface ground temperature (T_m) can be approximated by adding around 1.7°C to the average annual air temperature. Air temperatures in the Netherlands are measured by the Royal Netherlands Meteorological Institute (in Dutch: Koninklijk Nederlands Meteorologisch Instituut or KNMI). The KNMI has several weathering stations that measure the air temperatures over the year. In this research the data from the Rotterdam weathering station was used because this is a station close to the case study (KNMI, 2014). Daily data from 1999 to 2013 was used to calculate the average daily temperature and the average temperature of the Netherlands over these years. The reason for calculating the average temperatures instead of using the average temperatures given is that the given temperatures for Rotterdam are calculated from 1957 onwards. Figure 44 of the World Meteorological Organization (WMO, 2014), however, shows that the global temperature since 1950 has risen. According to WMO (2014) thirteen of the fourteen warmest years on record have occurred in the 21st century. Using average temperatures from over 50 years ago could thus give a too low estimate. Using the average temperature of the last 15 years should have given a more accurate value for the present time.

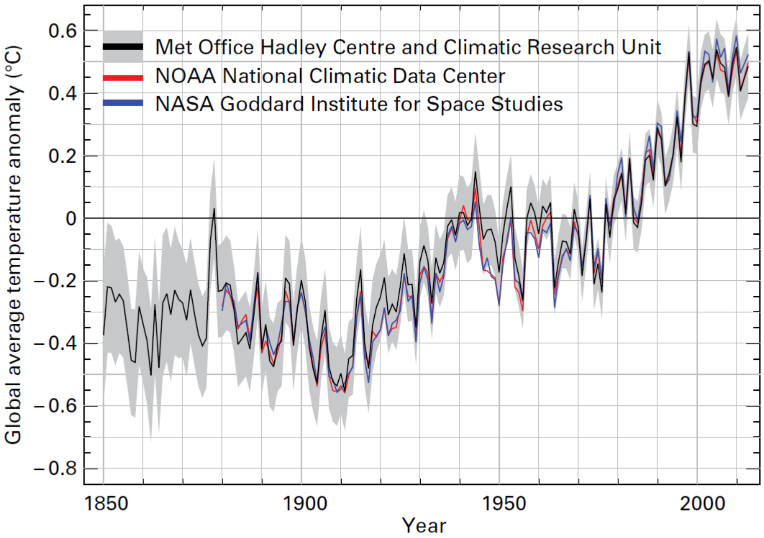


Figure 44 Annual global average temperature anomalies (relative to 1961 – 1990) from 1850 to 2013 (WMO, 2014).

The average daily temperatures were used to calculate the annual temperature amplitude at the surface (A_s) and the phase constant (t_0). By taking the lowest average daily temperature, subtracting this from the highest average daily temperature and dividing this by two, an annual temperature amplitude at the surface of 8.6 was obtained. The phase constant was a bit more difficult to obtain. For this, the average daily temperatures were put in a graph (see figure 45) and its formula (see formula 35) was obtained.

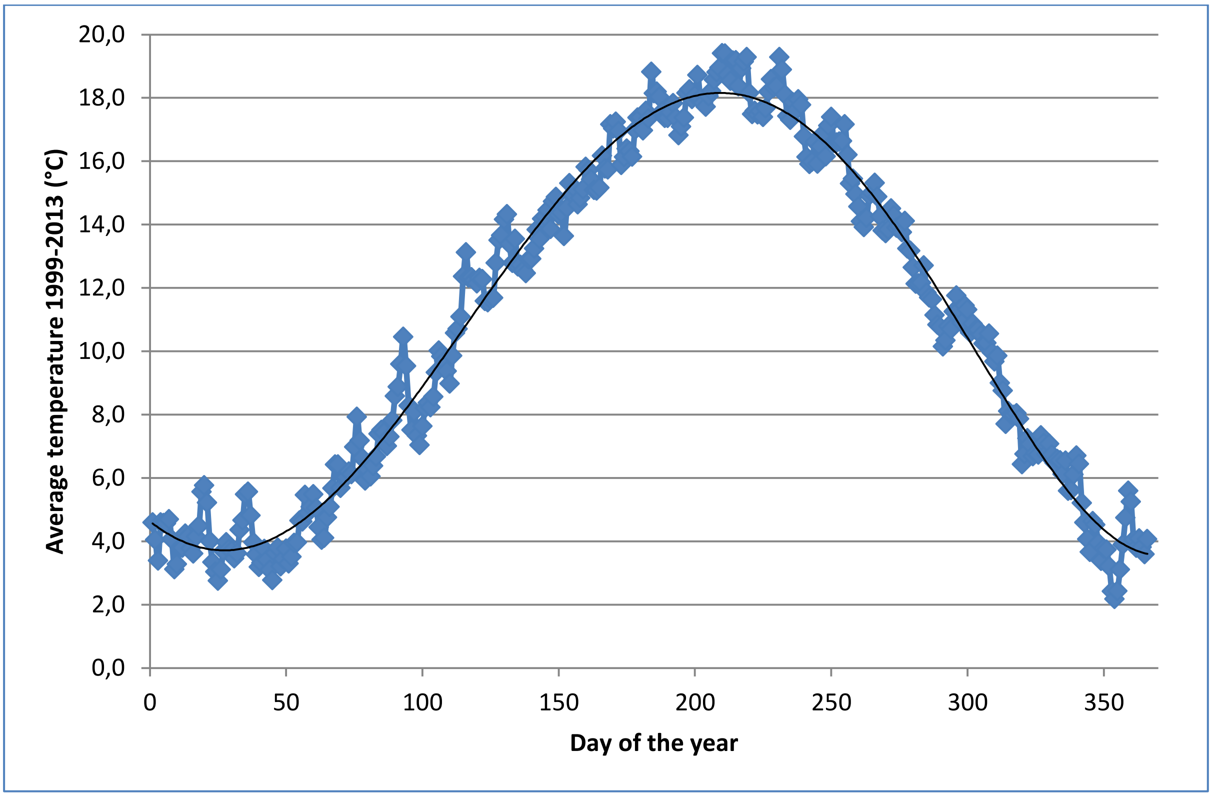


Figure 45 Average daily temperatures, of the years 1999-2013, over the year.

The first derivative of the formula (see formula 36) can be used to find the day of maximum and minimum temperature by making its result zero. Using trial and error, by filling in the x, the minimum was found at day 27.25, which was the phase constant.

Formula 35 Formula describing the average daily temperature fluctuation over time.

$$y = -5{,}84529 * 10^{-14} * x^{6} + 9{,}69719 * 10^{-11} * x^{5} - 4{,}15381 * 10^{-8} * x^{4}$$
$$+2{,}31863 * 10^{-6} * x^{3} + 1{,}18465 * 10^{-3} * x^{2} - 6{,}66277 * 10^{-2} * x + 4{,}62424$$

Formula 36 First derivative of the formula describing the average daily temperature fluctuation over time.

$$\frac{dy}{dt} = 6 * -5{,}84529 * 10^{-14} * x^{5} + 5 * 9{,}69719 * 10^{-11} * x^{4} - 4 * 4{,}15381 * 10^{-8} * x^{3}$$
$$+3 * 2{,}31863 * 10^{-6} * x^{2} + 2 * 1{,}18465 * 10^{-3} * x - 6{,}66277 * 10^{-2}$$

The average temperature of the Netherlands was calculated to be 10.756°C. Adding the 1.7°C gave an average surface ground temperature of 12.456°C. In order to be able to calculate the temperature in the subsurface at a certain depth there were still two variables missing, namely the depth and the thermal diffusivity of the soil. The floor of the subsurface building is located at a depth of 5 m, so the temperatures were calculated at a depth of 5 m for the floor and 2.5 m for the walls. Additional a depth of 1 m is measured for the floor of the aboveground building. According to Harris (2006) the thermal diffusivity in $m^{2}*day^{-1}$ can be calculated using formula 37. The values filled into the formula differ per type of soil. In order to calculate the thermal diffusivity the site specific soil composition was needed. The lithology of the subsurface at the location of the supermarket, as shown in figure 46, was obtained through Dinoloket (2014).

