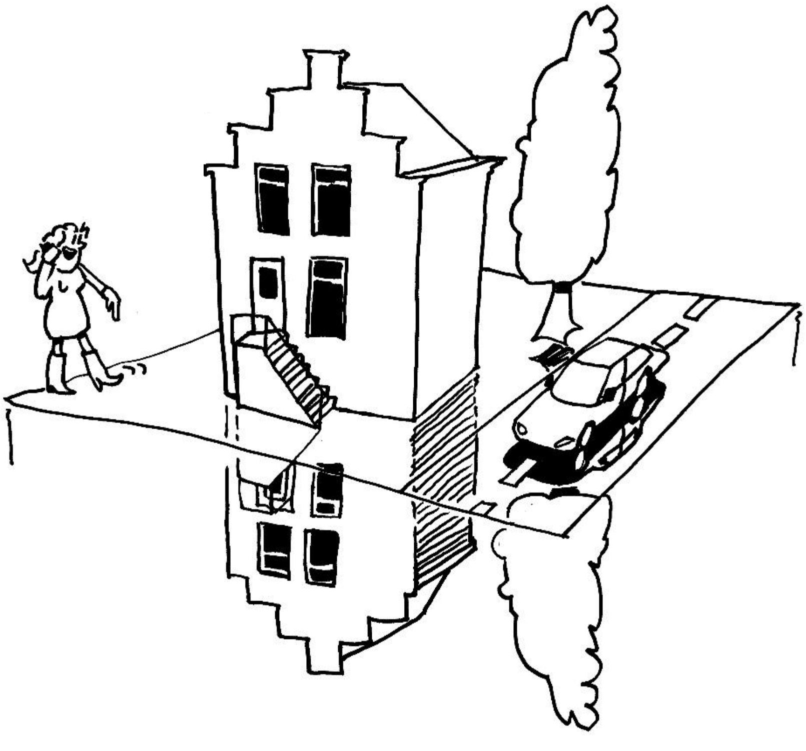
MASTERTHESIS

Subsurface construction from an energy point of view

Potential energy savings from underground construction

I.I.M. Pieters



Utrecht University

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Enabling Delta Life

Colophon

This research was conducted as final part of the master program Sustainable Development at Utrecht University and was carried out at Deltares.

Title	Subsurface construction from an energy point of view. *Potential energy savings from underground construction.* 45 ECTS
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Cartoon: Beeldleveranciers.nl

List of Symbols

Symbol	**Description**	**Unit**
a	amplitude	
α	heat transfer coefficient at the inside of the wall	$W/m^2 \cdot K$
A	Area	m^2
b	period	
c_p	specific heat	$kJ/kg \cdot K$
d	thickness	m
DD	degree days	#
k	heat transmission coefficient	$W/m^2 \cdot K$
N	ventilation rate	h^{-1}
Q	heat flow	W
Q_{annual}	annual heat loss	J
Q_v	heat loss through ventilation	J
ρ	specific mass	kg/m^3
R-value	thermal resistance	$m^2 \cdot K/W$
T	temperature	K
T_g	average year temperature	K
dT/dx	temperature gradient	K/m
ΔT	temperature difference	K
T_i	average temperature for day i	K
T_{ref}	reference temperature	K
U-value	thermal resistance (glass)	$W/m^2 \cdot K$
V	volume	m^3
λ	thermal conductivity	$W/m \cdot K$

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Abstract

Underground buildings are often overlooked as option to reduce energy requirements, while alleviating pressures on land. This study explores the potential energy savings from underground construction as compared to aboveground buildings in the Western part of the Netherlands. By comparing underground and aboveground energy losses through heat transfer to the environment at various temperatures, for different building materials and several depths over a time period of five years, an indication of the energy savings potential can be established. The results show that energy can be saved in specific circumstances. If beneficial indoor temperature requirements are set and the right building materials are used, energy can already be saved within five years. Putting the results in a broader perspective, there are opportunities for underground construction. In this exploratory study underground construction indicates to be beneficial under the right circumstance on an individual level. A combination of both aboveground and underground spatial planning could be a step forward to reduce energy consumption and CO_2 emissions. In addition to this, underground construction has the advantage to reduce aboveground land use problems. A next step is to analyse multiple underground buildings with different indoor temperature requirements.

Key words: underground buildings, energy savings potential, sustainability, DPSIR

Acknowledgements

This study is conducted at the research institute Deltares. I am very grateful for the opportunity to conduct my research and to get to know a working environment. Though the research has had its ups and downs, I really liked my time at Deltares. I would like to thank Derk van Ree, my supervisor at Deltares, who guided and supported me and was always full of ideas and suggestions. Next to this I would like to thank Wouter van der Star, researcher at Deltares, who offered great help by getting to know Comsol Multiphysics. In addition to this, the research couldn’t have been complete without the facilities that the TU Delft offered. I acknowledge the help and insights my supervisor from Utrecht University, Robert Harmsen, offered during this research.

Finally, special thanks to my family and friends; in particular Erik van der Meer, for his great help, support and patience at all times.

Ivana Pieters
Utrecht, June 2013.

~ People often think that the best way to predict the future is by collecting as much data as possible before making a decision. But this is like driving a car looking only at the rear-view mirror – because data is only available about the past. ~

C. M. Christensen

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Part I. Introduction to subsurface construction

1. Introduction

In 2010, half of the world's total population is living in urban regions and this is expected to grow to roughly 60% by 2030 (UN, 2005; 2009). The continuous growth of the world's population goes sometimes unnoticed, yet it is an important aspect of sustainability issues. The Brundtland Commission defined sustainability as follows: *"sustainable development is the development that meets the needs of the present generations without compromising the ability of future generations to meet their own needs"* (World Commission on Environment and Development, 1987). It takes into account the sustainable usage of resources without being at the expense of a certain quality of life, now and in the future.

This continuous population growth causes various problems such as food scarcity and a shortage of drinking water (NATO, 2013). All those people need space to live and work, hence increasingly more buildings and dwellings need to be constructed. In 2004, buildings were responsible for $1/3^{rd}$ of global energy related CO_2 emissions[1] (IPCC, 2007a).

In resolving the problem of lack of space for housing and city life facilities, the focus lies on building into the sky. Though this is a possible solution for the space problem, it can be questioned whether it is a sustainable one for several reasons. The urban environment influences the human well-being, therefore good-quality green spaces and walkable neighbourhoods are key to the urban quality of life. Green areas are in addition important to improve air quality and reduce the urban heat island effect and to encourage people to be physically active. (EEA, 2009) A city full of skyscrapers, garages, storage buildings reducing the green spaces does not contribute to the quality of city life and is therefore not sustainable. Next to this, the increase in energy consumption that goes hand-in-hand with an increase in the building stock, now often produced by finite and non-renewable resources, is unsustainable as well.

One of the possible solutions is going underground. Though underground construction is not a new idea, it is often overlooked as a possible strategy for sustainable buildings. By building certain constructions underground, the stress on the land use aboveground is reduced and the liveability of the city can be increased. The subsurface has specific characteristics which can be opportunities for underground construction. The fairly stable temperature and the lack of seasonal influence create an opportunity to build more energy efficient structures (Parker, 2004).

Though not very extensive, there is a branch of literature concerned with the usage of the urban underground and sustainability (Evans et al., 2009; Hudson & Hudson, 2003; Roberts, 1996). Within this topic, much attention is paid to infrastructure for transportation and utilities (water pipes, telecommunication etc.), storage facilities and thermal energy storage. It is remarkable that there is a gap in the scientific literature on a structured evaluation of the potential energy savings of underground buildings for storage, offices and living purposes, especially when comparing with literature on aboveground buildings. Mazarrón et al. (2012) assess the thermal inertia as passive thermal technique for wine cellars. It becomes clear that wine cellars do have an advantage for storing wine over aboveground storage. A pilot study by Sugai et al. (2012) did look into heat transfer in a converted disused tunnel. However, they focused on heat transfer between the newly constructed rooms, which ranged from cold to hot. They did not look to heat transfer from the building envelope to the environment. As becomes clear from the scientific literature, the information on underground construction and especially potential energy savings from underground construction as compared to aboveground, information is available, but very scattered. There is a lack of coherency within the research area; small subareas are researched, but the big picture is still missing.

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[1] Including indirect, electricity-related CO_2 emissions. Direct energy-related CO_2 emissions were 3Gt.

It is important to keep in mind that the underground can also be considered a finite and non-renewable resource. Therefore long term planning is essential when exploiting the underground (Bobylev, 2009; Hudson & Hudson, 2003). Failure to coordinate and regulate the underground developments will consequently be a potential waste of resources (He et al., 2012). This stresses the importance to put energy considerations for underground construction in the broader field of underground construction.

1.1 Aim and research question

Energy and resource efficiency have gained significant interest over the last years when looking at the construction industry, but the subsurface has rarely been dealt with separately. Different perspectives can be taken when analysing subsurface usage such as an environmental, an economical, and a functional or technical point of view.

Given the importance of energy consumption of the built environment, the focus of this research is on potential energy savings through heat loss reduction from underground construction as compared to aboveground construction. Recognizing the broader issues of the development and decision-making of underground construction, the results then need to be placed in a broader context to determine the possible impact of energy savings from underground construction in a broader perspective. To achieve this, an outlook of the results will be presented and linked to other sustainability aspects relevant to the construction industry and the built environment. This broader perspective and interpretation can lead to better decision-making for politicians and provides researchers with a framework which can be a starting point for further research. This results in the following research question:

What are possible implications in the field of subsurface construction in relation to the built environment when analysing the potential energy savings that might arise when comparing underground buildings with aboveground buildings over time in the Western part of the Netherlands?

In other words, this research quantifies potential energy savings within a policy and environmental (dependent on the location) framework, to mimic the reality and to base necessary assumptions on. The possible implications are given based on the results found, which is thus in the light of potential energy savings, and are placed in the context of going towards a more sustainable built environment. Since not all relevant issues at play within the built environment are studied, the implications presented are solely *possible* implications. The implications given are therefore indicative instead of absolute and all-embracing. Still, these implications can certainly give direction to the policy process, the market developments and future research.

1.2 Scope and delineation of the research

This research focuses on the energy savings that might arise from building constructions underground instead of aboveground. It compares the energy needs to keep a building at certain temperature, above –and belowground. The geographical scope is the Western part of the Netherlands, the Randstad area to be more specific. Buildings are the research unit; underground constructions for transportation purposes are not considered.

The focus point of the potential energy savings is purely heat transfer related and is a result of the interplay between temperature and thermal properties of the building envelope and the natural materials in the subsurface. Both temperatures at living room levels as temperatures used in chilled spaces are presented in this research, as different buildings functions have different indoor temperature requirements. Freezing temperatures are not taken into account, since the underground behaves differently when temperatures become lower than the freezing point. These effects are beyond the scope of this research.

Though the influence and effect of different typical construction materials are assessed when formulating the energy savings calculations, more technical construction issues such as stress, strain and deformation are left to the civil engineers. It is assumed that the structures aboveground and belowground can be built technically since this is already done. The main contribution of this research is to analyse what kind of energy savings can be achieved by building underground.

1.3 Outline

In the rest of this first part, the steps taken are elucidated in the research approach. In the second part, the technical field is described and a conceptual model is presented. The second part also entails the description of the calculations on the potential energy savings. The last part of the research is concerned with the implications of the results and can be perceived as a compass to further developments and additional research needed. The study ends with a conclusion.

2. Research Approach

2.1 Steps in the research

First, the technical field is described. This gives insight in the factors at play in the field of underground construction from an energy point of view. By linking concepts and effects, the main relations are presented in a conceptual model. This part of the study will be carried out by means of a literature study. The following sub-question will guide the description of the technical field:

1) *What factors play a role in assessing the energy use of an above –and belowground building?*

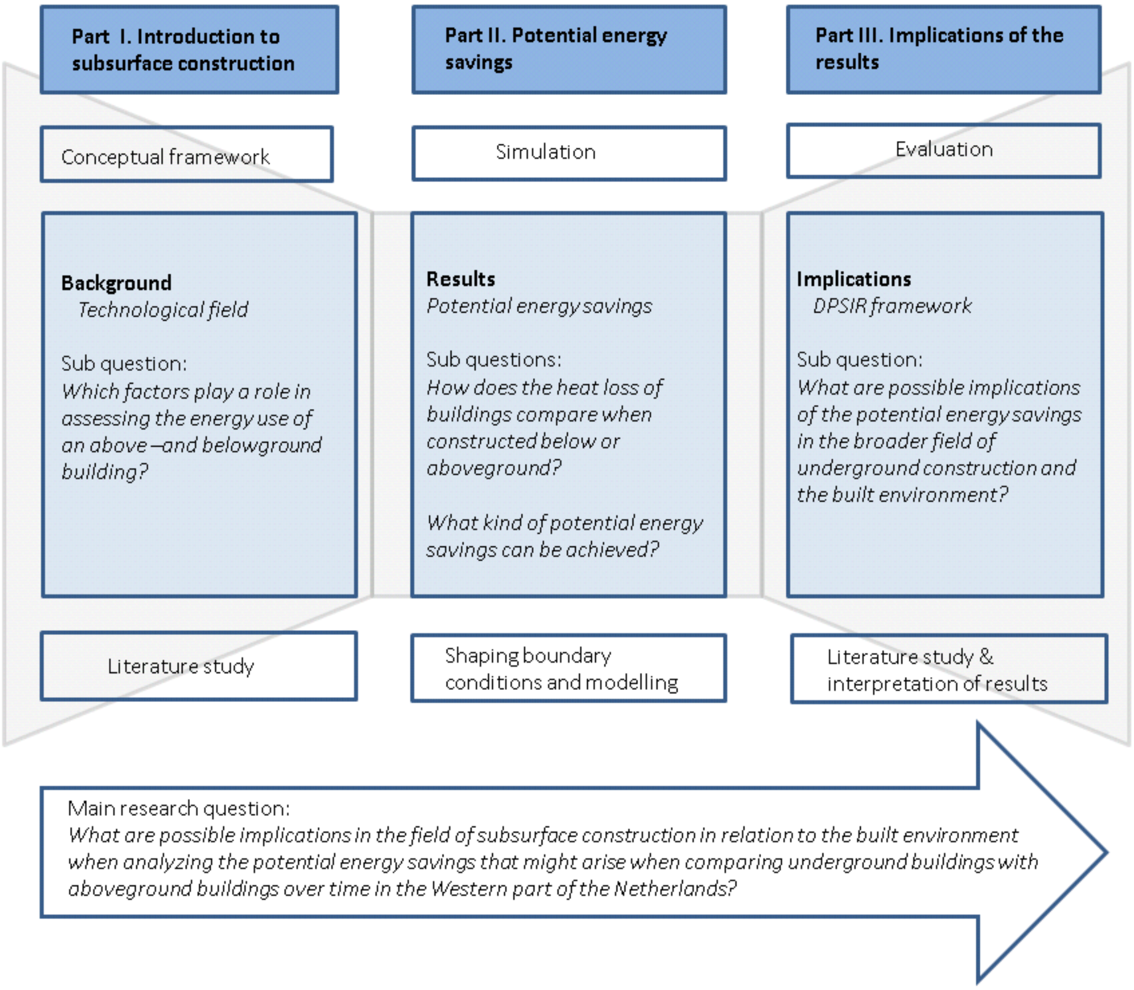
Hereafter, the actual energy savings potential must be calculated. A finite element software package named Comsol Multiphysics is used to model the situation researched. The precise steps taken and assumptions made are presented in the chapter itself. The following sub-questions are answered in the potential energy savings chapter.

2) *How does the heat loss of buildings compare when constructed below -or aboveground?*
3) *What kind of potential energy savings can be achieved?*

The results from the potential energy savings chapter will be interpreted, and put into a broader perspective. The DPSIR (Drivers – Pressures – State – Impact – Responses) framework will be used as guiding framework in this process. The DPSIR finds its origin in the Second Assessment of the Dobříš Report of the European Environmental Agency (EEA) (de Mulder et al., 2012). The framework helps to structure thinking about interplay between environment and socio-economic activities. It will be used as a means to explore possible implications stemming from the results found with the help of sub-questions two and three. The DPSIR evaluation will be partially based on a literature study and partially on the results from the energy savings chapter. The sub-question for the evaluation is:

4) *What are possible implications of the potential energy savings in the broader field of underground construction and the built environment?*

Answering the four sub-question will lead to an answer to the main research question. By determining and modelling the most important factors at play, the potential energy savings can be calculated. The implications for subsurface construction can be derived based on these potential energy savings. By requiring knowledge on the current situation in the built environment and combining this with the energy savings results, the outcomes can be interpreted and put into a broader perspective. With this, the implications of subsurface construction can be related to the broader field of a sustainable built environment. The research thus starts from a broad perspective, zooms-in to derive the potential energy savings, where after these results are put into a broader perspective. This research approach can be visualized as follows (Figure 1).



Which factors play a role in assessing the energy use of an above –and belowground building?

How does the heat loss of buildings compare when constructed below or aboveground?

What kind of potential energy savings can be achieved?

What are possible implications of the potential energy savings in the broader field of underground construction and the built environment?

What are possible implications in the field of subsurface construction in relation to the built environment when analyzing the potential energy savings that might arise when comparing underground buildings with aboveground buildings over time in the Western part of the Netherlands?

Figure 1, research steps, research questions and corresponding method used.