Formula 37 Formula to calculate the thermal diffusivity.

$$\alpha = \frac{\lambda}{\rho * C_M} * 24 * 3600 = \frac{\lambda}{C_V} * 24 * 3600$$

Legenda:

α = Thermal diffusivity ($m^{2}*day^{-1}$)
λ = Thermal conductivity ($W*m^{-1}*K^{-1}$)
ρ = Density ($kg*m^{-3}$)
C_M = Specific heat capacity ($J*kg^{-1}K^{-1}$)
C_V = Volumetric heat capacity ($J*m^{-3}K^{-1}$)

Looking at the lithology in figure 46 shows three different soil types are present in the first 5 m of the subsurface. The green part is clay, the yellow is fine sand and the red/brown is peat. The thermal diffusivity of the soil was calculated by using an average thermal conductivity and an average volumetric heat capacity in formula 37. The average thermal conductivity was calculated using formula 39. Before this formula could be used the average heat transmission coefficient of the soil was determined using formula 38. The heat transmission coefficients of the different layers were calculated by using formula 39 for the specific layer. The thermal conductivities used for each layer are obtained from a report from the Nederlandse Vereniging voor Ondergrondse Energieopslagsystemen (NVOE, 2006) and shown in table 45.

Formula 38 Formula to calculate the heat transmission coefficient of a multilayer wall.

$$k_{total} = \frac{1}{\frac{1}{k_{clay}} + \frac{1}{k_{sand}} + \frac{1}{k_{peat}}}$$

Formula 39 Formula to calculate the heat transmission coefficient of a layer.

$$\mathrm{k} = \frac{\lambda}{\mathrm{d}}$$

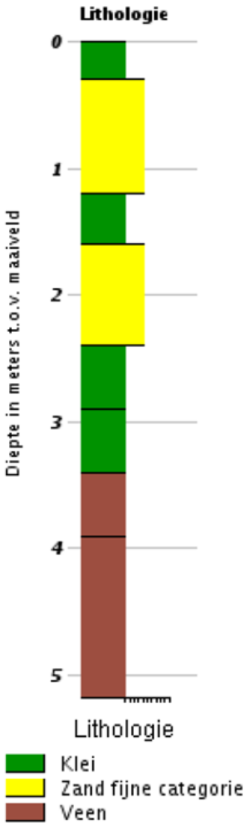


Figure 46 Lithology of drill sample at coordinates 71140, 435349 (Dinoloket, 2014)

The volumetric heat capacities of each soil type (see table 45), also obtained from the NVOE report, were multiplied by the fraction of appearance in the soil and summed up to obtain the average volumetric heat capacity of the soil. This volumetric heat capacity and thermal conductivity were used in formula 37 to calculate the thermal diffusivity of the soil. The input data and resulting thermal diffusivity are shown in table 45.

Table 45 Input data and resulting thermal diffusivity for the soil at location supermarket Brielle.

	Clay	*Fine sand*	*Peat*	***Total***
Size of layer (m)	1.7	1.7	1.6	5
fraction of total layer	0.34	0.34	0.32	1
Thermal conductivity (W*m^{-1}*K^{-1})	1.7	2.4	0.4	0.876
Unit thermal conductance k (W*m^{-2}*K^{-1})	1.000	1.412	0.250	0.175
Volumetric heat capacity (J*m^{-3} *K^{-1})	2.50E+06	2.55E+06	2.15E+06	2.41E+06
Thermal diffusivity (m^{2}*s)	6.80E-07	9.41E-07	1.86E-07	3.64E-07
Thermal diffusivity (m^{2}*day^{-1})	5.88E-02	8.13E-02	1.61E-02	3.15E-02

With all inputs known the subsurface temperatures were calculated using formula 34. For the aboveground temperatures the same formula was used. The depths then were zero, which meant that the parts of the formula with the depth in it disappeared and the formula became formula 40. For the aboveground temperatures both 10.756°C and 12.456°C were calculated to see the effect. In this research the 10.756°C was used for the aboveground scenarios, because this is the temperature in the air and the 12.456°C is the ground surface temperature. By filling in the formulas for each day and depth the temperatures of each day and at each depth were obtained (see figure 47).

Formula 40 Formula used for the aboveground temperature calculation

$$T_{(x,t)} = T_m - A_s * \cos[\frac{2\pi}{365.25} * (t - t_0)]$$

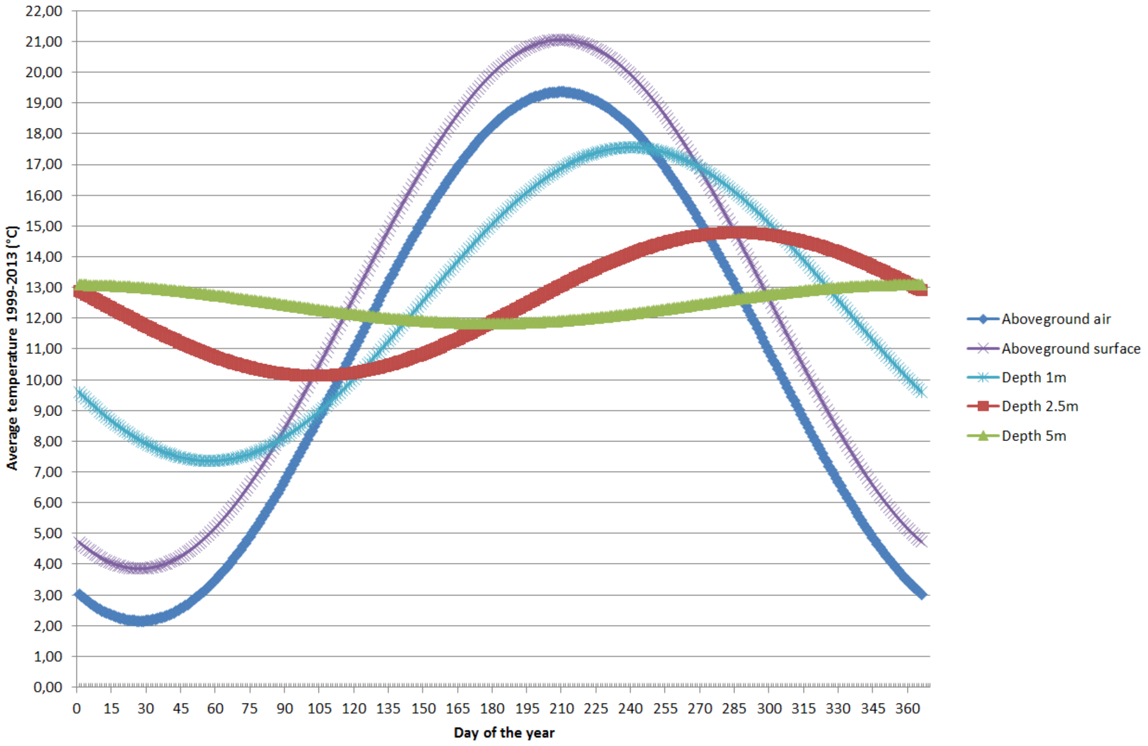


Figure 47 Calculated average daily temperatures over the year at different depths.

When examining the energy use for heating and cooling it is not really practical to calculate this for each day separately. The energy use will be measured over a certain period of time, which is almost always over a year. For this reason the concept of degree days was developed. According to Baumert (2003) "a degree day is a measure of the average temperature's departure from a human comfort level of 18°C". The degree days thus measure the difference between the average daily temperature and the human comfort level. In practice the comfort level can be changed depending on the situation. Furthermore, it can be used for both cooling and heating. Therefor there are two types of degree days, the Heating Degree Days (HDD) and the Cooling Degree Days (CDD). The HDD is calculated by subtracting the actual temperature from the reference temperature and the CDD is calculated by subtracting the reference temperature from the actual temperature. The degree days cannot be negative, meaning any negative value will become zero. As an example for the CDD, if the base temperature is 22°C and the temperature on day 1 is 24°C then the CDD for day 1 is 2°C. If day 2 has a temperature of 25°C the CDD for day 2 is 3°C and for both days together it is 5°C. The degree days can be calculated for a period of time by summing up the degree days for all days of this specific period, like for a year. Both formulas for calculating the HDD and CDD are shown in formula 41 (Blok, 2007). The resulting HDD and CDD over an average year in the period of 1999 to 2013 for different depths and average temperatures gave the results shown in table 46. These were further used in the energy calculations.

Formula 41 Formulas used to calculate the HDD (left) and the CDD (right).

$$HDD = \sum_{i=1}^{365} \max\left(T_{ref} - T_i, 0\right) \qquad CDD = \sum_{i=1}^{365} \max\left(T_i - T_{ref}, 0\right)$$

Table 46 HDD and CDD resulting from calculations on different depths and average temperatures.

	Depth (m)	Average T used (°C)	HDD (°C)	CDD (°C)
Aboveground air	-	10.756	3389.0	0.0
Aboveground surface	-	12.456	2807.6	0.0
Subsurface depth 1	2.5	12.456	2760.7	0.0
Subsurface depth 2	5	12.456	2760.5	0.0
Subsurface depth 3	1	12.456	2763.1	0.0

Appendix E. Construction and transport

Not only have the materials the building is constructed of had an impact in the life cycle of the building. Before the building was in place it also had to be constructed. The location had to be prepared, materials had to be transported to the location and these materials had to be put in place. These processes also use up energy and materials and thus have an impact. In this research the excavation and transportation of the soil, and the transportation of the materials to the location were taken into account. For other facets of the construction phase the data was insufficient and assumptions could not be made reliable. These facets included among others the pumping of groundwater out of the construction area and the piling of the piles in the subsurface.

Appendix E.1 Excavation and transportation of the soil.

Before the building was build, the location had to be prepared. Parts of the soil had to be removed to create space for the building. Removing this soil has an impact because excavators and trucks need to be used to remove the soil from the location. It was unknown what exact types of excavators were used to dig out the sand. In this research it was assumed that this was fully done by a hydraulic digger which loads the sand directly in a dump truck. In SimaPro the unit for excavation was the volume of sand that had to be removed. As calculated before, both buildings have an area of 2695.6 m^2. Although a larger area in real life was excavated it was assumed in this research that only the building area was excavated. The aboveground building has a depth of 1 m under the surface and the subsurface building has a depth of 5 m under the surface. The volume of soil that had to be removed for the aboveground building was thus 2695.6 m^3 and the volume of soil that had to be removed for the subsurface building was 13478.0 m^3 (see table 47).

This sand also had to be transported to a dumping location. For this the mass of the transported volume of soil needed to be known. The density of the soil was calculated using the fraction of each type of soil in the total soil layer. This fraction was multiplied by the density of that type of soil. The results were summed up to obtain an average density of the soil. Densities were obtained from AVCalc LLC (2014). The density of wet excavated clay was used as the density for clay, which is 1826 $kg*m^{-3}$. The density of fine sand was used as the density for fine sand, which is 1999 $kg*m^{-3}$. The density of moist peat was used as the density for peat, which is 801 $kg*m^{-3}$. With fractions of respectively 0.34, 0.34 and 0.32 the average density of the soil was calculated to be 1556.8 $kg*m^{-3}$. The mass of the transported soil thus was 4197 tonne for the aboveground building and 20983 tonne for the subsurface building (see table 47).

Table 47 Volume and mass of soil excavated and transported from the building location.

	Depth (m)	*area (m^2)*	*Volume soil (m^3)*	*Mass soil (kg)*	*Mass soil (tonne)*
Aboveground building	1	2695.6	2695.6	4196572.9	4196.6
Subsurface building	5	2695.6	13478.0	20982864.3	20982.9

It was unknown where the sand was dumped. It was thus assumed this transportation would not be done over a large distance. In this research a distance of 10 km was assumed that the dump trucks had to travel from building location to dump site. A truck then had to travel 41966 tkm for the aboveground building and 209,829 tkm for the subsurface building (see table 48).

Table 48 Amount of tonne-kilometre needed for excavated sand transportation from building location to dumpsite.

	Transport mode	*Tonne-kilometre (tkm)*
Aboveground building	Transport by freight lorry>32 metric ton EURO5 (RER)	41965.7
Subsurface building	Transport by freight lorry>32 metric ton EURO5 (RER)	209828.6

Appendix E.2 Transportation of materials

During the construction of the building, not only the sand that is excavated needed to be transported. The materials that were used in the building also needed to be delivered at the location. The distance over which these materials were transported was dependent on the manufacturer of each product and the location of this manufacturer. Table 49 and table 50 show the location of the different manufacturers and the assumed distance that was covered to deliver the materials. This distance was obtained by planning an optimized route in Google maps (Google, 2014).

In SimaPro the input unit for freight transport was tonne-kilometre (tkm). This unit was obtained by multiplying the distance covered by the load of a truck. The load of a truck is the mass of the material it transports. The mass of each specific material was calculated in appendix B. Because the tonne-kilometre was calculated using the load of a truck, an empty truck returning to the manufacturer was not measured. Not taking this into account was, however, not a bad assumption. In practice manufacturers do not have an own transport service which delivers the materials. Often a specialized transport company is hired to do this for them. Transport companies work for multiple clients, so they can plan a route in which they are most of the time filled. When a product is thus brought to the location of the supermarket, it is likely that the truck that delivered it went to another company close to the supermarket to get another product which had to be transported. This way there are less empty kilometres.

The tonne-kilometres per part of the building are shown in table 51. Some parts of the building are much heavier than other parts. For each part a different type of truck was thus needed. In this research the most efficient trucks were assumed to be used. In SimaPro these were the EURO5 trucks. Table 49 and table 50 show the type of trucks that were assumed to be used for each part of the building.

Table 49 Distance and transportation mode used from manufacturer to construction location part 1.