Part II. Potential energy savings

3. Technical Background

The main aim of this section is to give an overview of the field of underground construction and the role of the various factors in this field. Therefore, the technical field will be outlined, after which a conceptual model can be established. This visualizes the main factors at play.

3.1 Technical field: the energy related drivers

The technical field of underground construction entails a lot of variables, parameters, mechanisms and concepts. It is important to create a coherent overview of the technical field before a model is constructed and simulated. In this way, the basic mechanisms and interactions at play become visible. Based on this, the model (with the necessary assumptions) can be set up.

3.1.1 Environment

The main difference when comparing aboveground and belowground buildings is the environment they are placed in. For aboveground buildings the environment in which exchanges take place is the air and for belowground buildings this is the ground or subsurface. For the aboveground situation, air makes up the buildings' environment. The temperature of air is subject to seasonal changes. This can be described by a sine function. This yearly temperature function is based on daily averages. This results in omission of the daily temperature variation which is a sine function as well. The outdoor temperature can thus be described as a yearly sine function with a daily sine function over it, which has greater amplitude and of course a smaller period. Next to this, heat is transported to and from the building due to wind, or natural convection.

3.1.2 Soil characteristics

The environment in which an underground building is placed is the subsurface or soil. Generally, the temperature still varies in the first 15 meters of depth sinusoidal with time due to seasonal changes, albeit weakened and delayed (as compared to the aboveground seasons), around 15 meters deep the ground temperature stabilizes at the average yearly temperature (see Figure 2). In this research an underground temperature of 10°C is assumed for the Netherlands, which is the long year average air temperature (KNMI, 2005). Going deeper, the geothermal gradient increases due to heat coming from the core of the earth a typical value of the geothermal gradient is 1.5- 3°C/100m found in the Netherlands, Germany and Belgium (Karg et al., 2004; GSEGWP, 1988).

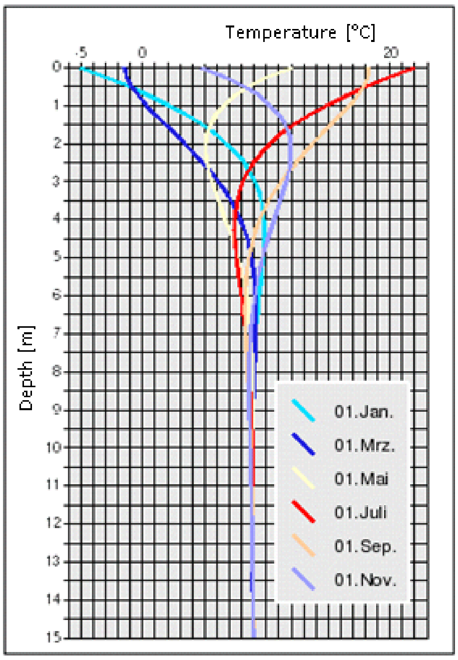


Figure 2, general underground temperature profile (Geotechnische Büro, 2002).

Taking a closer look at the soil characteristics density, specific heat capacity and thermal conductivity are the main characteristics at play. They describe the behaviour of the medium through which the heat transfer takes place, also known as thermal diffusivity. Obviously, an underground building is not subject to wind. However, heat transportation can take place as a result of groundwater flow. The subsurface has in addition a buffering effect and is resilient. With respect to heat and energy transfer in the soil, this buffering effect causes the importance of time. How fast does the heat spread? How long will it take to reach a certain point? These are underlying questions with regard to the buffering effect of the soil.

There are many different kinds of soils; the composition differs at almost every location. In the Netherlands four main soil materials can be distinguished; clay, peat, saturated sand and unsaturated sand. Taking the map of the Netherlands it can roughly be split in two; in the west, the soil is mostly clay or peat and in the east there are mostly sandy soils (Figure 3).

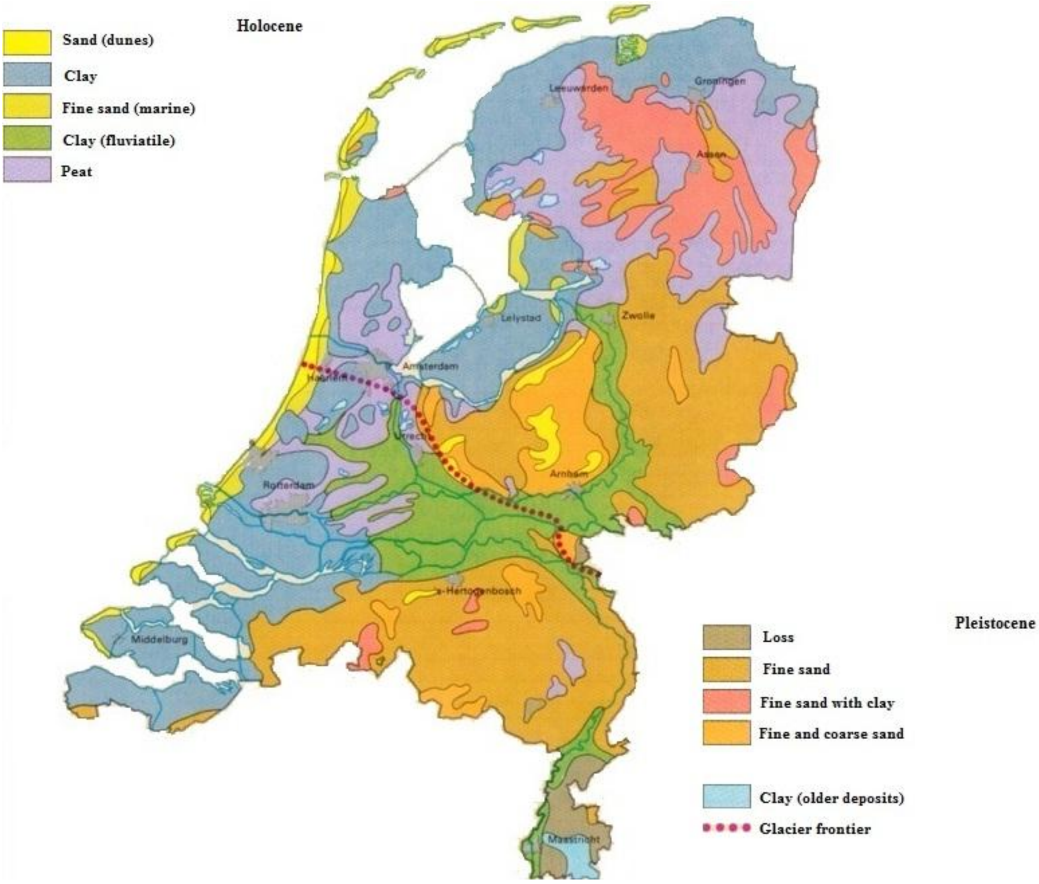


Figure 3, soil types in the Netherlands (Atlas van Nederland, 1987).

Clay and peat are the most prominent soil types in the Western part of the Netherlands. Since the pressure on the landscape is far higher in the west of the Netherlands, the Randstad area, this is a more interesting field to look into opportunities for underground construction.

3.1.3 Indoor climate

The required indoor climate, or in this case indoor temperature, differs per building and is closely linked to function of a building. The indoor temperature of a building plays an important role for the heat transferred from the building. It is not about the absolute value of the temperature, but it is the temperature difference between the indoor temperature and outdoor temperature that is an important driver for heat transfer (Blok, 2009).

3.1.4 Building materials

The building materials also have their own thermal characteristics and thus influence the heat flux through the wall (Blok, 2009). Combined with the indoor temperature requirements of a building and the underground temperature at a certain location, this plays a major role in determining the potential of underground construction.

The factors influencing the potential energy savings discussed in the technical field are illustrated in Figure 4 by means of a conceptual model.

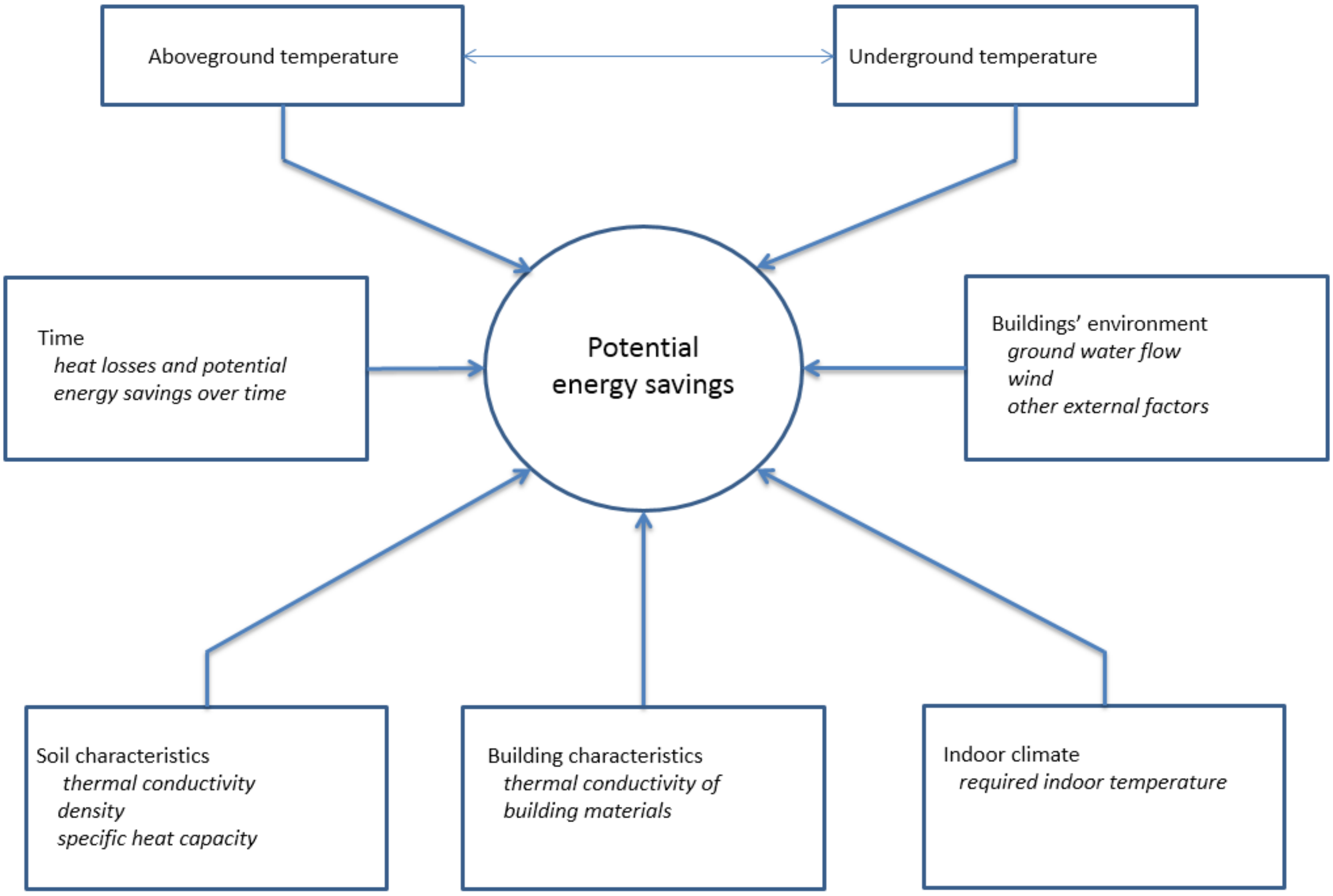


Figure 4, conceptual model.

4. Potential energy savings from underground construction

This chapter entails the exploration of the potential energy savings from underground construction. Both the aboveground situation and underground situation are an adjusted representation of reality. To explore the energy savings potential of underground construction, many assumptions must be made to come to a first comparison. This study must therefore be perceived as exploratory and will result in an indication of possible energy savings potential.
First, the underground part will be elucidated, followed with the aboveground part. Hereafter, a comparison is be made between the two and conclusions are drawn.

4.1 Underground

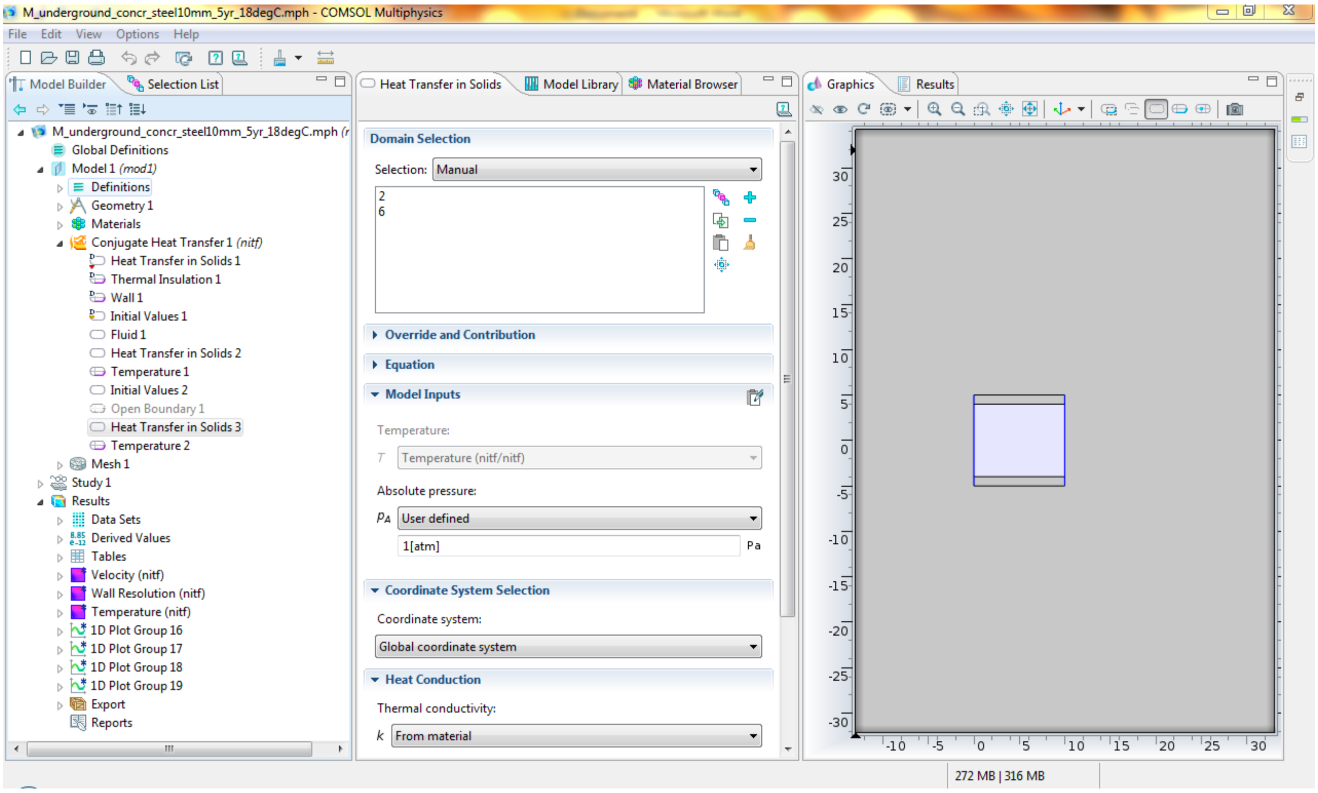
Underground heat transfer is not commonly used in today's energy efficiency calculations of buildings. Aboveground calculation methods are not usable, since the soil is a different medium than air and therefore the heat is transferred and diffused differently. Due to the complexity of constructions interacting with the earth it is inevitable to make assumptions regarding the variables, parameters and conditions influencing the heat transfer. Analytical models provide fast and accurate results only for simple cases. Numerical methods can cope with a higher degree of complexity, but can normally not be used manually. Therefore Comsol Multiphysics 4.3, a finite element software package, was used to model the underground heat transfer problem. This computer code includes predefined physics interfaces (e.g. for applications as structural mechanics, fluid flow and heat transfer). Material properties, sources and boundary conditions can be spatially varied, made time dependent or can be describe as a function of the dependent variables.(Comsol, 2013) The various physical interfaces can be coupled in order to simulate a problem.

The general modelling process in Comsol consists of five consecutive steps:

1) Geometry definition
2) Problem specification (setting boundary conditions and initial values)
3) Meshing
4) Solution (actual simulation of the model)
5) Results (post processing and visualization)

In the model, the underground building will be set up. As indicated in the conceptual model, temperature of the soil and the building can be set, as well as material (thermal) properties. In addition, the model is set to be time dependent in order to get insight in the heat transfer over time. The interface of Comsol is presented in Figure 5. It consists of three parts. In the part at the right the geometry is defined and shown. In the mid section the boundary and domain values can be adjusted. The screen at the left is used to select the physical interface, couple interfaces, select materials, impose boundary conditions, create meshing and analyse results.

Below, the specific modelling procedure, including the necessary assumptions is set forth. Due to these required assumptions the results must be interpreted with the assumptions made in mind. This means more specifically that the potential energy savings are only valid for this type of situation. For each new location an in-depth assessment is needed since soil characteristics, building geometry and other environmental factors are location specific and all these factors influence the final potential energy savings.



Selection: Manual
2
6

Temperature:
T Temperature (nitf/nitf)

Absolute pressure:
pA User defined
1[atm] Pa

Coordinate system:
Global coordinate system

Thermal conductivity:
k From material

Figure 5, Comsol interface.