	Roof	***Walls***	***Piles***	***Floor, supports and columns concrete***	***Floor, supports and columns steel***
Manufacturer	Atlas bouwtechnisch adviesbureau	Atlas bouwtechnisch adviesbureau	Herrewijnen Heiwerken Spijkenisse b.v.	Mebin	Diepstraten waeningstaal b.v.
Manufacturer location	Industrieweg 12, 4104 AR Culemborg	Industrieweg 12, 4104 AR Culemborg	Veerweg 9, 3201AW Spijkenisse	Dintelweg 125, 3198LB Europoort Rotterdam	Buitenweistraat 2, 3372BC Hardinxveld-Giessendam
Distance (km)	94.4	94.4	14.9	8.9	56.2
Transport by freight lorry>32 metric ton EURO5 (RER)	v	v	v	v	v

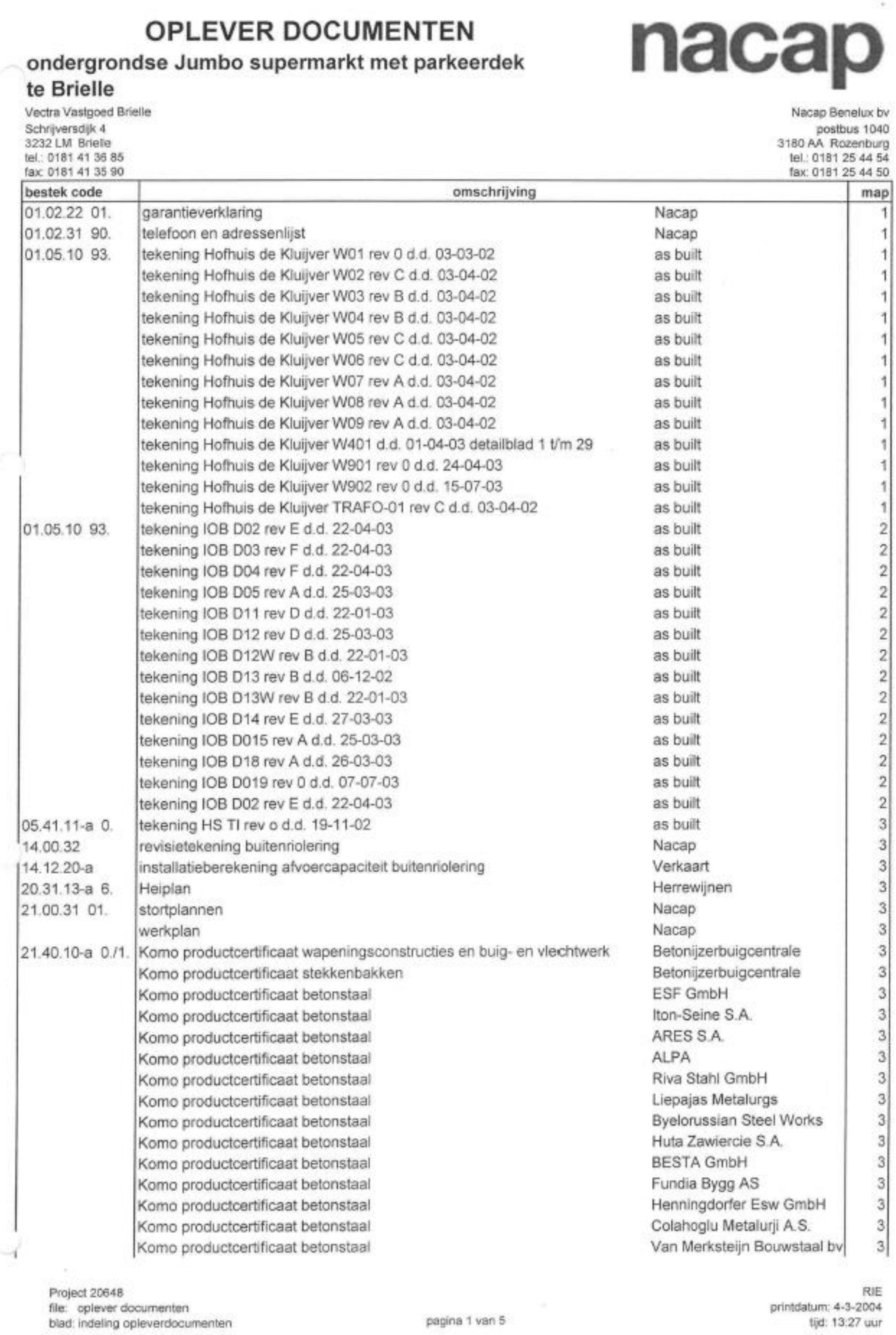
Table 50 Distance and transportation mode used from manufacturer to construction location part 2.

	Stairs	***Railings***	***Windows***	***Insulation XPS***	***Insulation Rockwool 119***	***Insulation Rockwool 211 Vario***
Manufacturer	Steenhuis beton B.V.	Biemans Constructie Rijen	van den Heuvel	Pontmeyer Brielle	Rockwool B.V.	Rockwool B.V.
Manufacturer location	Kaapweg 12, 9982EG Uithuizermeeden	Markiezenbaan 1, 5121DS Rijen	s-Gravelandseweg 396, 3125BK Schiedam	Seggelant Zuid 9, 3237ME Brielle	Industrieweg 15, 6045JG Roermond	Industrieweg 15, 6045JG Roermond
Distance (km)	308	94.4	28.4	2	197	197
Transport by freight lorry 16-32 metric ton EURO5 (RER)	v	-	-	-	-	-
Transport by freight lorry 7,5-16 metric ton EURO5 (RER)	-	-	-	v	v	v
Transport by freight light commercial vehicle Europe	-	v	v	-	-	-

Table 51 Tonne-kilometre calculated for each part of the building in the different scenarios.

	Tonne-kilometre (tkm)							
	Subsurface 1	Subsurface 2	Subsurface 3	Aboveground 1	Aboveground 2	Aboveground 3	Aboveground 4	Aboveground 5
Roof	43582.6	43582.6	43582.6	29055.1	43582.6	21791.3	29055.1	29055.1
Walls	70939.8	70939.8	70939.8	47293.2	70939.8	35469.9	47293.2	47293.2
Piles	21465.1	21458.9	21468.1	31116.2	31819.9	30764.3	31108.8	31119.7
Floor, supports and columns concrete	18301.8	18301.8	18301.8	12201.2	18301.8	9150.9	12201.2	12201.2
Floor, supports and columns steel	4750.2	4750.2	4750.2	3166.8	4750.2	2375.1	3166.8	3166.8
Floor, supports and columns	23052.0	23052.0	23052.0	15368.0	23052.0	11526.0	15368.0	15368.0
Stairs	6126.1	6126.1	6126.1	0.0	0.0	0.0	0.0	0.0
Railings	51.4	51.4	51.4	0.0	0.0	0.0	0.0	0.0
Windows	87.8	87.8	87.8	87.8	87.8	87.8	87.8	87.8
Insulation XPS	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
Insulation Rockwool 119	403.1	0.0	554.3	403.1	403.1	403.1	0.0	554.3
Insulation Rockwool 211 Vario	1911.7	0.0	2867.6	1911.7	1911.7	1911.7	0.0	2867.6

Appendix F. Index deliverables subsurface supermarket Brielle



OPLEVER DOCUMENTEN

ondergrondse Jumbo supermarkt met parkeerdek
te Brielle

nacap

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bestek code	omschrijving		map
01.02.22 01.	garantieverklaring	Nacap	1
01.02.31 90.	telefoon en adressenlijst	Nacap	1
01.05.10 93.	tekening Hofhuis de Kluijver W01 rev 0 d.d. 03-03-02	as built	1
	tekening Hofhuis de Kluijver W02 rev C d.d. 03-04-02	as built	1
	tekening Hofhuis de Kluijver W03 rev B d.d. 03-04-02	as built	1
	tekening Hofhuis de Kluijver W04 rev B d.d. 03-04-02	as built	1
	tekening Hofhuis de Kluijver W05 rev C d.d. 03-04-02	as built	1
	tekening Hofhuis de Kluijver W06 rev C d.d. 03-04-02	as built	1
	tekening Hofhuis de Kluijver W07 rev A d.d. 03-04-02	as built	1
	tekening Hofhuis de Kluijver W08 rev A d.d. 03-04-02	as built	1
	tekening Hofhuis de Kluijver W09 rev A d.d. 03-04-02	as built	1
	tekening Hofhuis de Kluijver W401 d.d. 01-04-03 detailblad 1 t/m 29	as built	1
	tekening Hofhuis de Kluijver W901 rev 0 d.d. 24-04-03	as built	1
	tekening Hofhuis de Kluijver W902 rev 0 d.d. 15-07-03	as built	1
	tekening Hofhuis de Kluijver TRAFO-01 rev C d.d. 03-04-02	as built	1
01.05.10 93.	tekening IOB D02 rev E d.d. 22-04-03	as built	2
	tekening IOB D03 rev F d.d. 22-04-03	as built	2
	tekening IOB D04 rev F d.d. 22-04-03	as built	2
	tekening IOB D05 rev A d.d. 25-03-03	as built	2
	tekening IOB D11 rev D d.d. 22-01-03	as built	2
	tekening IOB D12 rev D d.d. 25-03-03	as built	2
	tekening IOB D12W rev B d.d. 22-01-03	as built	2
	tekening IOB D13 rev B d.d. 06-12-02	as built	2
	tekening IOB D13W rev B d.d. 22-01-03	as built	2
	tekening IOB D14 rev E d.d. 27-03-03	as built	2
	tekening IOB D015 rev A d.d. 25-03-03	as built	2
	tekening IOB D18 rev A d.d. 26-03-03	as built	2
	tekening IOB D019 rev 0 d.d. 07-07-03	as built	2
	tekening IOB D02 rev E d.d. 22-04-03	as built	2
05.41.11-a 0.	tekening HS TI rev o d.d. 19-11-02	as built	3
14.00.32	revisietekening buitenriolering	Nacap	3
14.12.20-a	installatieberekening afvoercapaciteit buitenriolering	Verkaart	3
20.31.13-a 6.	Heiplan	Herrewijnen	3
21.00.31 01.	stortplannen	Nacap	3
	werkplan	Nacap	3
21.40.10-a 0./1.	Komo productcertificaat wapeningsconstructies en buig- en vlechtwerk	Betonijzerbuigcentrale	3
	Komo productcertificaat stekkenbakken	Betonijzerbuigcentrale	3
	Komo productcertificaat betonstaal	ESF GmbH	3
	Komo productcertificaat betonstaal	Iton-Seine S.A.	3
	Komo productcertificaat betonstaal	ARES S.A.	3
	Komo productcertificaat betonstaal	ALPA	3
	Komo productcertificaat betonstaal	Riva Stahl GmbH	3
	Komo productcertificaat betonstaal	Liepajas Metalurgs	3
	Komo productcertificaat betonstaal	Byelorussian Steel Works	3
	Komo productcertificaat betonstaal	Huta Zawiercie S.A.	3
	Komo productcertificaat betonstaal	BESTA GmbH	3
	Komo productcertificaat betonstaal	Fundia Bygg AS	3
	Komo productcertificaat betonstaal	Henningdorfer Esw GmbH	3
	Komo productcertificaat betonstaal	Colahoglu Metalurji A.S.	3
	Komo productcertificaat betonstaal	Van Merksteijn Bouwstaal bv	3