4.1.1 Mathematical approach

For the representation of the underground construction, the Heat Transfer Module is used in Comsol. It is based on the energy balance of the system created. Various forms of energy can contribute to this energy balance e.g. conduction, convection, radiation, Joule heating, also heat sources and heat sinks can be included. Its basic feature describes conduction in systems with constant thermal conductivity, as a function of temperature itself, or any other model variable. Conduction is the main driver for energy transfer in the system described for this study. This form of heat transfer is proportional to the temperature gradients present in a system. Mathematically, this is formulated by Fourier’s law. To calculate heat transfer in a plain wall, the amount of heat transferred per unit time is proportional to thermal conductivity of the material, the temperature gradient and the surface area.

$$Q = -\lambda A \, {}^{dT}\!/_{dx}$$ Formula [1]

Where:
Q = heat flow[2] [W]
A = area [m^2]
λ = thermal conductivity [W/m•K]
dT/dx = temperature gradient [K/m]
(Blok, 2009)

The thermal conductivity k, is a material characteristic and indicates the material’s ability to transfer heat. A high k value indicates that the material is a good conductor of heat and thus reflects its high ability to transfer heat. The minus sign reflects the fact that heat is transferred in the direction with the lowest temperature. Dividing the heat transfer rate by the area A, formula [1] can be rewritten as

$$q = -\lambda \, {}^{dT}\!/_{dx}$$ Formula [2]

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[2] Flow and flux can be used interchangeably.

Where q is called *heat flux per unit area [W/m²]* and is thus the amount of heat transferred per time unit through an area (which is often set at one square meter).

4.1.2 Geometry

The system modelled is a 2D representation of a ground or soil domain with a building in it, which is envisaged as a cube. The size of the building modelled is 10 by 10 metres. The simulation results in the surrounding of the building should not be influenced by the boundary conditions that have been chosen. It is necessary to optimize the model dimensions to keep it within practical limits for this study, since the size of the model also determines the simulation time. In order to determine the necessary minimum boundary distance, the influence of this distance has been determined by changing the distance and evaluating the heat flux at three fixed points[3]. This is done at points next to the steel wall, for the reason that this side is most sensitive for heat transfer due to the thermal characteristics of steel. Therefore, if the change in boundary distance is not significantly for this case, it will also suffice for the concrete walls. After running the model with different sizes of the soil domain it was determined that the change from 50 metres to 60 metres distance resulted in a changed in all points of less than 5%, which is small enough to put the boundary at 50 metres. In addition to this, the actual boundary conditions are exactly known, namely the ground temperature of 10°C, therefore a change of 5% is acceptable. The geometry is presented Figure 6. After adding insulation, the geometry looks as follows (Figure 7).

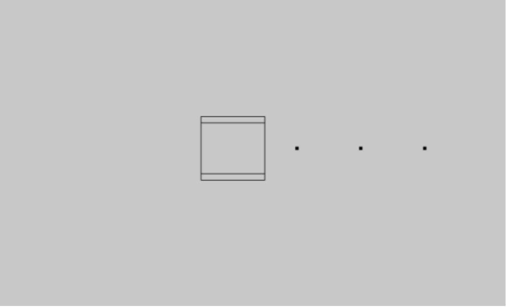

Figure 6, geometry.

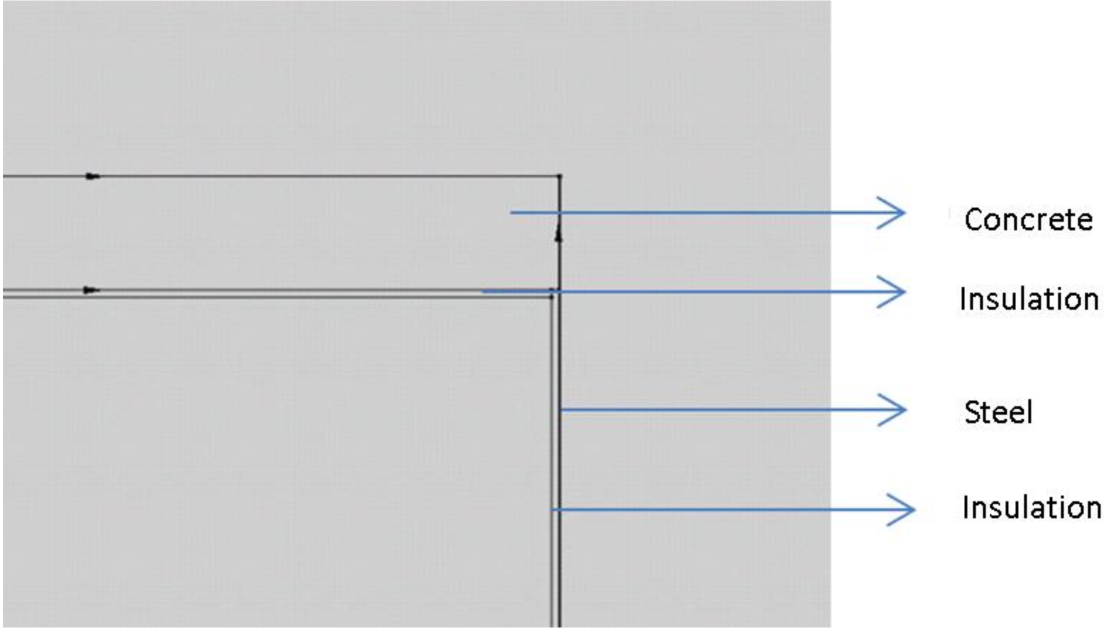

Figure 7, geometry close-up with insulation and steel walls.

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[3] At 10, 20 and 30 metres from the wall. Note that the point at 10 metres is the most important since the heat from the building is transferred to approximately 12 metres.

4.1.3 Construction details

In the model geometry, each domain and boundary gets assigned a specific material. The materials can be selected from the built-in material database in Comsol, or the parameter values can be added manually. Using this feature, the system obtains the information needed on the physical properties such as thermal conductivity, heat capacity and density in order to perform the calculations. This section describes the materials used in the model.

Construction method

Although this research does not go into specific construction methods, it is important to know what kinds of materials are used. There are two main construction methods to be distinguished. The first method is an underground construction by which the walls are totally made of concrete. This technique can be applied up to 55 meters of depth (Franki, 2012). Typical wall thicknesses for this type of construction range from 0.6 -2.0 meters, although 0.8, 1.0 and 1.2 meter are most commonly applied based on the standard equipment dimensions (COB & CUR, 2010). For the underground model, 1.0 meter will be used. Another construction method is the use of steel sheet pile retaining walls, with concrete floor and roof sections. There are very many variations possible for a steel retaining wall, depending on the technical and economic requirements of the construction project. In this case a profile of average thickness was chosen (the PU 12 10/10 to be precise, since the u-profile is widely applied), d = 10mm (ARBED, 2004).

Thermal properties of the materials used

The thermal properties of steel and concrete that have been used in the model are presented in Table 1. Air is selected from the predefined material library. It is dependent on the temperature and behaves as an ideal gas. This is done because an extra pressure constraint is avoided when the fluids act according to the ideal gas law. By letting the system behave according to the ideal gas law, uncertainty is reduced and possible errors in the pressure field are omitted in this way.

The influence of insulation in underground buildings will be evaluated as well. There are three groups of insulating material; organic materials, inorganic materials and plastic foams. Organic materials such as wool, straw etc. are not considered in this research. Inorganic insulation materials are for example glass wool and expanded perlite. Examples of plastic foams are polyurethane and coated foils. Polyurethane is often applied in the form of foam sheets. (Rijksoverheid, 2010) About 20% of all insulation material used is in this polyurethane (PUR) foam sheet form (ibid); since this insulation material is so commonly applied it will be used here as well for both the underground and aboveground buildings. Commonly used thicknesses of the insulation vary between 3-10 centimetres. Here, a thickness of 6.5 centimetres will be used. Both concrete and insulation values are used for the aboveground calculations as well.

Table 1, Thermal properties steel and concrete (Bejan, 1993; Kingspan Unidek, 2012; Recticel, 2007).

Material name	Thermal conductivity [W/m•K]	Density [kg/m^3]	Heat capacity [J/kg•K]
Concrete	1.8	2300	800
PUR foam sheet	0.023	30	1470
Steel	17[4]	8522	0.46

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[4] For steel applies the same as for insulation material, there are very many types. Some types have a much higher thermal conductivity of 43 [W/mK] (ARBED, 2004). Using this type of steel would eventually lead to smaller potential energy savings from retaining walls (though this might not be wise from an energy point of view).

4.1.4 Energy and heat related phenomena

Location

Each location has its own unique soil composition and thus unique thermal characteristics. As already described in section 3.1, the Western part of the Netherlands is most interesting for underground construction when taking into account the pressure on the land. In this area, clay and peat are the most prominent soil types. Though these soils are known to have a high groundwater level, they do have a low groundwater flow, thereby justifying considering the soil as a static entity in the model (see Appendix A). Since peat is worldwide not a very common soil type, clay is the most relevant soil to use in the model[5]. The following typical characteristics for clay are used in the model (Table 2).

Table 2, clay thermal properties.

Property	Range	Typical value used	Source[6]
Thermal conductivity [W/m•K]	0.15-2.5	1.5	(EngineeringToolbox.com, 2012c)
Density [kg/m^3]	1073-1826	1800	(EngineeringToolbox.com, 2012a)
Heat capacity [J/kg•K]	800-1480	1300	(Ehow, 2012; EngineeringToolbox.com, 2012b)

Ventilation

Ventilation is necessary to keep a space liveable. Both aboveground and underground buildings require the same amount of ventilation. Aboveground windows can be opened, whereas in underground structures the total ventilation requirement is regulated mechanically. Typically, the volume of air is refreshed with another volume of air. This can be for example 'aboveground' air and thus has the same temperature that prevails aboveground at that time. Consequently, it influences the indoor temperature and thus indirectly influences the heat transfer from the building. In reality, heat exchangers would be placed in the upper part of the soil above the building to reduce the energy losses from ventilation. Due to this complexity, ventilation is omitted from the model. However, to get a sense of the influence of ventilation a short calculation is made with the outcomes of part III and is presented in Appendix B.

Deep and shallow subsurface

Buildings are not always built at depths beyond 15 meters, but more often a part of the building or the entire building is situation in the first meters of the soil. Therefore, the model is extended with a temperature sine function that describes the yearly temperature fluctuation (see Appendix C). The aboveground seasonal influence is taken into account by setting the top boundary condition not at a fixed temperature, but by a temperature described by a sine function with a period of one year.

In this case, only the roof of the underground building is influenced by the temperature change, while others stay the same. Therefore, only this wall needs to be evaluated. For both construction methods this the concrete wall, with and without insulation.

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[5] In this way, the results are more representative if a worldwide perspective would be taken.

[6] These values were found on websites. That kind of source does provide one with a lot of typical values for all kinds of clay, but is not the most reliable source. Therefore the values given in Bejan (1993) were used as reference. Here, the types of clay provided were very limited, but it was checked for whether the value lay within the range given by the engineering toolbox. For all three properties holds that the low values are for dry clay and the high values are for wet clay.

For the deep subsurface simulations, a thermal gradient resulting from geothermal effects (core of the earth) is not taken into account as it is considered not relevant for the construction depths considered.

4.1.5 Solution and Results

Meshing

In order to arrive at a solution, the system must be broken down in small pieces (finite elements). A complex system of points called *nodes* makes up a grid called a *mesh*. A smaller mesh size corresponds to larger number of finite elements. This means that the calculation time increases exponentially with the number of elements and making the results more detailed and more accurate up to a certain extent. Comsol provides an automatic mesh, and user defined meshes (ranging from extremely fine to extremely coarse). It is best to start with an automatic mesh, which can then be further adjusted. In order to keep the simulation time needed to run the model at an acceptable level, a coarser mesh can be useful, while a finer mesh can be applied when no problems with running time occur and/or details are present in the model representation, since a finer mesh gives more accurate results. By doing this, the final mesh used was physics controlled, normal, with finer settings on adjacent entities (Figure 8). This finer mesh was needed at the wall boundaries and corners, since different materials and temperatures come together here, and therefore more precise calculation steps need to be taken to come at a fully converged solution[7].

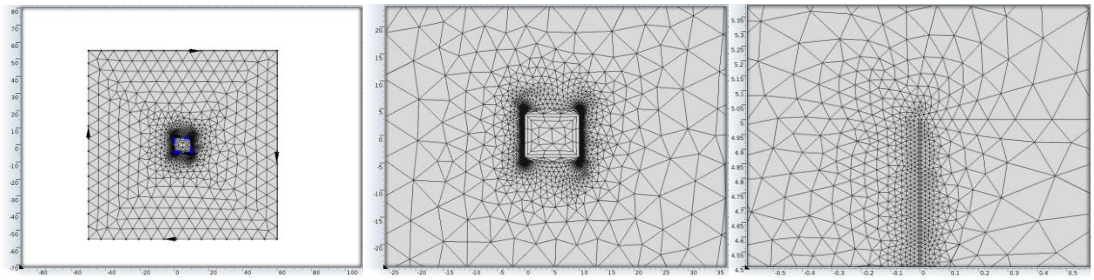

Figure 8, Mesh of the whole system (left and mid) and mesh at wall boundary (right).

Time frame

Once an underground building is constructed, it will be present for decades (the design life can be over 100 years). To make all the computations on such a long time frame is too laborious and will take too much time to get all the results wanted. Therefore another logical timeframe must be chosen. In the Netherlands, legislation in the field of underground thermal energy storage is established in the past few years. One of the issues is the intervention in the soil energy balance. For this reason, every underground thermal energy storage unit has to have a neutral energy balance over the course of five years (Staatsblad, 2013). Since thermal energy storage also interferes with the underground temperature, as well as underground buildings, this is a justified time period to assess the results.

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[7] When a solution can not be converged, no appropriate solution can be found for the given input data. This can, for example, be the case when the time step is too large or when the input values, together with the boundary conditions and the model geometry are not consistent.

After performing the simulation for the selected model[8], the following temperature plots can be made of the system (Figure 9).

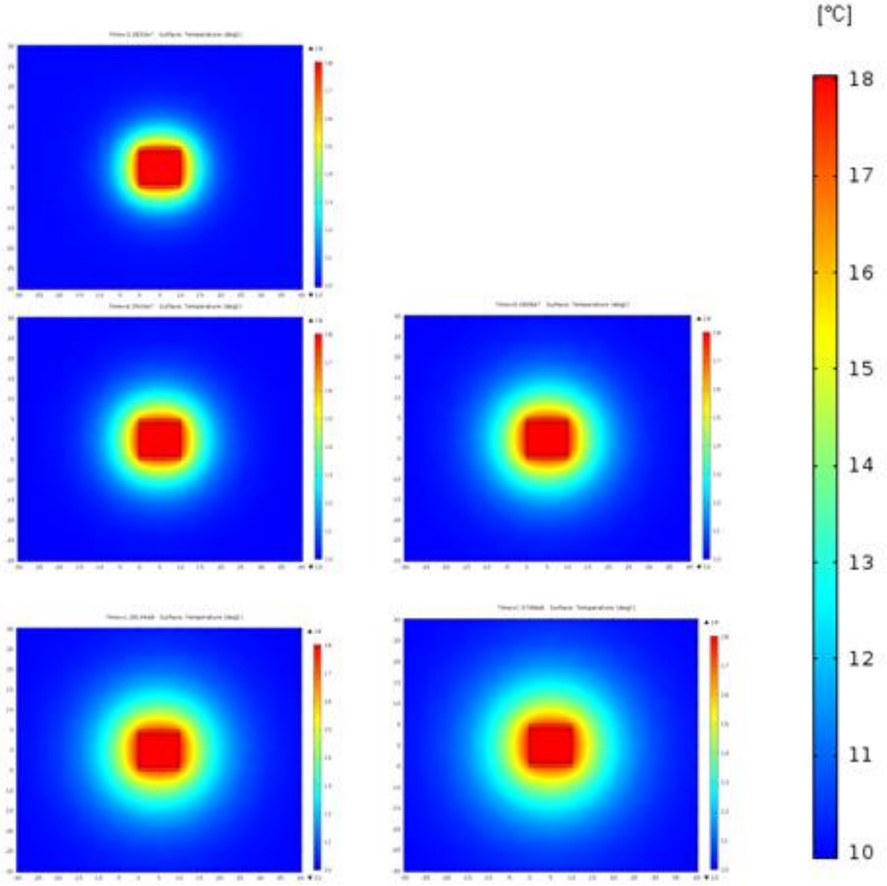

Figure 9, example of temperature plots at t= 1 yr, 2yr, 3yr, 4yr and 5yr.

Next to the temperature profile, various outputs can be generated. In this case, the heat flux (see formula 2) is of interest, displayed in Figure 10.

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[8] All model runs start at t=0, stop at t=1825 [day] and have a step size of 1 day.