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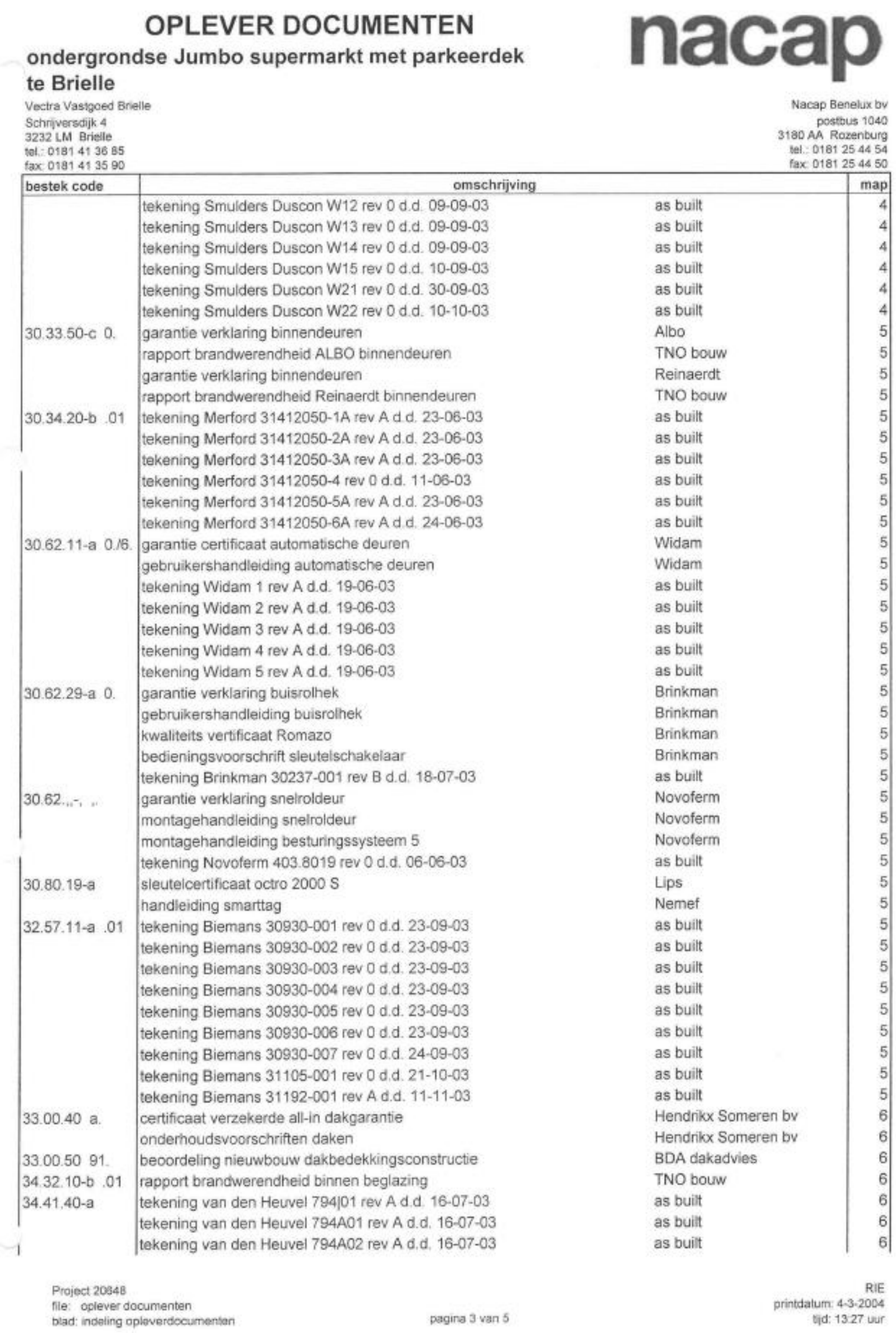
bestek code	omschrijving		map
	Komo productcertificaat betonstaal & wapeningsnetten	Thibo Bouwstaal bv	3
21.50.10-a	Garantie verklaring waterdichte voegafdichting	JAKI	3
22.42.10-a/b 1.	Komo productcertificaat kalkzandsteen	CVK	3
22.42.11-b 0.	Komo productcertificaat verdiepingsvloer 1350- 52/25244	Echostreek	3
	Komo productcertificaat verdiepingsvloer 3600+ 52/25244A	Echostreek	3
	berekening verdiepingsvloer 3600+ 52/25244A	Echostreek	3
	Komo productcertificaat dakvloer 52/25244B	Echostreek	3
	berekening dakvloer 52/25244B	Echostreek	3
23.00.31	werkplan ondersteuning kelderdakvloer 01-0243301-B001 blad 1/2	Peri	3
	werkplan ondersteuning kelderdakvloer 01-0243301-B001 blad 2/2	Peri	3
23.42.41-a 0.	Komo productcertificaat voorgespannen bekistingplaatvloer	Oeterbeton	3
	tekening Atlas L1 rev A d.d. 06-05-03	as built	3
	legplan 450- Atlas L1 d.d. 06-05-03 elementen 1 t/m 167	as built	3
	tekening Atlas 2b rev A d.d. 11-03-03	as built	3
	tekening Atlas 2o rev A d.d. 11-03-03	as built	3
	tekening Atlas K2 rev 0 d.d. 20-02-03	as built	3
23.50.31-a 0.	Komo productcertificaat bouwelementen van beton	Oeterbeton	4
	tekening Atlas L2 rev B d.d. 09-05-03	as built	4
	tekening Atlas W1 rev C d.d. 01-05-03	as built	4
	legplan Atlas W1 d.d. 09-05-03 wand elementen 1 t/m 58	as built	4
	tekening Atlas W2 rev C d.d. 09-05-03	as built	4
	legplan Atlas W1 d.d. 09-05-03 wand elementen 60 t/m 88	as built	4
	Komo productcertificaat bouwelementen van beton	Fassaert Beton bv	4
23.61.11-a 0.	Komo productcertificaat bouwelementen van beton	Steenhuis Beton bv	4
23.61.11-a 0.	statische berekening prefab elementen & tekeningen	Steenhuis Beton bv	4
24.00.20	Komo productcertificaat triplex	Ets Mathe SA	4
	Komo productcertificaat triplex	CEMA	4
25.00.30 90.	tekening Smulders Duscon A01 rev A d.d. 04-09-03	as built	4
	tekening Smulders Duscon L01 rev A d.d. 03-09-03	as built	4
	tekening Smulders Duscon L02 rev B d.d. 04-09-03	as built	4
	tekening Smulders Duscon L03 rev B d.d. 20-08-03	as built	4
	tekening Smulders Duscon L04 rev A d.d. 20-08-03	as built	4
	tekening Smulders Duscon L05 rev A d.d. 19-09-03	as built	4
	tekening Smulders Duscon L06 rev A d.d. 23-09-03	as built	4
	tekening Smulders Duscon L07 rev B d.d. 05-12-03	as built	4
	tekening Smulders Duscon L08 rev 0 d.d. 06-10-03	as built	4
	detail berekeningen	Smulders Duscon	4
25.00.31	werkplan staal	Smulders Duscon	4
25.31.10-a 0.	garantiecertificaat staalconstructie	Smulders Duscon	4
25.31.10-a 5.	tekening Smulders Duscon W01 rev 0 d.d. 22-05-03	as built	4
	tekening Smulders Duscon W02 rev A d.d. 04-06-03	as built	4
	tekening Smulders Duscon W03 rev 0 d.d. 19-08-03	as built	4
	tekening Smulders Duscon W04 rev 0 d.d. 19-08-03	as built	4
	tekening Smulders Duscon W05 rev 0 d.d. 21-08-03	as built	4
	tekening Smulders Duscon W06 rev 0 d.d. 08-09-03	as built	4
	tekening Smulders Duscon W07 rev 0 d.d. 09-09-03	as built	4
	tekening Smulders Duscon W08 rev 0 d.d. 09-09-03	as built	4
	tekening Smulders Duscon W09 rev 0 d.d. 09-09-03	as built	4
	tekening Smulders Duscon W10 rev 0 d.d. 09-09-03	as built	4
	tekening Smulders Duscon W11 rev 0 d.d. 09-09-03	as built	4



OPLEVER DOCUMENTEN

ondergrondse Jumbo supermarkt met parkeerdek te Brielle

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bestek code	omschrijving		map
	tekening Smulders Duscon W12 rev 0 d.d. 09-09-03	as built	4
	tekening Smulders Duscon W13 rev 0 d.d. 09-09-03	as built	4
	tekening Smulders Duscon W14 rev 0 d.d. 09-09-03	as built	4
	tekening Smulders Duscon W15 rev 0 d.d. 10-09-03	as built	4
	tekening Smulders Duscon W21 rev 0 d.d. 30-09-03	as built	4
	tekening Smulders Duscon W22 rev 0 d.d. 10-10-03	as built	4
30.33.50-c 0.	garantie verklaring binnendeuren	Albo	5
	rapport brandwerendheid ALBO binnendeuren	TNO bouw	5
	garantie verklaring binnendeuren	Reinaerdt	5
	rapport brandwerendheid Reinaerdt binnendeuren	TNO bouw	5
30.34.20-b .01	tekening Merford 31412050-1A rev A d.d. 23-06-03	as built	5
	tekening Merford 31412050-2A rev A d.d. 23-06-03	as built	5
	tekening Merford 31412050-3A rev A d.d. 23-06-03	as built	5
	tekening Merford 31412050-4 rev 0 d.d. 11-06-03	as built	5
	tekening Merford 31412050-5A rev A d.d. 23-06-03	as built	5
	tekening Merford 31412050-6A rev A d.d. 24-06-03	as built	5
30.62.11-a 0./6.	garantie certificaat automatische deuren	Widam	5
	gebruikershandleiding automatische deuren	Widam	5
	tekening Widam 1 rev A d.d. 19-06-03	as built	5
	tekening Widam 2 rev A d.d. 19-06-03	as built	5
	tekening Widam 3 rev A d.d. 19-06-03	as built	5
	tekening Widam 4 rev A d.d. 19-06-03	as built	5
	tekening Widam 5 rev A d.d. 19-06-03	as built	5
30.62.29-a 0.	garantie verklaring buisrolhek	Brinkman	5
	gebruikershandleiding buisrolhek	Brinkman	5
	kwaliteits vertificaat Romazo	Brinkman	5
	bedieningsvoorschrift sleutelschakelaar	Brinkman	5
	tekening Brinkman 30237-001 rev B d.d. 18-07-03	as built	5
30.62.[illegible]	garantie verklaring snelroldeur	Novoferm	5
	montagehandleiding snelroldeur	Novoferm	5
	montagehandleiding besturingssysteem 5	Novoferm	5
	tekening Novoferm 403.8019 rev 0 d.d. 06-06-03	as built	5
30.80.19-a	sleutelcertificaat octro 2000 S	Lips	5
	handleiding smarttag	Nemef	5
32.57.11-a .01	tekening Biemans 30930-001 rev 0 d.d. 23-09-03	as built	5
	tekening Biemans 30930-002 rev 0 d.d. 23-09-03	as built	5
	tekening Biemans 30930-003 rev 0 d.d. 23-09-03	as built	5
	tekening Biemans 30930-004 rev 0 d.d. 23-09-03	as built	5
	tekening Biemans 30930-005 rev 0 d.d. 23-09-03	as built	5
	tekening Biemans 30930-006 rev 0 d.d. 23-09-03	as built	5
	tekening Biemans 30930-007 rev 0 d.d. 24-09-03	as built	5
	tekening Biemans 31105-001 rev 0 d.d. 21-10-03	as built	5
	tekening Biemans 31192-001 rev A d.d. 11-11-03	as built	5
33.00.40 a.	certificaat verzekerde all-in dakgarantie	Hendrikx Someren bv	6
	onderhoudsvoorschriften daken	Hendrikx Someren bv	6
33.00.50 91.	beoordeling nieuwbouw dakbedekkingsconstructie	BDA dakadvies	6
34.32.10-b .01	rapport brandwerendheid binnen beglazing	TNO bouw	6
34.41.40-a	tekening van den Heuvel 794|01 rev A d.d. 16-07-03	as built	6
	tekening van den Heuvel 794A01 rev A d.d. 16-07-03	as built	6
	tekening van den Heuvel 794A02 rev A d.d. 16-07-03	as built	6