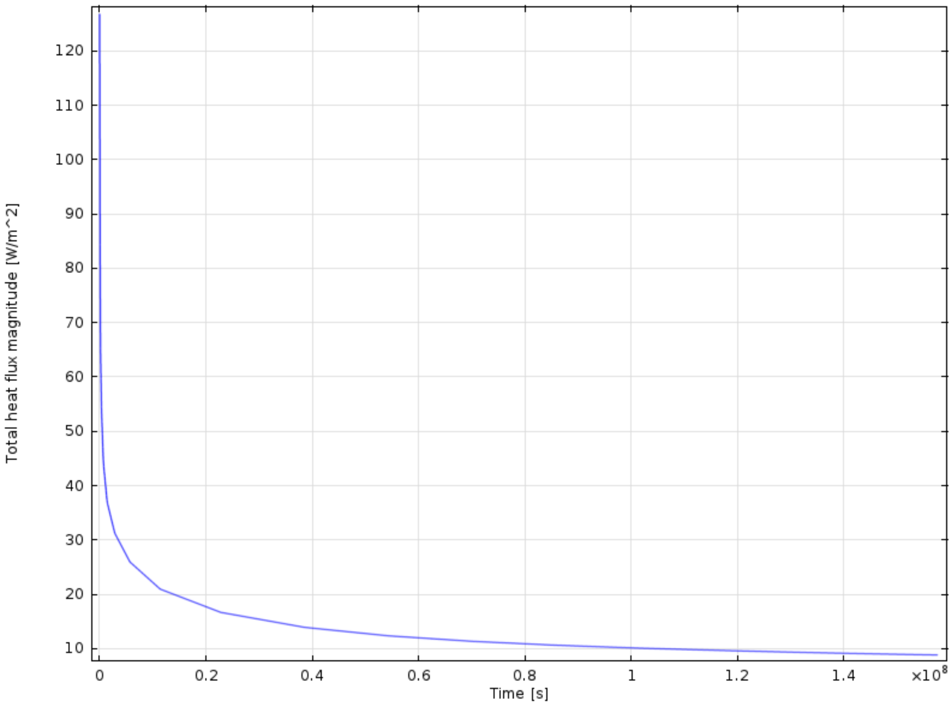

Figure 10, heat flux across the wall of underground building.

At the start, a lot of energy flows directly into the soil. Once the energy has heated up the soil, the soil will act as a buffer, which can be perceived as extra 'insulation'. Now, the temperature gradient between the wall and soil is much smaller and therefore less energy is needed; the heat flux goes down. The line will eventually, after many years, end in an equilibrium state.[9]

In order to say something about the results, we are interested in the total amount of energy used. Taking the integral over time, the area under the curve can be calculated, which is equal to the total energy used over that period of time. This is the method used to obtain the total energy used in a specific time period in the underground model. The total energy consumption per squared meter side wall of the concrete underground construction is presented in Table 3.

Table 3, total energy loss of a concrete underground building [MJ/m^2].

	After				
T_{indoor}	1 year	2 years	3 years	4 years	5 years
18 °C	114.5	183.9	241.7	293.6	342.3
11 °C	11.5	18.4	24.1	29.4	34.2
4 °C	68.8	110.4	145.2	176.3	205.6

The construction technique with steel retaining walls is one step more complex. The sidewalls are made from steel sheet pile walls, but the ground floor and roof are made of concrete. Since the geometry of the building in this model has walls of equal length, it is justified to calculate the heat flux through the steel wall and the inherent heat loss and average this with the concrete wall. This gives a fair comparison to the other walls, since the research unit is a representative 1m^2 for the whole building. This will be referred to as *retaining wall(s)* from now on. This result in the following total energy losses (see Appendix D for steel only)

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[9] While this may take a long computer computation time, it can easily be estimated. Q=λ/d *ΔT. With λ of clay = 1.5, d the thickness of the soil domain which is 50 metres. Delta T varies per situation, but is 8 in case of an indoor temperature of 18. This results in an equilibrium state of 0.24 W/m^2.

Table 4, total energy loss of a retaining wall underground building [MJ/m^2].

	After				
T$_{indoor}$	1 year	2 years	3 years	4 years	5 years
18 °C	182.0	290.4	380.9	462.2	538.8
11 °C	21.3	34.0	44.6	54.1	63.1
4 °C	127.9	203.9	267.4	324.7	378.3

A next step is to consider the influence of insulation in both structures. This resulted in the following energy losses (Table 5 and Table 6).

Table 5, total energy loss of a concrete underground building with insulation [MJ/m^2].

	After				
T$_{indoor}$	1 year	2 years	3 years	4 years	5 years
18 °C	52.2	85.6	116.3	145.3	173.4
11 °C	6.5	10.7	14.5	18.1	21.7
4 °C	39.1	64.2	87.2	109.0	130.0

Table 6, total energy loss of a retaining walls underground building with insulation [MJ/m^2].

	After				
T$_{indoor}$	1 year	2 years	3 years	4 years	5 years
18 °C	75.8	139.1	197.8	253.2	306.7
11 °C	9.5	17.4	24.7	31.6	38.3
4 °C	56.9	104.3	148.4	189.9	230.0

4.1.6 Seasonal influence on heat losses

When considering the shallow subsurface, with the roof section exposed to the aboveground temperature fluctuation, the following temperature plots can be created (Figure 11).

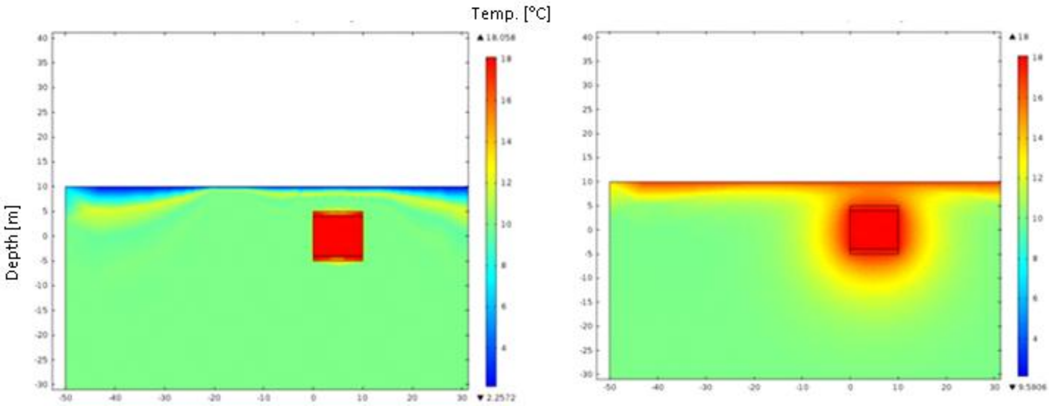

Figure 11, underground building with seasonal influence in winter months (t=1 left) and in summer months (summer in year 5, right).

This results in the following energy losses (Table 7 and Table 8).

Table 7, total energy losses from a concrete roof with seasonal influence [MJ/m^2].

	After..				
T_{indoor}	1 year	2 years	3 years	4 years	5 years
18 °C	103.3	178.4	250.6	322.2	394.5
11 °C	17.2	31.7	47.0	62.2	237.3
4 °C	70.6	126.6	182.1	237.3	292.8

Table 8, total energy losses from a concrete roof with insulation and seasonal influence [MJ/m^2].

	After..				
T_{indoor}	1 year	2 years	3 years	4 years	5 years
18 °C	53.8	92.8	131.5	170.1	208.9
11 °C	6.7	11.6	16.4	21.2	26.1
4 °C	40.3	69.6	98.6	127.5	156.7

It must however been said, that this extension of the model is less accurate than the original model. This is caused by the fact that the heat flux does not result in equilibrium, but oscillates with the aboveground temperature fluctuation (albeit with a damped and delayed effect of the aboveground temperature sine function). For this reason, the time step is lowered to 0.5 day, which increases the accuracy of the integration. Still, care should be taken when interpreting the results. However, including a temperature sine does indicate whether more or less heat is lost through the roof of the underground structure as compared to the deep underground situation. It therefore provides insights relevant for constructions in the upper part of the underground.

4.2 Aboveground

4.2.1 Mathematical approach

Aboveground buildings are very heterogeneous when it comes to size, materials used and environmental factors. In order to compare the aboveground building with the underground building, the same research unit is used (1m^2). Various types of side walls will be evaluated at different temperatures. The following formula will be used to calculate the heat transfer through the building envelope

$$Q = \lambda * \frac{\Delta T}{d} * A = k * \Delta T * A \qquad \text{Formula [3]}$$

Where:
Q = heat flow through the walls, windows and roof [W]
λ = thermal conductivity [W/m•K]
ΔT = temperature difference across the wall [K]
d = thickness of the wall [m]
k = heat transmission coefficient (unit thermal conductance) = λ/d [W/m2•K]
A = surface area of the wall [m^2]
(Blok, 2009)

Below, the concepts needed for the temperature difference component and the heat transmission component in this equation will be elaborated upon, after which the final results are presented.

4.2.2 Degree days

The heat losses through ventilation and transmission both depend on the temperature difference between the inside of the building and the environment. This temperature gradient is different each day, which means that integration over the whole year is needed. By using the concept of degree days, this can be integrated separately. A reference temperature for the inside temperature is set. This temperature depends on the function of the building, but for living space this is somewhat lower than the actual temperature in the building, since there are internal heat sources in the building such as all kinds of electric equipment and humans itself. A reference temperature of 18°C is commonly used for the Netherlands for living spaces (Blok, 2009; Wever, 2008; Agentschap NL, 2012). Next to this, in the degree day calculation, average day temperatures for a given year are used. However, the indoor temperature varies from, for example, 20°C during the day time (16 hours) to 15°C during the night time (8 hours). This results in a weighted daily indoor temperature of 18°C.
In buildings with other functions than living or working, and thus other indoor temperatures, a fixed temperature will be assumed of 11°C and 4°C. These buildings might require cooling during the summer, which is explained below. Evidently, the choice of the reference temperature is of great influence for the resulting degree days (Figure 12).

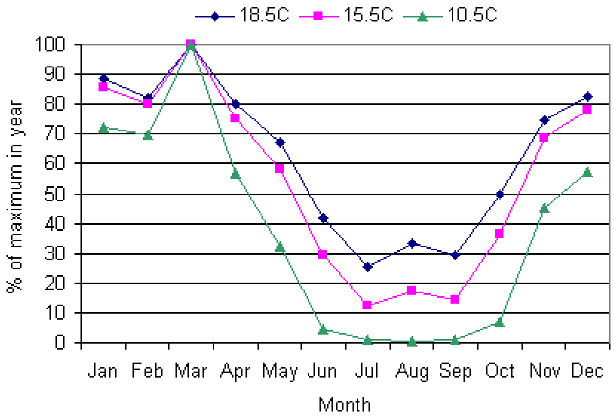

Figure 12, Relative influence of chosen reference temperature on degree days (Energy Lens, 2013)

The degree day approach can be a useful tool to help estimate the building's future energy use. For each day the actual temperature is compared to the reference temperature. If the actual temperature is below the reference temperature with for example a ΔT of 2°C, we have two *heating* degree days (HDD). Adding up all these temperatures over a certain year results in the amount of *heating* degree days (with a variation of typically 10% on a year-to-year basis [Blok, 2009]). The number of degree days is zero if the actual temperature exceeds the reference temperature. Formula 4 represents the degree day principle.

$$DD = \sum_{i=1}^{365} \max(Tref - Ti, 0) \qquad \text{Formula [4]}$$

Where:
DD = the number of degree days per year
T_{ref} = a reference temperature
T_i = the average temperature for day i
(Blok, 2009).

Cooling degree days

Next to heating degree days there is its counterpart cooling degree days (CDD). Though the concept of HDD is commonly applied with energy monitoring and HDD statistics are widely available, the concept of CDD is not. As is the case with the HDD the base temperature is an important aspect of the end result. The complexity lies in the presence of latent loads and the wide variety of cooling systems in use (CIBSE, 2006). The influence of the base temperature in the resulting cooling degree days is reflected in Figure 13.

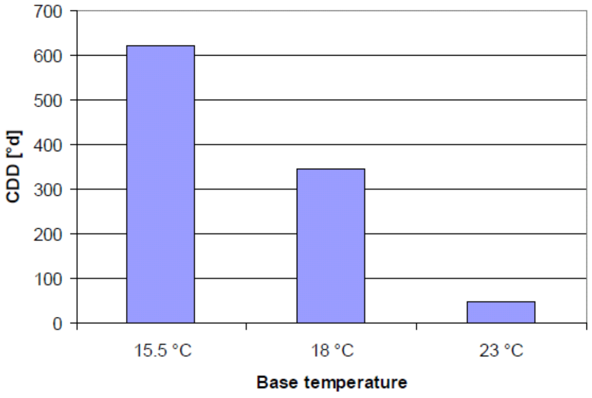

Figure 13, CDD for three different base temperatures (Prek & Butala, 2010).

The main difference between CDD methods available is the degree of detail. Some methods are more general, while others require detailed specifications of HVAC[10] systems. The 'buildings' in this research are reduced to a cube and are perceived as a black box. In this black box, only the required indoor temperature and the materials of which is box is made are known. The model is thus used for hypothetical buildings, without predetermined air-conditioning systems. For this reason the method of Day (2005 p. 118), a prominent writer on the subject of degree days, is used. In this method a mean monthly base temperature is set based on reasoned judgement. This temperature can be used for all months simultaneously. It is a very practical approach, still it is consistent with theory and empirical data (R^2= 0.9541) It in addition identifies main features of energy use. In the light of this research the main benefit of this method is the omission of detailed information on specific air-conditioning systems[11].

This all comes together in Figure 14. A reference temperature is set (at 18°C) and the limit of the bandwidth for the CDD is set based on reasoned judgement (Day, 2005). If the temperature is below 18°C people will get cold and heating is required. However, if the temperature is somewhat above 18°C it is not immediately uncomfortable. Therefore cooling is only needed when the temperature rises above 22°C.

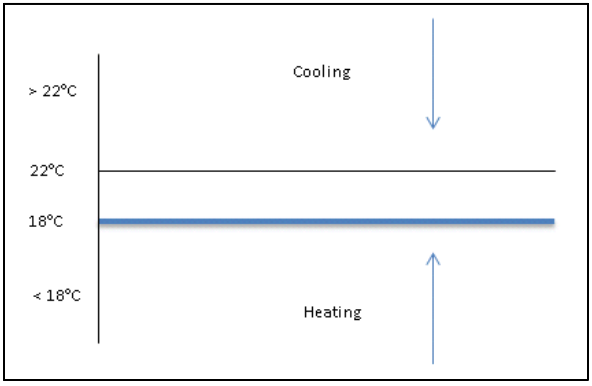

Figure 14, temperature, heating and cooling.

In the case of the 11 and 4°C indoor temperatures, this bandwidth is not present. It is assumed that heating or cooling is needed at the moment the temperature differs from the initial value. This is actually what happens in a chilled building, since it has no comfort function. Its purpose is to assure users of the building that the temperature stays fixed.

Other factors influencing temperature and degree days

When comparing aboveground and underground buildings, a difference can be noticed in the heat losses from the wall caused by wind. According to empirical work by Kosny & Mohiuddin (2004) the wall heat loss caused by wind is about 13% of the total wall heat loss. Rain might have cause the heat loss to increase as well. Next to this, the incoming solar radiation causes the indoor temperature to rise extra (compared to underground buildings). These effects can be taken into account by the so-called *weighted* degree days. The weighted degree days include a correction factor, in which all possible factors influencing heat transfer are accounted for. It is based on empirical work on the relationship between gas consumption and degree days[12]. The influence of incoming sunlight, rain and wind are highly location dependent. Since this research aims to make a general comparison between above –and belowground, this correction factors will suffice.

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[10] Heating, ventilation and air-conditioning

[11] This does result in higher winter values and lower summer values due to the fact that there is no incorporation of fictitious latent load as is done in other methods. The aim is however to compare the aboveground with the underground situation and not the degree days in different seasons of the year.

[12] (F. Heuven, personal communication, April 15th, 2013).The correction factors differ per season and are set to be the following for the Netherlands: Nov – Feb: 1.1 , March and October: 1.0 , April – Sept: 0.8

Determining the degree days

The amount of HDD and CDD can relatively easily be calculated in Excel by using temperature data from weather stations and applying it to the reference temperature and correction factors (and reference temperature range for CDD).

Table 9, degree days, based on weather station the Bilt (KNMI, 2013).

$T_{indoor\ [°C]}$	HDD	CDD	Total DD
18	2902	6	2909
11	1104	818	1922
4	221	2533	2753

4.2.3 Construction details: heat transmission coefficient

Wall profiles

Another component needed is the heat transmission coefficient. As shown in formula 3, the heat transmission coefficient is a ratio between the thermal conductivity of the wall material(s) and the thickness of the wall. For this reason, several types of walls are evaluated, according to different regulations. To make a steady comparison with the underground building, a wall profile of $1m^2$ is chosen (see box 1).

Typical wall profile

The typical wall profile considered in this research consists of the following elements. Ten centimetres of bricks, PUR foam insulation sheet of 6.5 centimetres and ten centimetres of concrete (Table 10).

Table 10, thermal conductivities used for typical wall profile.

Material name	Thermal conductivity [W/m•K]
Bricks*	0.45
PUR foam sheet	0.023
Concrete	1.8

**based on Blok, 2009.*

The combined heat transmission coefficient can now be calculated by applying λ/d (see formula 3)

More energy efficient wall profiles

In the spring agreement of this year, the minister announced an increase of the official R-value from 3.5 in 2013 to a uniform 5 [m^2•K/W] in 2015[13]. Although some parties recommend a differentiated R-value for different parts of a building (roof, walls), these numbers will be used for the *2013 wall profile* and *2015 wall profile* (Lente-akkoord, 2009). As opposed to the typical wall profile, where the material eventually determined the R-value, here the R-value is used, making exact knowledge on the materials used redundant.

Glass

Aboveground buildings of course have windows as well. It is estimated that 15% of a wall consists of glass. The building act states that HR++ glass must have a U-value, the typical

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[13] R-value of the typical wall profile is 2.8

name used to express heat transfer through glass, of 1.1 [W/m^2•K] and at least 2.2 [W/m^2•K], which is set to 1.65 [W/m2•K] from 2013 on (BRIS, 2012). This results in the following total k-values (Table 11) to be used in formula 5.

Table 11, heat transmission coefficients for different types of wall profiles.

	k [W/m^2•K] wall	k [W/m^2•K] glass	k [W/m^2•K] total
Typical wall profile	0.32	2.2	0.37
2013 wall profile	0.29	1.65	0.33
2015 wall profile	0.2	1.1	0.23

Convection inside the building

In the model made for the underground heat transfer situation, convection inside the building is taken into account. Since convection is a complex phenomenon to express mathematically, a correction factor, or heat transfer coefficient α is introduced. The total heat transfer coefficient k [W/m^2•K] can now be described as in formula 5.

$$k_{tot} = \frac{1}{\frac{1}{\alpha}+\frac{1}{k1}+\frac{1}{k2}+\frac{1}{k3}} \qquad \text{Formula [5]}$$

Where:
k_{tot} = total heat transmission coefficient [W/m^2•K]
α = heat transfer coefficient at the inside of the wall [W/m^2•K]
(Blok, 2009).

Normally, another α corrects for outdoor environment factors, such as wind speed and the orientation of the wall. However, here is chosen for a more general correction factor in terms of the weighted degree days. The total degree days is corrected for outdoor environmental influences, which is based on actual gas consumption as described above.

Adding the correction factor α, with a value of 8[14], to the heat transmission coefficients of table 8, the following final coefficients are established (Table 12).

Table 12, total heat transmission coefficients.

	k [W/m2•K] total
Typical wall profile	0.35
2013 wall profile	0.31
2015 wall profile	0.22

Box 1. Omission of roof and ground floor.

As described in section 4.2.3 under *more energy efficient wall profiles* there are different kind of R-values possible for different kind of building part, e.g. roofs, walls, floors. There is no consensus yet whether this distinction will also be made for future energy efficiency requirements. The ground floor, or slab, also interacts with the underground, so no standard equations can be used there. For these reason the various types of 1m^2 of a (side) wall is chosen as research unit for the aboveground situation.

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[14] This is the value used for the heat transmission coefficient at the inside of the wall in Blok, 2009.

4.2.4 Results

Combining the heat transmission coefficients and the number of degree days for one square meter of wall over a time period of one year in formula 6, results in the following amount of heat loss (Table 13, Table 14, Table 15).

$$Q = k * A * DD * (24 * \frac{3600s}{day}) \qquad \text{Formula [6]}$$

Where:
Q_{annual} = annual heat loss from the wall [J]
k = average heat transfer coefficient of the building envelope [W/m2•K]
A = surface area [m^2]
DD = number of degree days [K/day]
(Blok, 2009).

Table 13, Annual energy loss at T_{indoor}= 18°C.

	k [W/m2•K] total	DD	Q [MJ/m^2]
Typical wall profile	0.35	2909	88.77
2013 wall profile	0.31	2909	78.77
2015 wall profile	0.22	2909	55.71

Table 14, Annual energy loss at T_{indoor}= 11°C.

	k [W/m2•K] total	DD	Q [MJ/m^2]
Typical wall profile	0.35	1922	58.65
2013 wall profile	0.31	1922	52.04
2015 wall profile	0.22	1922	36.81

Table 15, Annual energy loss at T_{indoor}= 4°C.

	k [W/m2•K] total	DD	Q [MJ/m^2]
Typical wall profile	0.35	2753	84.01
2013 wall profile	0.31	2753	74.54
2015 wall profile	0.22	2753	52.72

4.3 Comparing above -and belowground

In order to make a rational comparison between the above –and belowground, it is important to keep the comparison as unbiased as possible. This is of importance since the research focusses on the difference between the two.

As described in 4.2.3, there are different wall profiles to be distinguished. First, a *typical* wall profile, which can be found in existing buildings, will be compared to the model results. Next to this, a *2013* and *2015* wall profile[15] will be analysed against the results. These profiles are in line with the legal binding energy efficiency requirements of those years. The method used to derive the savings is presented in box 2.

A distinction is made between energy savings in the selected year and the total energy savings with preceding years included (cumulative energy savings). As already became apparent in Figure 10 the heat flux decreases over time for the underground situation, while this aboveground not the case. For the first comparison, the whole calculation table is provided. For the other cases, the calculation tables can be found in Appendix D. Hereafter, only the cumulative potential energy savings (at the end of each year) will be shown. The following results will be presented:

Deep subsurface

- Concrete wall
- Retaining wall
- Concrete wall with insulation
- Retaining wall with insulation

Shallow subsurface

- Concrete roof
- Concrete roof with insulation

Table 16 gives an overview of the variables of interest of this study which are analysed in both the aboveground –and belowground.

Table 16, variables analysed in the calculations.

	Aboveground	Underground
Indoor temperature	4, 8, 11°C	4, 8, 11°C
Outdoor temperature	Long average temperature function	10°C; long year average temperature and influence of aboveground temperature function on underground buildings in the shallow subsurface.
Construction materials	A typical wall, a wall which complies to 2013 regulations and a wall which complies to 2015 regulations	Concrete, steel sheet pile walls. Both options with and without insulation.

In addition, some fixed variables such as the time dependency (five years taken as a standard) and soil characteristics (thermal characteristics of clay). All cases are analysed at three temperatures and compared to the aboveground situation.

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[15] As described in section 4.2.3

Box 2. On the energy saving potential

The energy savings potential is determined as follows. First of all, only energy savings arising from a difference in heat losses is considered. The calculation method used to determine the savings from underground construction as compared to aboveground construction can be illustrated by the following example.

Annual aboveground heat loss: 80 MJ/m^2
Annual underground heat loss: 35 MJ/m^2
Energy savings potential: $\frac{80-35}{80} * 100 = 56.25\%$

In year two, the cumulative heat losses from the underground building is selected by taking the integral from 0→2 [years] and the annual aboveground heat loss is multiplied with two. Again, the same calculation is used to derive the energy saving potential. The energy savings potentials are thus relative to the aboveground situation.

Analysis of potential sources of error in the comparison
The following measures have been taken to assure an unbiased comparison between the underground and aboveground calculations. First of all, both methods use the same heat transfer formula (1 and 3). A difference can be found in the way ΔT is calculated. In the finite element model, the temperature difference is calculated for each time step, which is set a 1 day. With the degree days method, the average daily temperature is used to calculate the temperature difference, so the time on which the temperature difference is based is in both cases the same. Next to this, the degree day method is tested against actual gas consumption and after introducing a correction factor, it has a very high correlation. The degree day method is also an accepted method used to describe heat transfer in an aboveground building and is accepted by organizations as the KNMI (NMA, 2008)

So, the degree day method can be used for this research. However, in the case of small potential energy savings, the relative importance of the method used increases and therefore the uncertainty increases as well. For large potential energy savings uncertainty

4.3.1 Deep Subsurface results

Table 17 provides the aboveground part for the comparison. Table 19 is input for energy required per year in Table 18. Based on this the savings per year can be calculated, which are also presented in Table 18. In this case, the aboveground situation is compared to the concrete underground construction method with an indoor temperature of 18°C. In year one, the total saving are, logically, equal to the savings in year one. Negative savings imply that additional heat is needed in the underground situation as compared to the aboveground case.

Table 17, annual required energy for an aboveground building.

Compared to a:	k [W/m2•K] total	DD	Q [MJ/m^2]
Typical wall	0.35	2909	88.77
2013 wall	0.31	2909	78.77
2015 wall	0.22	2909	55.71

Table 18, energy saving potential calculation table.

Compared to a:	Q [MJ/m^2] year 1	savings year 1 [%]	Q [MJ/m^2] year 2	savings year 2 [%]	Total savings year 2 [%]	Q [MJ/m^2] year 3	savings year 3 [%]	Total savings year 3 [%]	Q [MJ/m^2] year 4	savings year 4 [%]	Total savings year 4 [%]	Q [MJ/m^2] year 5	savings year 5 [%]	Total savings year 5[%]
Typical wall	114.5	-28.9	69.4	21.8	-3.6	57.8	34.9	9.2	51.9	-41.6	17.3	48.8	45.0	22.8
2013 wall	114.5	-45.4	69.4	11.9	-16.7	57.8	26.6	-2.3	51.9	-34.1	6.8	48.8	38.1	13.1
2015 wall	114.5	-105.5	69.4	-24.6	-65.1	57.8	3.7	-44.6	51.9	-6.9	-31.7	48.8	12.4	-22.9

Table 19, underground energy losses.

	T_{indoor} 18°C
Time [d]	**Q [MJ/m^2]**
365	114.5
730	183.9
1095	241.7
1460	293.6
1825	342.3

From this we can conclude that in the first year, extra energy is needed. This energy is used to 'heat up' the surrounding soil. In the second year, underground construction already saves energy for the typical wall and the 2012 wall. Compared to the most efficient wall, the 2015 wall, no savings are achieved in the second year; it will take three years until (the first) savings are achieved. The total energy savings are positive for the first two walls from the fourth year on. In the fifth year, the total energy saving vary from 23% as compared to a typical wall, to 23% extra heat needed as compared to the most energy efficient aboveground wall. In Figure 15, all evaluated temperatures and wall types are put into one graph.

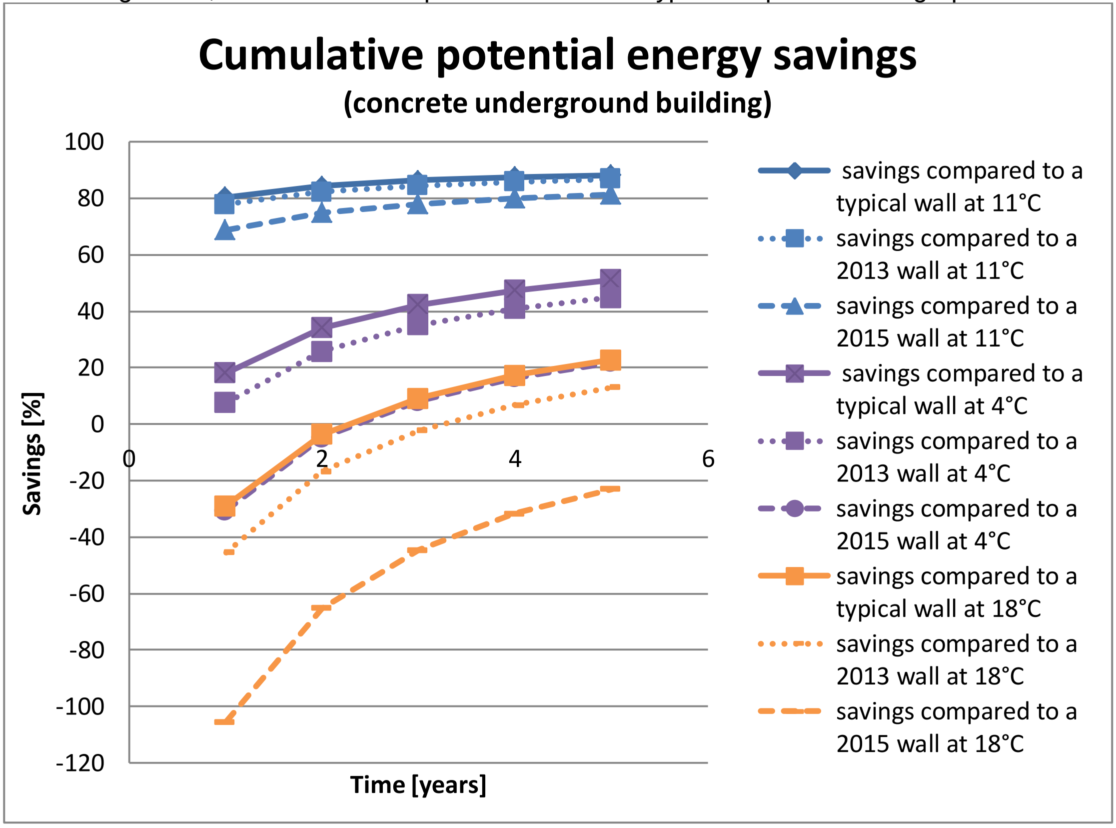

Figure 15, cumulative potential energy savings concrete underground building.

Results with the same indoor temperature are shown in the same colour. A first results that stands out from the graph, is the downward drop of the lines of the same temperature (same colour). This is the technological change of the aboveground wall profiles (more energy efficient aboveground walls) due to policy-induced change effects.

When comparing the aboveground and underground situation, both with an indoor temperature of 11°C, the highest energy savings through heat loss reduction can be achieved. This can be explained by the fact that this temperature is almost the soil temperature; therefore not much heat flows into the soil. In the aboveground case on the other hand, the temperature still drops in the winter and rises in the summer. Therefore, the temperature difference is still present in the aboveground situation and extra energy to either heat or cool is needed. This together results in a large energy savings potential when this type of building (building with an indoor temperature of 11°C) is built underground.

At a indoor temperature of 4°C potential energy savings are already achieved in the first year for the first two wall profiles. Taking a look at the total potential energy saving after 5 years, it can be seen that the expected saving compared to a typical wall can be as high as 50%, but in the case of the most efficient wall this is reduced to 20%.

Retaining walls

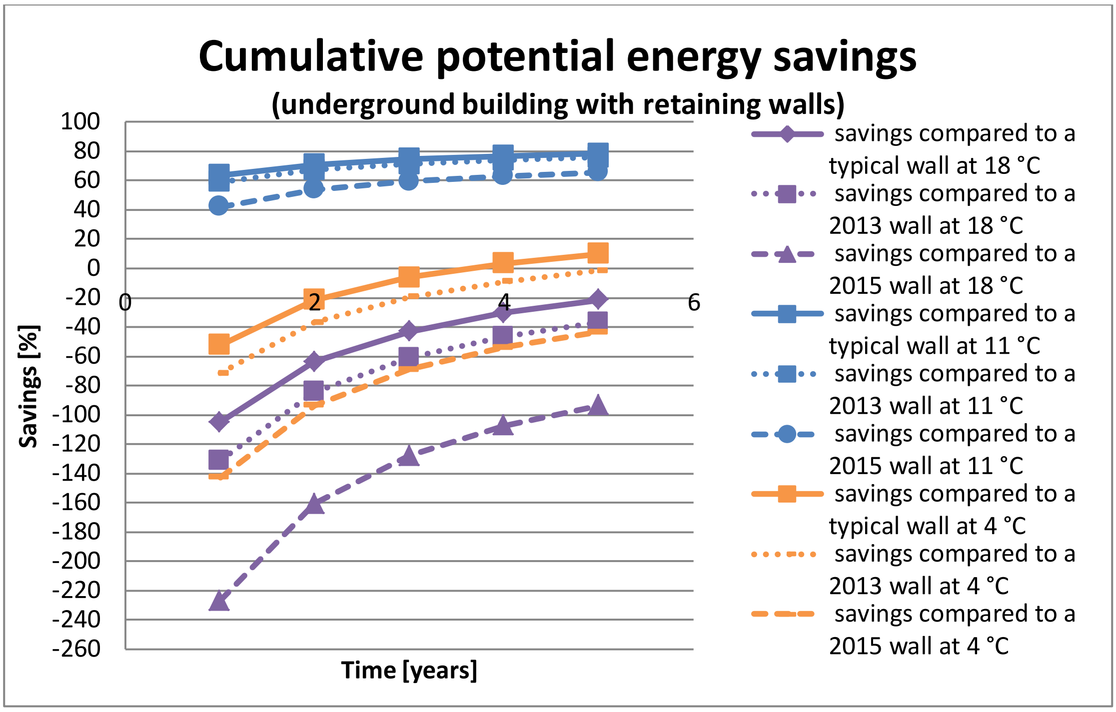

Figure 16, cumulative potential energy savings for a retaining wall underground building.

At an indoor temperature of 18°C it can be seen that potential energy saving from a retaining wall method as described takes more years to establish than for a concrete construction. Yearly energy savings are present in year 5 for the two less energy efficient aboveground constructions, but total energy savings are not realised within a timespan of five years. The reason for this is clear, and comes down to the thermal properties of steel as compared to concrete. Steel conducts, after all, heat far better than concrete.

At an indoor temperature of 11°C, significant potential energy saving can be achieved with the retaining wall method as well, albeit lower than in the case of a complete concrete construction. At 4°C, yearly potential energy savings are achievable from year 2 and 3 on for the two least energy efficient aboveground constructions. For the 2015 wall profile, it will take longer than five years to reach both yearly and total energy savings.

All in all, it can be concluded that is always more beneficial to construct an underground building with the concrete construction method to achieve a higher energy savings potential. Next to this, an indoor temperature close to the underground temperature results in large energy savings potential. When comparing an underground living space to new buildings in 2015, there are no savings possible within a timespan of five years. However, one must keep in mind that this timespan is chosen and underground buildings often have a much longer life time, but these timescales are for practical reasons beyond the scope of this research. This will be elaborated upon in section 4.3.3.

Comparing the graphs

For easy comparison of the graphs, check Appendix E.