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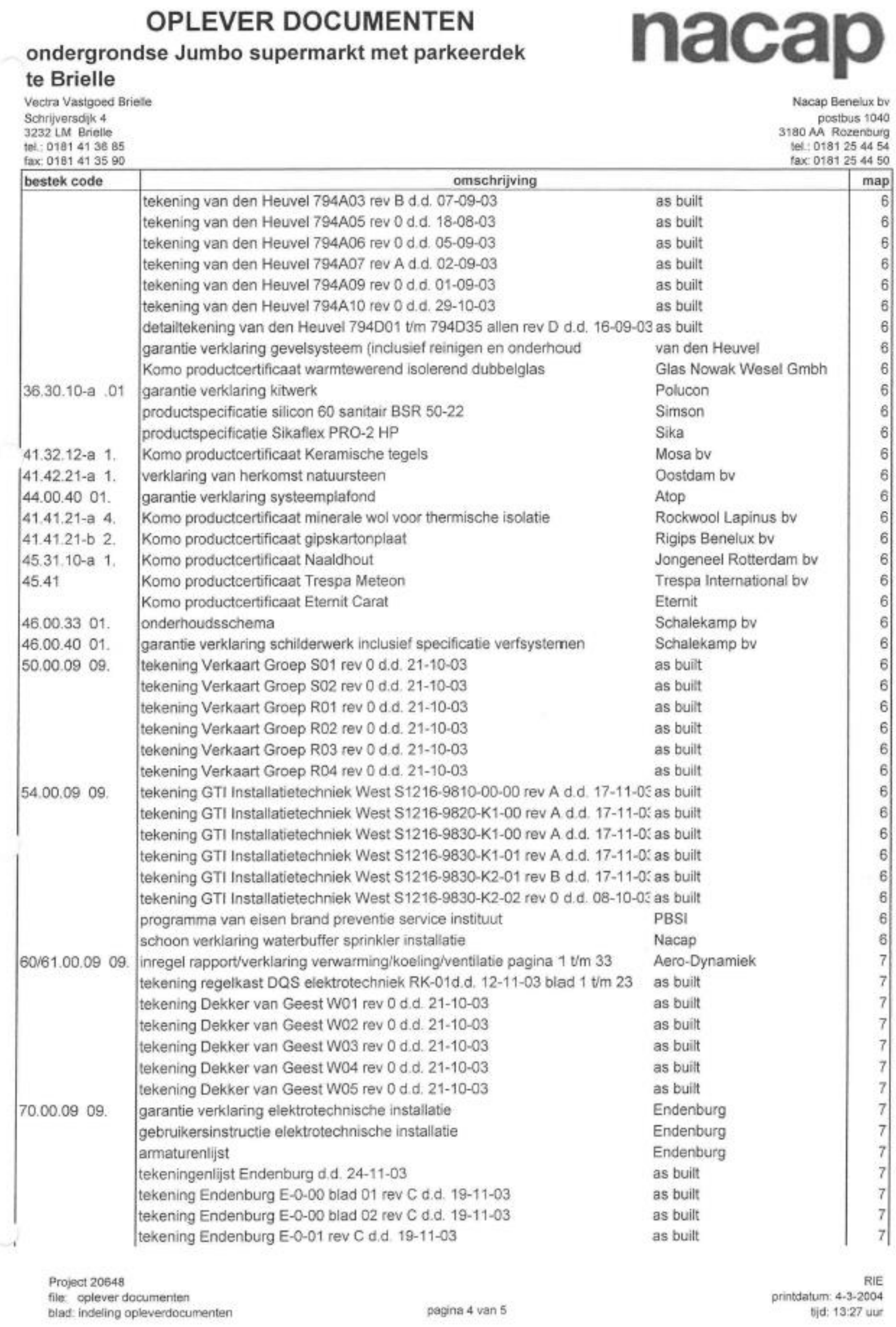

OPLEVER DOCUMENTEN

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bestek code	omschrijving		map
	tekening van den Heuvel 794A03 rev B d.d. 07-09-03	as built	6
	tekening van den Heuvel 794A05 rev 0 d.d. 18-08-03	as built	6
	tekening van den Heuvel 794A06 rev 0 d.d. 05-09-03	as built	6
	tekening van den Heuvel 794A07 rev A d.d. 02-09-03	as built	6
	tekening van den Heuvel 794A09 rev 0 d.d. 01-09-03	as built	6
	tekening van den Heuvel 794A10 rev 0 d.d. 29-10-03	as built	6
	detailtekening van den Heuvel 794D01 t/m 794D35 allen rev D d.d. 16-09-03	as built	6
	garantie verklaring gevelsysteem (inclusief reinigen en onderhoud	van den Heuvel	6
	Komo productcertificaat warmtewerend isolerend dubbelglas	Glas Nowak Wesel Gmbh	6
36.30.10-a .01	garantie verklaring kitwerk	Polucon	6
	productspecificatie silicon 60 sanitair BSR 50-22	Simson	6
	productspecificatie Sikaflex PRO-2 HP	Sika	6
41.32.12-a 1.	Komo productcertificaat Keramische tegels	Mosa bv	6
41.42.21-a 1.	verklaring van herkomst natuursteen	Oostdam bv	6
44.00.40 01.	garantie verklaring systeemplafond	Atop	6
41.41.21-a 4.	Komo productcertificaat minerale wol voor thermische isolatie	Rockwool Lapinus bv	6
41.41.21-b 2.	Komo productcertificaat gipskartonplaat	Rigips Benelux bv	6
45.31.10-a 1.	Komo productcertificaat Naaldhout	Jongeneel Rotterdam bv	6
45.41	Komo productcertificaat Trespa Meteon	Trespa International bv	6
	Komo productcertificaat Eternit Carat	Eternit	6
46.00.33 01.	onderhoudsschema	Schalekamp bv	6
46.00.40 01.	garantie verklaring schilderwerk inclusief specificatie verfsystemen	Schalekamp bv	6
50.00.09 09.	tekening Verkaart Groep S01 rev 0 d.d. 21-10-03	as built	6
	tekening Verkaart Groep S02 rev 0 d.d. 21-10-03	as built	6
	tekening Verkaart Groep R01 rev 0 d.d. 21-10-03	as built	6
	tekening Verkaart Groep R02 rev 0 d.d. 21-10-03	as built	6
	tekening Verkaart Groep R03 rev 0 d.d. 21-10-03	as built	6
	tekening Verkaart Groep R04 rev 0 d.d. 21-10-03	as built	6
54.00.09 09.	tekening GTI Installatietechniek West S1216-9810-00-00 rev A d.d. 17-11-03	as built	6
	tekening GTI Installatietechniek West S1216-9820-K1-00 rev A d.d. 17-11-0	as built	6
	tekening GTI Installatietechniek West S1216-9830-K1-00 rev A d.d. 17-11-0	as built	6
	tekening GTI Installatietechniek West S1216-9830-K1-01 rev A d.d. 17-11-0	as built	6
	tekening GTI Installatietechniek West S1216-9830-K2-01 rev B d.d. 17-11-0	as built	6
	tekening GTI Installatietechniek West S1216-9830-K2-02 rev 0 d.d. 08-10-0	as built	6
	programma van eisen brand preventie service instituut	PBSI	6
	schoon verklaring waterbuffer sprinkler installatie	Nacap	6
60/61.00.09 09.	inregel rapport/verklaring verwarming/koeling/ventilatie pagina 1 t/m 33	Aero-Dynamiek	7
	tekening regelkast DQS elektrotechniek RK-01d.d. 12-11-03 blad 1 t/m 23	as built	7
	tekening Dekker van Geest W01 rev 0 d.d. 21-10-03	as built	7
	tekening Dekker van Geest W02 rev 0 d.d. 21-10-03	as built	7
	tekening Dekker van Geest W03 rev 0 d.d. 21-10-03	as built	7
	tekening Dekker van Geest W04 rev 0 d.d. 21-10-03	as built	7
	tekening Dekker van Geest W05 rev 0 d.d. 21-10-03	as built	7
70.00.09 09.	garantie verklaring elektrotechnische installatie	Endenburg	7
	gebruikersinstructie elektrotechnische installatie	Endenburg	7
	armaturenlijst	Endenburg	7
	tekeningenlijst Endenburg d.d. 24-11-03	as built	7
	tekening Endenburg E-0-00 blad 01 rev C d.d. 19-11-03	as built	7
	tekening Endenburg E-0-00 blad 02 rev C d.d. 19-11-03	as built	7
	tekening Endenburg E-0-01 rev C d.d. 19-11-03	as built	7

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bestek code	omschrijving		map
	tekening Endenburg E-1-01 rev F d.d. 19-11-03	as built	7
	tekening Endenburg E-V-01 rev A d.d. 19-11-03	as built	7
	tekening Endenburg E-V-02 rev A d.d. 19-11-03	as built	7
	tekening Endenburg E-S-01 rev F d.d. 19-11-03	as built	7
	tekening Endenburg 03-0421-1 blad 01 rev B d.d. 19-11-03	as built	7
	tekening Endenburg 03-0421-1 blad 02 rev C d.d. 19-11-03	as built	7
	meetrapport aarding	Koster vof	7
	testrapport verdeelpanelen	Endenburg	7
80.00.40	garantie verklaring liften	ThyssenKrupp bv	7
80.12.10-a	tekening ThyssenKrupp Aufzugswerke 03 063-001/A rev A d.d. 21-02-03	as built	7
80.12.10-a	installatieberekening lift conform NPR 5081	ThyssenKrupp bv	7
80.80.11-a	liftboek	ThyssenKrupp bv	7
	testrapporten liftonderdelen	ThyssenKrupp bv	7
81.11.19-a 1./01	garantie verklaring rolpaden	ThyssenKrupp bv	7
	certificaat van deugdelijkheid 3231-009-01	Liftinstituut	7
	keuringsrapport 3231-009-01	Liftinstituut	7
	certificaat van deugdelijkheid 3231-009-02	Liftinstituut	7
	keuringsrapport 3231-009-02	Liftinstituut	7
	bedieningshandleiding voor rolpad Orinoco	ThyssenKrupp bv	7
	tekening Thyssen Fahrtreppen E-42607.00-1.02 rev 2 d.d. 22-08-03	as built	7
82.11.19-a 1.	gebruikershandleiding goederenheffer A-1500	EBD	7
82.11.19-a .01	tekening EBD 03 rev 0 d.d. 19-05-03	as built	7

Appendix F.1 Locations deliverables supermarket Brielle were used

Page	***Document code***	***Document name***	***Used for***
Title page, 9	-	Aerial photograph of the supermarket in Brielle	Title page figure and figure 5
12	01.05.10 93.	Tekening Hofhuis de Kluijver W02	Figure 7
12	01.05.10 93.	Tekening IOB D02	Figure 8
14	41.41.21-a 4.	Komo productcertificaat minerale wol voor thermische isolatie	Wall and floor insulation
14	33.00.50 91.	Beoordeling nieuwbouw dakbedekkingsconstructie	Thickness roof insulation
15, 23	34.41.40-a	Garantie verklaring gevelsysteem (inclusief reinigen en onderhoud)	Type of windows installed
26	01.02.31 90.	Telefoon en adressenlijst	Manufacturers addresses
B.1	01.05.10 93.	Tekening IOB D12W and IOB D13W	Reinforcement in the floor
B.1	01.05.10 93.	Tekening IOB DO2, IOB D12 and IOB D13	Total floor area calculation
B.1	01.05.10 93.	Tekening IOB D14 DRSN 10 and DRSN 28	Steel use in supports
B.2	01.05.10 93.	Tekening IOB D18	Concrete and steel use in columns
B.2	01.05.10 93.	Tekening IOB DO4	Thickness of the floor and supports
B.5	32.57.11-a .01	Tekening Biemans 30930-001 to 30930-007, Biemans 31105-001 and Biemans 31192-001	Steel use in railings
B.6	01.05.10 93.	Tekening IOB D11	Information about the piles
B.15	34.41.40-a	Tekening 794A02, 794A07, 794A10 and detail drawings 794D01 – 794D35	Calculation of the windows
C.4	80.80.11-a 80.12.10-a	Liftboek, Installatieberekening lift conform NPR 5081	Elevator for people
C.5	82.11.19-a 1. 82.11.19-a .01	Gebruikshandleiding goederenheffer A-1500 and tekening EBD 03.	Information regarding the elevator for goods
C.5	81.11.19-a 1./01	Tekening E-42607.00-1.02	Information about the moving walks