So far, the results indicate advantages of underground construction form an energy point of view for some situations. These advantages might be more substantial if insulation is added to the walls of the underground buildings as well, which is currently not the case. First, let's consider a concrete underground building in the deep subsurface with insulation. The results are shown in Figure 17.

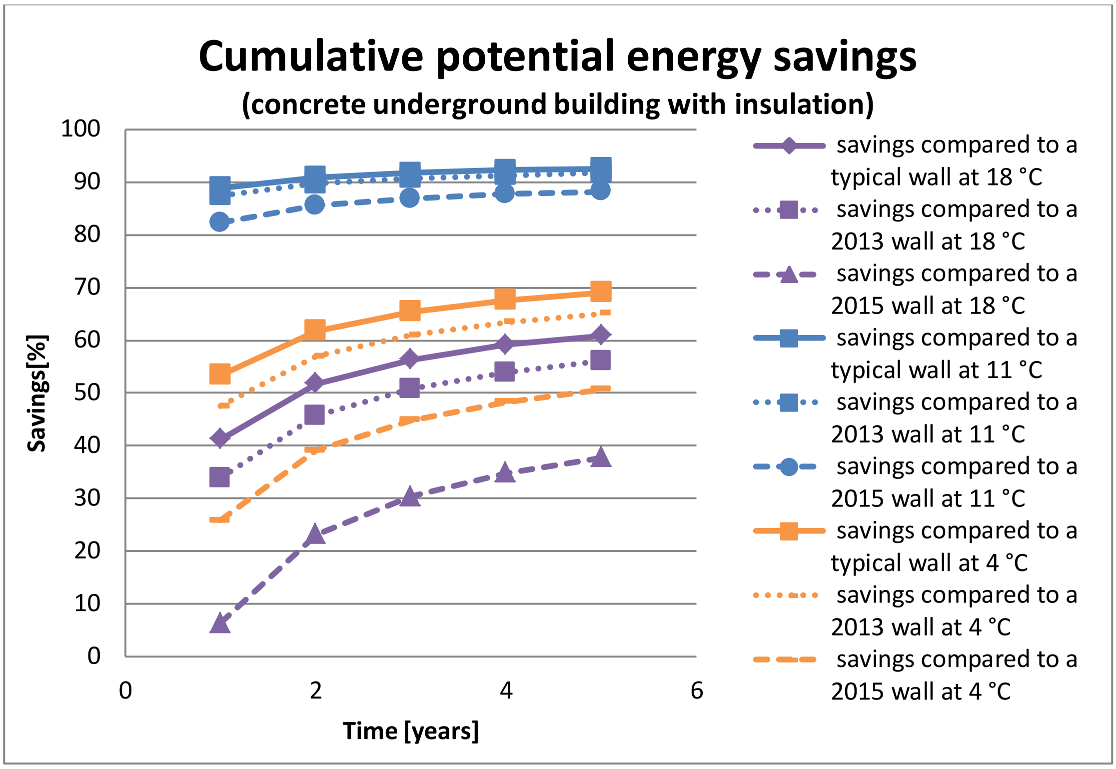

Figure 17, cumulative potential energy savings from a concrete underground building with insulation.

The first thing to be noticed is that all energy saving potentials lie above the zero line, and thus all result in actual savings. As expected, with underground insulation, the energy savings potentials are bigger. Especially the comparison with the 2015 wall profile is interesting for living spaces (at 18°C). By adding insulation to the concrete structure, the total energy savings after five year change from -23% (extra energy still needed) to an energy savings potential of almost 38% as compared to an aboveground structure.

Since the energy savings potentials were already high at an indoor temperature of 11°C, the benefits of insulation are not as big as for other indoor temperatures. Therefore, placing insulation in buildings with an indoor temperature around the soil temperature might not be reasonable if economic arguments are taken into account as well. The cost to install the extra insulation might be more than the cost savings through the extra energy saved. Further research is needed to verify this statement.

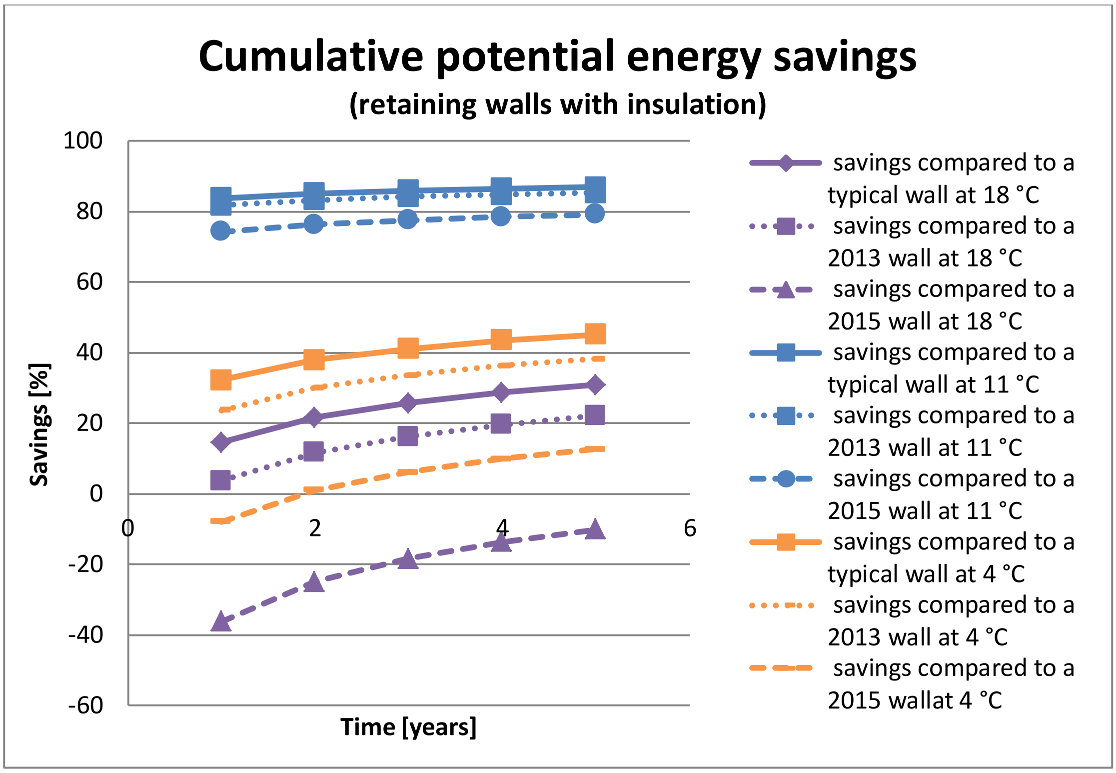

Figure 18, cumulative energy savings from a retained wall underground structure with additional insulation.

Figure 18 shows the results of a retaining wall with insulation. The most interesting cases are the ones with an indoor temperature of 18°C en 4°C. After five years, a living space compared to the typical and 2013 wall profiles result in energy savings (31 and 22%, respectively) where this required extra energy after five years when no insulation as installed (21 and 37%, respectively). At 4°C, this effect is present for the 2013 and 2015 wall profiles. Compared to the 2013 wall profile, adding insulation results in extra energy needed of 1.5% without insulation and with insulation an energy savings potential of 38%. Compared with the 2015 wall profile, first 43% extra energy is needed, while with insulation an energy savings potential of almost 13% is achieved after five years. At an indoor temperature of 11°C, this result is somewhat smaller and is all in the order of 10% increase (from around 70% to around 80%). All in all the, extra energy saved by adding insulation lies in the range of 4-10%[16] at 11°C. For the buildings with an indoor temperature further from the soil temperature this varies[15] between 18-83%.

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[16] All cases considered

4.3.2 Shallow subsurface results

In this section, the results of the shallow subsurface, modelled with a temperature sine on the upper boundary of the soil domain are presented (Figure 19 and Figure 20).

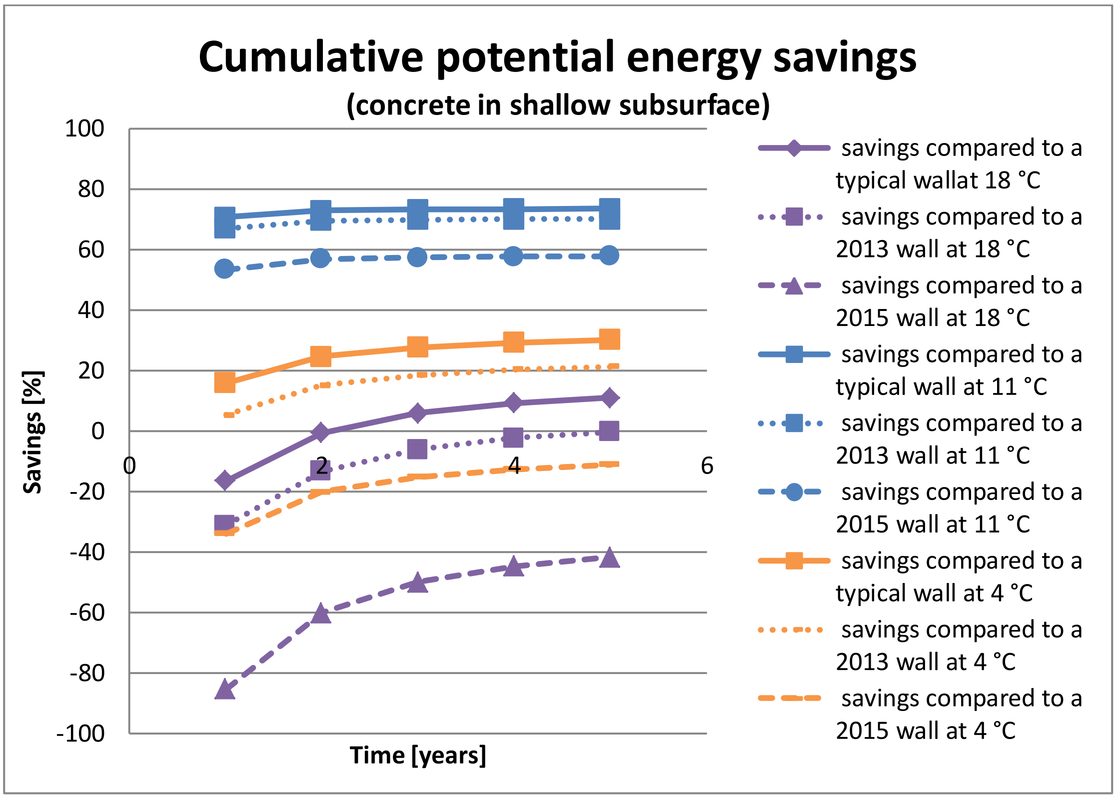

Figure 19, cumulative potential energy savings from a roof profile of a building situated in the shallow subsurface.

In this situation, the potential energy savings are higher than in the case of a retaining wall, but lower than in the case of a concrete wall. The cumulative savings arrive at a stable level relatively fast. This is caused by the temperature sine. The roof profile experiences the temperature fluctuation of the aboveground temperature, but due to the soil in between the ground level and the structure itself, this temperature sine is delayed and damped. For this reason, the cumulative potential energy savings do in some cases not increase every year (see Appendix D, Table 81), but stay around a certain level. This can be explained by the fact that aboveground the same amount of annual heat losses is added and underground only the part of that same year. Since, this sine function is delayed (phase shift) and damped (lower amplitude) and therefore it depends on the year which part of the sine, which thus influences the energy loss, is added to the total. So, the total heat losses do increase, but the energy savings are measured as a percentage relative to the aboveground situation, which explains this effect.

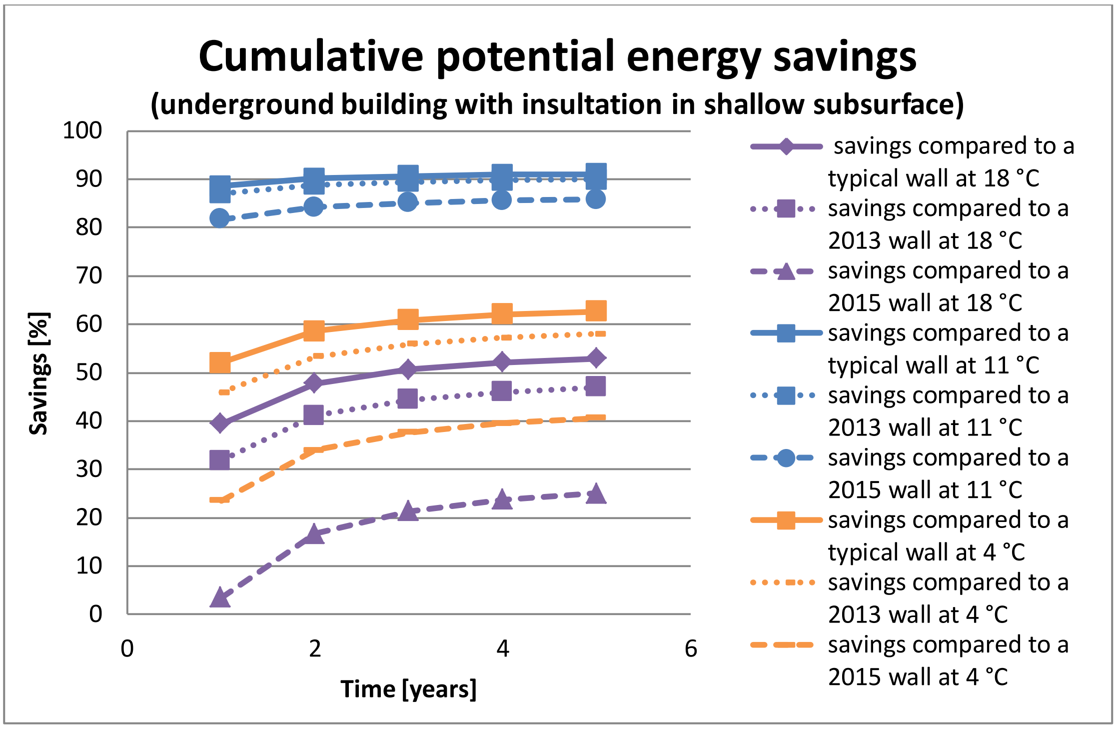

Figure 20, cumulative potential energy savings with the influence of insulation and aboveground temperature influence.

At last, the effect of insulation and the aboveground temperature influence is presented in Figure 20.Here the same trends can be seen. When comparing this model to the model with solely the seasonal temperature influence, additional energy needed for living rooms in the model without insulation is turned into energy savings when insulation is added. At a temperature of 11°C, the already high energy savings without insulation are further increased with insulation. In the case of an indoor temperature of 4°C the typical wall and 2013 wall profile extra energy savings are achieved, and compared to the 2015 wall profile the extra energy needed without insulation is turned into an energy savings potential.

4.3.3 Time perspective

As mentioned before, buildings have a longer life time than the five years assessed in this research. Therefore, for one simulation a longer time span is analysed. Preferably, the simulation was performed over time span of 50, however, the limit to which the model could run was 27.6 years. Therefore a run is made for 25 years for the concrete case at 18 °C to get an indication of the contribution of those 5 years assessed. The cumulative energy after 25 years is 743.3 MJ/m^2 and this was 342.3 MJ/m^2 after 5 years. The proportion of those five years to the 25 years is thus 39%. For the different wall types, the results are shown in Table 20. Since the cumulative potential energy savings are not linear they cannot be extrapolated. If this was the case, the tipping point (at 0% savings) could be presented for each simulated situation, thereby showing the amount of years needed before energy savings can be expected. This would now only be possible if the function of the heat flux can be set up, in which t (for each year) can be assessed. This is currently not an option in Comsol.

Table 20, cumulative potential energy savings after 25 years.

Compared to a:	Cumulative savings year 25 [%]	Cumulative savings year 5 [%]
Typical wall	60.4	22.8
2013 wall	55.4	13.0
2015 wall	37.0	-22.9

4.3.4 Impact beyond the Netherlands

This research focused on the Dutch situation, more specifically on the Dutch situation in the Western part of the country. What can the results mean to other locations all over the world? Since the underground temperature compared to the building indoor requirements plays a very significant role in the relative energy savings this impacts which type of buildings benefits most from underground construction in terms of energy saving. It thus is important to explore the underground temperatures resulting from climatic variations. As mentioned in part I, the soil temperature reflects the mean annual temperature below the depth influenced by seasonal variations.

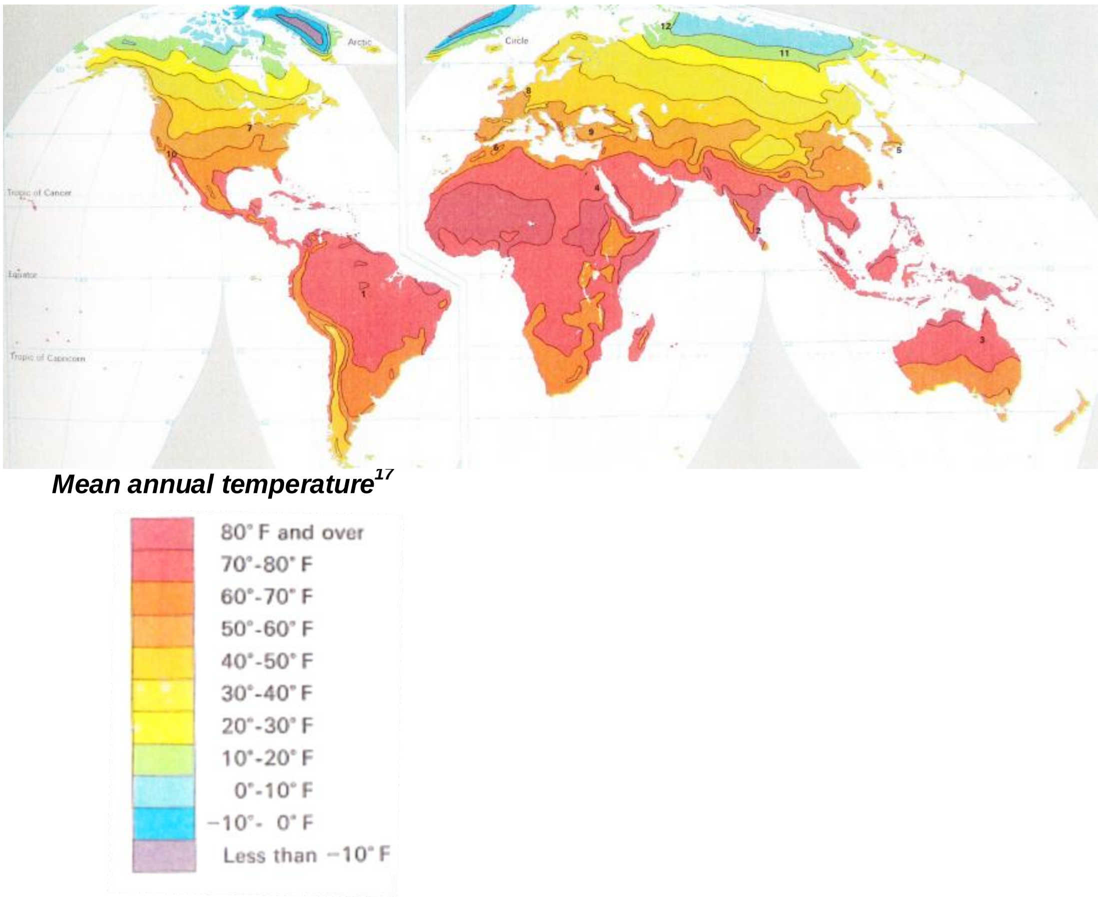

Figure 21, mean annual temperatures (World Atlas, 1979).

In highly populated areas, some parts of Asia for example, the temperature is turns out to be more favourable for living spaces. Here soil temperatures[18] are in the range of 18-27°C (Figure 21). The same is true for the Northern part of Latin America. More Northern parts of the world, including the Netherlands, benefit most from buildings with an indoor climate around 10°C, which is close to the average soil temperature. On the other hand, climate change will have an impact on the temperature, both above– and underground as well. The question remains to what extent. Most likely, the temperature will rise with a few degrees (IPCC, 2007b), thereby making a larger area of the world more suitable for underground living spaces in order to reduce energy consumption for heating and cooling.

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[17] °C = (°F-32)/1.8, e.g. 50 °F is 10 °C and 80°F is 26.7°C.

[18] Assuming that long yearly average aboveground mean temperature results in the average soil temperature here as well.

4.4 Discussion of part II

This part of the study made a contribution to the potential energy savings resulting from underground construction. It thereby aimed to make a coherent overview of factors at play in heat transfer from buildings to the subsurface and of course aimed to indicate the energy savings potential of underground buildings as compared to aboveground buildings. With many variables at play, it was necessary to make assumptions in order to derive at meaningful results. This chapter reflects upon choices made and the impact of these choices on the results.

Both ‘buildings’ are modelled as a box of 10 by 10 meters. The roof section and ground floor of the aboveground building are omitted to abridge the calculations. Roof sections are often insulated best (since heat rises) and potential energy savings could therefore be slightly lower if these sections are taken into account. The ground floor is adjacent to the soil, and is therefore difficult to analyse. Extra research is needed to produce models on this heat transfer issue. The underground model is two dimensional. A 3D model would mimic reality better, but took too much computations for the computer used. This means however, that the system reasons from the point of an infinite long plane in the y-direction[19]. This is important to keep in mind, since there might be discrepancies in the way heat dispersion appears in 2D and 3D. Figure 22 illustrates a possible effect of this choice made. In a 2D model, all the heat that is released is forced to stay in this 2D plane. In a 3D model, this heat can disperse in all dimensions. To illustrate, let’s assume heat transfer from point A to point B and a fixed amount of heat X. In the 2D model this amount X might be enough to reach point B. However, in the 3D model, this heat can also displace in all directions and might therefore not be enough to reach point B. The 2D model can therefore result in an overestimation of the heat transfer to point B.

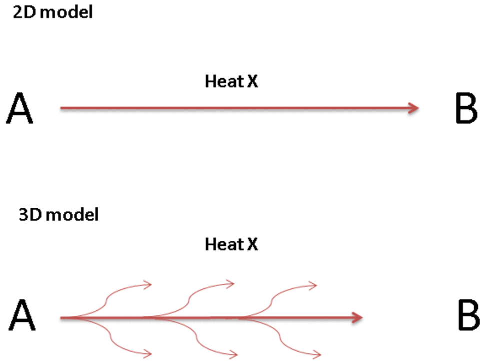

Figure 22, heat dispersion in a 2D and 3D model.

Ventilation and groundwater flow are both left out of the equation. Underground mechanical ventilation rates are most likely higher than aboveground mechanical ventilation rates. This causes extra energy consumption. However, it only affects the heat transfer through the building’s envelope to a minimum and is therefore left out. Groundwater flow might be higher in some locations, which would then drain the energy in the soil at a faster pace, resulting in higher energy losses. Ventilation, groundwater flow and specific soil characteristics are next steps to expand the model. Another addition in the model could be made by allowing the heat stored around the buildings to return into the house again. In this way, only a small part e.g. one meter of the soil is heated up and used as a buffer. This comparable to a central heating system, but is not obvious to model. In addition to this, energy losses from a real life underground building should be monitored in order to verify the extended model. The assumptions necessary to construct the model resulted in the fact that this study must be perceived as exploratory. The outcomes indicate that there is potential for energy savings, this must however be further studied.

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[19] It must be kept in mind that according to the 3D coordinate system Comsol uses, the z-direction is vertical, the y-direction in the plane and the x-direction along the plane, which thus differs from the 2D x-y coordinate system.

Time turned out to be an important component in the heat transfer problem. Only a small time span could be assessed here. In an ideal situation energy losses throughout the whole lifetime of a building, both the operational lifetime as its construction and demolition phase should be taken into consideration. This can in the future be done by performing a life cycle analysis.

All in all, the assumptions in this research affect the results. The results can not be interpreted as absolute; they are indicative of the potential energy savings. Therefore, a more complete model is desirable for the future. As for now, this part of the study has made a contribution to come to a coherent piece of work on energy losses in underground buildings as compared to aboveground buildings.

4.5 Conclusion of part II

Various factors play an important role when assessing heat losses of above –and belowground buildings. Next to thermal characteristics of the materials, the degree to which the environment is able to transport the heat is also an important factor, as air has a lower thermal conductivity than clay. Yet, underground buildings experience a better isolated environment, since there is no (or very little) transport of heat into their environment. For aboveground buildings, the heat transported from the building by convection thus plays an important role.

The results imply that it can be, from an energy perspective, beneficial to construct buildings underground (under specific circumstances). In some cases, no energy is saved during the first five years. It can however be said that it is always more beneficial to employ a purely concrete building technique instead of one with steel retaining walls. In addition, the energy savings potential is most significant for buildings with indoor temperatures around 10°C; which is the average soil temperature in the Netherlands. It is furthermore important to what types of aboveground building materials the underground building is compared; this influences the relative potential energy savings. In the graphs presented in this part, this can be seen by the downward displacement of the curve with the same temperature, which is induced by stricter energy efficiency regulations.

Insulation of underground structures creates additional energy savings. However, these extra savings are only small (ranging from 4 - 10%) for both underground building types (concrete and retaining walls) with an indoor temperature close to the underground temperature. The decision to place insulation in these cases must therefore be put in a wider context. Economic considerations might come in play, since it must be assessed whether the extra cost of the insulation is covered by the monetary additional savings realised by the insulation. For buildings with an indoor temperature further from the soil temperature, insulation does create significant additional savings (ranging from 18 – 83 %). In some cases[20] this means that a tipping point from additional energy needed to energy savings can be realised within five years by adding insulation. Next to this, by placing insulation in a concrete underground building, energy can be saved in buildings with living room temperature as well. Due to the broad range of additional energy savings, the influence of insulation must for every case be assessed. This does not only apply for the insulation effect, but for all factors at play. Each location will have its specific soil composition and thereby thermal characteristics. Places which do have a high ground water flow (e.g. situated at the bottom of a hill slope next to a river in sandy soils) are not considered. Based on the finding that the degree to which the environment of the building dictates the heat transport is important, it might not be favourable to build underground in such environments. However, more specific research is required for these types of locations. The results imply that different types of buildings, with different indoor temperature requirements, can be located around the world. The results suggest that spaces at living room temperature can, for example, beneficially be brought underground in

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[20] For example: concrete wall at 18°C compared to a 2015 wall profile, retaining wall at 18°C compared to a typical and 2013 wall profile and a retaining wall at 4°C compared to a 2013 and 2015 wall profile.

some parts of Asia, since the average soil temperature is around living room temperature there.

What holds for the interpretation of the results also holds for the interpretation of the comparison of the results. This study must be perceived as exploratory and the results presented are an indication of possible energy savings potential. For every specific location, additional research is needed to assess the possible energy savings. In addition to this, more advanced models should be created, e.g. groundwater flow models can be linked to the underground heat transfer model and further steps can be made in the level of detail in the representation of the building.

Part III. Implications of the results

5. Implications

This part will put the results from part II of this study into a broader perspective. The outcomes of this part II indicate that energy savings by underground construction might be interesting in certain circumstances. However, this this only one part in the field of subsurface construction. Other issues are of importance when considering subsurface construction, such as costs and environmental impacts throughout the entire building's lifetime. Next to this, the possible implications of the results found are not static; they are dynamic and have dynamic effects in the broader field of underground construction and the (built) environment. To capture the possible implications, with a focus towards a more sustainable built environment, the DPSIR (Drivers – Pressures – State – Impact – Responses) framework will be used (Figure 23). This is a framework that has found a more common application in the field of environmental policy analysis in an international context (especially at the European level) (Carr et al., 2007). Given the complexity and dynamic effects in analyzing the impacts from the numerical analysis in part II, using this framework will provide the required structure to the evaluation process without undue focus on specific numeric outcomes. Given the fact that this framework is not commonly applied in the field of energy and underground construction it is explained in general terms in section 5.1.

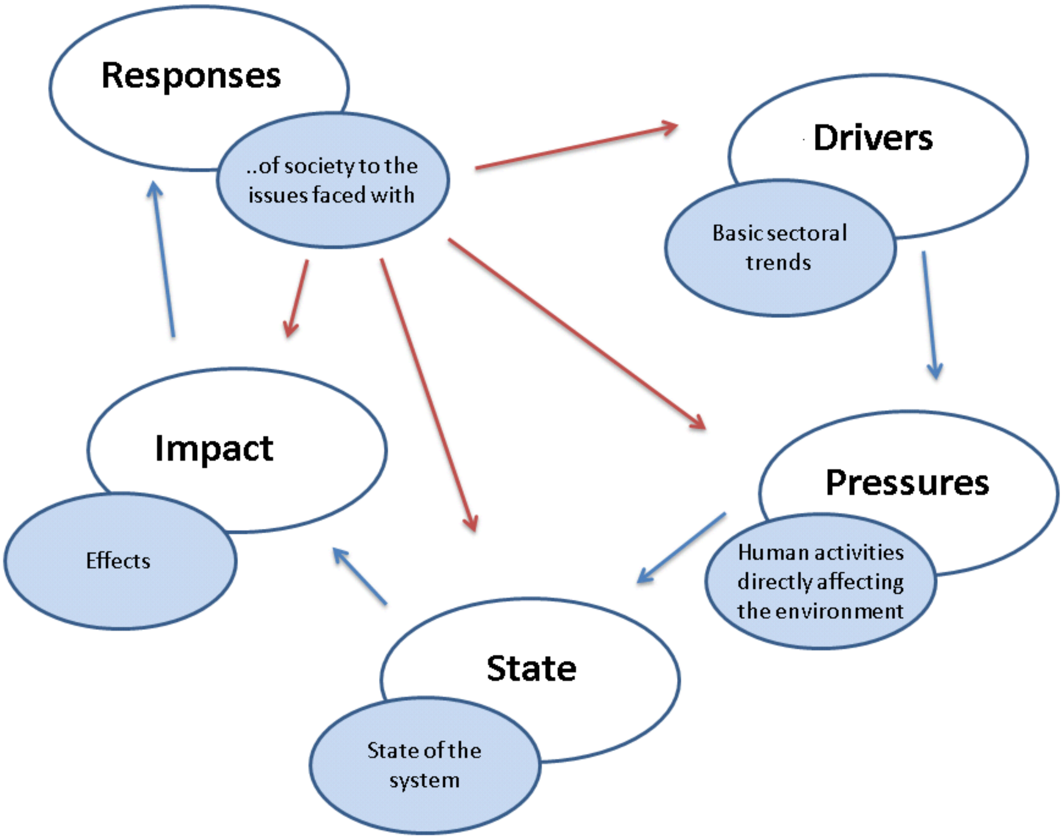


Figure 23, DPSIR framework (modified from EEA, 1999).

5.1 General framework

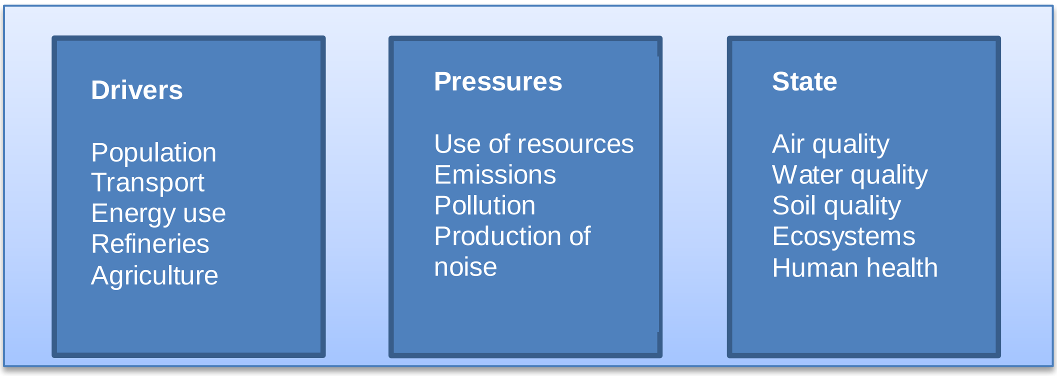
The DPSIR framework is a system analysis tool and can be adjusted and applied for specific topics. This framework helps structure dynamic topics. The blocks are linked to each other and therefore a change in one of the blocks induces changes in the other blocks as well. Human activities driven by basic sectorial trends lead to pressures on the environment. These result in interactions with the current state of the system. The changes are described in terms of impacts. The induced changes then may elicit societal responses which in turn feed back on the forces that have lead to the need for these responses[21]. Originally, the framework used by the EEA suggests assessing environmental issues (EEA, 1999). For this study, the scope is expanded to assess the domain of underground construction.

Driving forces can be defined as socio-economic 'needs'. They are the developments in basic sectorial trends that impel the existence of human beings (Martins et al., 2012). Figure 24 displays some of the most common examples of drivers, pressures and state. Population is, for example, a driver in many systems. It can entail all kinds of characteristics of the population, such as age structure, education levels and political stability (Kristensen, 2004). Each example can be worked out at a higher level of detail, which is the actual analysis of the system described by the DPSIR framework.

The activities of humans to meet the needs described by drivers exert *pressures* on the environment. Pressures can be dived in three main categories 1) excessive use of resources 2) emissions to air, water and soil 3) changes in land use. The pressures are the result of the production processes and consumption pattern of humans.(Kristensen, 2004) The drivers and pressures are thus closely linked. The relationship between the drivers and pressures can be described as an eco-efficiency indicator. When the economic activities resulting from the drivers lead to less pressure, the eco-efficiency of the system is improving. (EEA, 1999)

The *state* is the condition of the system, which is focused on the environment in the original DPSIR framework. In later studies, the socio-economic conditions were, next to the natural conditions, taken into account as well. The state is dynamic; the aim is to reflect the current (environmental) quality and trends. The relationship between the pressures and the state is based on the dispersion of those pressures. (Carr et al., 2007) The way in which, for example pollution is spread over a certain area, has a direct influence on the state of that area.

The changes in trends observed in the state may have socio-economic or environmental *impacts* on the performance of society (Kristensen, 2004). In other words, these are the (negative) effects of the human activities. The chain of events ends in the *responses* of society to the undesired impacts. This often translates in policy and targets (de Mulder et al., 2012). The responses can, in turn, affect any of part of the DPSIR framework (Kristensen, 2004), which is reflected by the red arrows in Figure 23.



Drivers	**Pressures**	**State**
Population	Use of resources	Air quality
Transport	Emissions	Water quality
Energy use	Pollution	Soil quality
Refineries	Production of noise	Ecosystems
Agriculture		Human health

Figure 24, examples of drivers, pressures and state (Kristensen, 2004).

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[21] As explained on the EEA website: http://ia2dec.ew.eea.europa.eu/knowledge_base/Frameworks/doc101182/

5.2 Application of the framework

It is important to recognize that various DPSIR scenarios can be assessed based on the perspective taken. First, the current system, or business as usual situation of the built environment is analyzed with the DPSIR framework. Hereafter, the results from part II of this report are placed in the framework. In this way, the possible implications of the results from the potential energy savings can be described in terms of prospects towards a more sustainable built environment. The dynamic character of the framework suits the purpose of this study. The aim is not to provide a complete assessment of all other factors at play in the field of underground construction in relation to the built environment, but to provide insight in the main underlying factors involved, when taking an energy, sustainability and economic point of view. The results are thus placed in a broader societal and environmental context.

5.2.1 Current system

Drivers

Drivers:

- Energy use in the build environment
- Population growth, increase in wealth and trend towards individualism

The built environment of today can be characterized as energy intensive. Buildings are currently accountable for 25-40% of the worldwide primary energy use[22], which is more than automotive and air transport combined. This results in 30% of the world wide CO_2-emissons (IPCC, 2007a), since most of the energy used in buildings comes from fossil fuels. This driver originates in the human need to have comfortable shelter.

The United Nations (UN) provides population estimates and projections, based on three different scenarios. In the high scenario, it is expected that there will live 10.6 billion people on the planet by 2050, and 8.1 and 9.3 billion people in the low and medium prospect (UN, 2011), respectively (cf. 6.97 billion people in 2011(UN, 2012)). Taking the medium scenario, the increase in population will continue up and until 10.1 billion people in 2100 and will thereafter stabilize. Though these very long term projections beyond 2050 are uncertain, it is reasonable to expect a 30% increase in population till 2050 (de Mulder et al., 2012). In addition to this, people are becoming wealthier. They eat more and higher quality food, which also demands more (rural) land, on which people then no longer can live (EEA, 2009; de Mulder et al., 2012). In large parts of the world there is a trend towards individualism, this combined with ageing (especially in Europe) results in a growth of the number of (small) households and thus further increases of space demand per person. Population growth, in combination with a more luxurious lifestyle and a trend towards individualism, has lead to growth of the built environment. This in turn interacts with the first driver described; more buildings lead to an increase in energy use.

Pressures

Pressures:

- Increased use of resources
- CO_2 emissions
- Changes in land use

The three main categories by which the pressure can be described are present in the system of the built environment as well. First of all, the use of resources is intensified by building more structures. When these buildings are then used, more energy is used (e.g. for space heating and cooling). This leads to an increase in CO_2 emissions. As a consequence of the changes in the driving factor population, more buildings (e.g. for residential, working and leisure purposes) are needed, which thus induces changes in land use. This change in land use mainly takes place in urban environments. In 2011, about half of the world's population was living in urban areas (52%) (UN, 2012). In 1970 there were only two megacities; Tokyo and New York. Today, this has increased to 23 cities

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[22] Lecture by E. Worrell on sectors & energy use – Buildings, Utrecht University, 2012.

and this will further increase to 37 in 2025. Each continent will than have at least one megacity. (UN, 2012) To illustrate this, between 1990 and 2000 alone, urban land surface in Europe expanded by three times the size of Luxembourg (EEA, 2009). The Randstad area in the Netherlands was already characterized as very heavily urbanized in 1990 (Ottens, 1990).

State

The state of this system is the area in which the buildings are built. The population growth, urbanization and increasing wealth together reduce the land available for good-quality green spaces and walkable neighbourhoods. These are key to what is considered the urban quality of life (EEA, 2009). The availability of suitable land for the required functions is limited, which has its impact on the state of the urban living environment. Next to this, the increase in CO_2 emissions as described under *pressures* cause (unwanted) global climate changes in various forms (Harvey, 2000). The human health and wellbeing aspect as characterization of the state is thus the main component in the built environment system.

State:

- Quality of live

Impact

The urbanization and land use change and the reduced land for good-quality green spaces have as effect that the city sprawls (EEA, 2009). As a consequence, the distance to green spaces only increases. The increase in space demand causes the skyline of cities to change since more and more buildings are built into the sky.

Impact:

- Urban sprawl
- Heat island effect
- Increased demand on HVAC installations

Global climate change leads to more extreme weather events. There is evidence that changes in the climate system already touches human health. Increased mortalities are already observed as a result from extreme, heat , cold, drought floods and changes in air and water quality (Patz et al., 2005). The heat island effect (Figure 25) is an example of climate change in an urban environment. Buildings block heat from radiating into the sky, in addition the materials used in cities absorb higher levels of radiation as compared to natural vegetation (which is lacking in urban areas). Another effect of a density built environment is the halt to wind crossing through the city, which in turn limits heat exchange. For all these reasons, a city environment tends to show a pattern of high temperatures in its most density built core[23]. The more extreme weather events and the urban heat island effect impact the indoor temperature regulation of buildings. Peaks of cooling and heating demand can be expected from these events. This in turn leads to and increase in energy consumption.

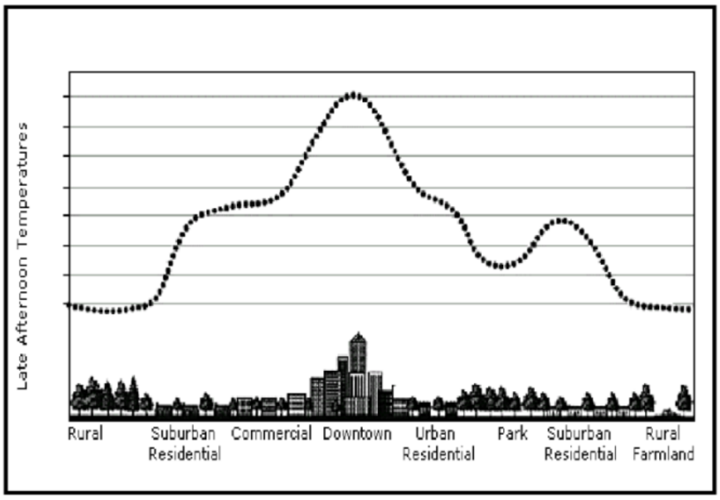

Figure 25, sketch of an urban heat island profile (modified from [3]) The inner city can register up to 5-11°C warmer than the surrounding rural areas (Patz et al., 2005).

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[23] Lecture by R. Brolsma, Deltares, June 15th 2012.

Responses

The responses take place at different levels. The European Commission has put a set of binding legislation in place, the so-called climate and energy package[24]. Each member state has its own responsibility to form country specific legislation to reach the targets set. For the building sector in the Netherlands specifically, this has lead to energy efficiency targets. One of the main requirements for new built constructions is the EPC (energy performance coefficient) which articulates the energy efficiency performance of a building in a numeric value. Over the years, the required value of the EPC becomes stricter (Rijksoverheid, 2013a). In addition to this, the government expects that in 2020 all new build properties will be (almost) energy neutral; meaning that over a time period of one year a building uses the same amount of energy as it produces (ibid).

Responses:

- Climate and energy policy
- Energy performance index for built environment

5.2.2 Completing the cycle: introducing the results from part II.

This section will take the potential energy savings as found in part II into account. Knowing that energy can be saved, and assuming that underground construction will be deployed as a measure to contribute to reduce energy consumption and unwanted changes in the climate, what kind of effects can this have on the other blocks in the DPSIR framework (depicted by the red arrows in Figure 23)? In other words; what are the possible impacts of more focus on underground construction, thereby taking the results found in part II into account?

Changes in drivers

In light of the response of society to reduce energy consumption and emissions, the potential energy savings by underground construction can now be seen as a *need*. Reaching targets set, in order achieve energy and emission reductions is another need, to which underground construction can then contribute to achieve.

Changes in pressures

As CO_2 emissions were a pressure resulting from the energy consumption in the buildings sector, this study has shown that significant energy reduction can be achieved when bringing the right types of buildings under the right circumstances underground.

The (urban) land use will now experience a shift towards more underground structures (though aboveground buildings will stay dominant). In this way, underground construction can alleviate the pressure on land use and the pressure of CO_2 emissions on the climate system. On the other hand, pressures can be charactarized by excessive use of resources as well (see section 5.1) Since this study only focused on the operational energy consumption, a life cycle analysis should be carried out as well. A life cycle analysis of an (underground) building takes into account all resources (materials, energy) needed from the first step in the production process to the demolishing phase of the building. It is important to take this also in account when arguing about the motivations to build more structures underground[25]. Combining impacts of material and energy use throughout a building's lifetime might translate in other sustainability outcomes than only focussing on energy use during the operational lifetime.

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[24] http://ec.europa.eu/clima/policies/package/index_en.htm

[25] Moving earth for underground construction might, for example, result more excessive use as resources in the construction phase as compared to aboveground construction.

Changes in state

Increased market penetration of subsurface construction would change the state of the environment. By employing underground construction the state, as described, can improve. On the short term, the possibility to create green spaces can be increased by constructing more underground. On the (very) long term, the negative consequences of CO_2 emissions can be mitigated. In this way, human health and the quality of city life can be improved. However, bringing buildings with a specific indoor temperature requirement underground, impacts the natural soil temperature.

Changes in impact

The most visible impacts of employing underground construction on a larger scale is the reduction in the sprawling of cities and the reduction of building density in the core of the city. With this, the liveability of the city can increase. By reducing the amount of aboveground buildings and increasing vegetation, the urban heat island effect can be reduced, which also contributes to the quality of life in cities.

On the other hand, an increase in the construction of underground buildings with specific indoor temperature requirements, can lead to possible geochemical changes in the soil and the depletion of soil bacteria caused by high(er) temperatures (RIVM, 2009).

Taking the trends towards energy neutral construction into account, one may argue that the relative energy savings argument may become redundant if aboveground buildings are built in such a way that hardly any energy is needed during its operational lifetime (i.e. zero-energy or passive buildings). However, the potential energy savings from underground construction can contribute to reach the targets in the years up and until the start of construction of zero energy buildings.

The state might also change from a socio-economical point of view. Underground construction is currently more expensive than aboveground construction (see box 3). And, as already mentioned above, the use of resources during the building's lifetime could possibly increase. Increased construction in the underground could therefore have a negative impact on the society as a whole solely looking from economic perspective in terms of investments in the construction itself. Another possibility is thus to discourage underground construction, based on the current economical argumentation. This might then, in the light of the potential energy that can be saved, and potential CO_2 emissions that might be mitigated during its operational life time, also have a negative impact on the society as a whole. Besides, the negative externalities from aboveground building; which reduces the available green spaces and increases the demand on resources need to be valued in a societal cost benefit approach, which takes these aspects into account. This approach is however another area of research, since these assessments are currently hampered by the omission of valuations for ecosystem services and the value of subsurface space (de Mulder et al., 2012). A (life cycle) cost-benefit analysis comparing aboveground and underground construction needs to be undertaken to determine the validity of the economical arguments in a broader perspective.

Box 3. Costs of underground construction

There is a structural lack of data availability on underground buildings costs. (Romero & Stolz, 2002). This is most likely caused by the fact that underground buildings are generally private owned and therefore cost data are confidential. However, there is consensus on the fact that underground construction is more expensive than aboveground construction, especially the initial investment costs are higher (Bobylev, 2009; Evans et al., 2009; Knip & van Berkel, 2000; Reilly & Parker, 2007; Romero & Stolz, 2002). Japan Echo Inc. (1997) estimated that construction costs of underground buildings are typically twice the amount as those for aboveground construction.

Operational costs, on the other hand, are expected to be lower than for aboveground buildings. Maintenance of underground structure requires minimum expenses; the construction is protected from external influences (Bobylev, 2009; Reilly & Parker, 2007). Additional operational cost will probable stem from higher underground (mechanical) ventilation rates.

Changes in response

All the changes in the the blocks toghether lead to a change in the response as well. Though a strategic vision for the underground is being developed for the Netherlands and expected to be finished the second half of 2013 (Rijksoverheid, 2013b), the underground as accommodation for living, working or other type of spaces is often overlooked, as became apparent in the vision on the sustainable use of the subsurface (Ministerie van VROM, 2010). Underground construction is not really viewed as an alternative for (problematic) aboveground constructions. It is an 'invisible' resource for policy makers and project managers (Knip & van Berkel, 2000). It was always a matter of 'first come, first serve'. Such an approach has a high risk to waste resources and can fail to maximize public support (Lin & Lo, 2008).

It is therefore important that future policy and regulations take into account underground construction. This can be both in spatial planning and energy efficiency regulations. Of course, aboveground regulations with regard to energy efficiency and spatial planning must be combined with the underground insights, in order to come to an integrated approach. In this way, society can benefit most from potential energy savings from underground construction and better avoid possible conflicts from various underground activities (next to underground construction, the underground is used for cables, (waste) water, IT, etc.). Possible negative impacts, such as geochemical changes in the soil should be avoided by regulating underground construction activities, as already is the case for thermal energy storage[26]. However, before putting a new policy in place, an appropriate assessment framework should be made, to make deliberate decisions on above –and underground constructions and combinations of it. An important first response must thus be to perform a more system based research in the field of underground construction, as for example described in section 4.4 and in the further steps below. A next step is then to put a policy in place for which the effects in turn must be monitored in order to obtain the maximum benefit from potential subsurface energy savings.

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[26] Though a longer timespan to come to a neutral energy balance must be considered for underground construction.

Further steps

The findings from part II are based on an individual building level. A next action which determines the state is to explore the changes at a system's level by a scale-up of the underground habitat. The DPSIR framework could be used again to analyse the effects of such a scale-up. Then, buildings with indoor temperature requirements other than the most beneficial could potentially be brought underground. Additional research should focus on the potential energy savings from buildings with different temperatures and their interaction with each other and the environment. Heat exchangers[27] can contribute to achieve energy savings from buildings with a temperature requirement that lies further from the optimal temperature. In other words, in this situation the energy savings would not take place at the individual level only, but will take place at a system level. To plan such an underground habitat, more research is needed related to the efficiency of exchange of energy between buildings in the underground and the possible consequences of the subsurface system thermal inertia; one must know for example what the optimal distance between the buildings is to optimize the energy used. This is again location specific, dependent on the dimensions, required functionalities and capabilities of the buildings.

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[27] As opposed to normal heating, since heat exchangers are more efficient.

5.3 Recommendations

Based on the findings in part II and III several recommendations can be made for future steps in the research area of underground construction. It is clear that underground construction can contribute to energy savings in the construction sector. In order to determine the savings potential it is recommended to investigate the market size (number of buildings) that benefit from bringing (parts of it) underground as well as to determine the volume of underground space suitable for construction. This in turn can be used as a basis for the market potential for potential energy savings. This study has led to the calculation of relative energy savings from underground construction for a strongly simplified representation of a building both above –and underground. The focus was on the relevant mechanisms at play. To determine the potential energy savings for an actual building the heat transfer model should be extended[28] to achieve a higher accuracy for the energy savings potential. The model should then be validated against a real life underground building whose energy losses are measured for calibration and validation of the simulation model. This can then lead to an estimate of the total energy savings of the previously determined market size. This can be summarized as follows:

- The proportion of underground construction possible in the Netherlands must be investigated in terms of numbers of buildings or volume of suitable underground space.
- This should then be combined with an extended heat transfer model to achieve a higher accuracy for the energy savings potential calculations. This model should be validated against a real life underground building whose energy losses are measured.
- If this proves to be promising, a next step can be taken to include potential energy savings from underground construction at a system level; meaning that the potential of buildings with different indoor temperature requirements brought underground should be assessed.
- Next to this, sound analyses should be made which include other important factors concerning subsurface construction, such as costs (initial investment and maintenance) and total use of resources[29]. This should lead to an assessment framework which incorporates technical, environmental and socio-economical factors, to make an informed decision on either underground or aboveground construction (or a combination of both).
- Then, policy-makers should create a policy framework which supports and regulates underground construction on a long term basis. This should be done in congruence with aboveground regulations. The effects of the new policy should be monitored, by for example the Economic Institute for Buildings, in order to get insight in the development and size of the underground construction market.

Knowing the difficulties for both the under –and aboveground buildings with regard to policy and potential energy savings, a combination of both aboveground and underground spatial planning could be a step forward to reduce energy and CO_2 emissions. In contrast to aboveground buildings, specific legislation for sustainable (in terms of energy efficiency and resource-efficiency) underground construction is lacking. There are clear opportunities, but also threats that require a framework to arrive at a more sustainable built environment.

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[28] With at least with groundwater flows, ventilation effects and various soil types.

[29] And the CO_2 emissions inherent to it.

6. Conclusion

The potential energy savings of underground buildings was subject of this study. The research aimed to provide general and indicative statements on the energy savings potential. By performing calculations in a finite element model and Excel the heat transferred from aboveground and underground buildings to their surroundings was compared for typical building and location factors in the Western part of the Netherlands. Based on a comparative analysis on the energy losses in five years, the energy savings potential was derived.

Underground buildings have the potential to reduce the heat transfer from the building and thus have the potential to reduce energy demand as compared to aboveground buildings. This potential can only be achieved under certain conditions. The implications for subsurface construction in the Netherlands are based on temperature requirements, building materials used and the depth at which the structure is situated. Buildings with an indoor temperature requirement of around 10°C are most favourable to build underground. In this way the stable soil temperature is benefited from the most. Aboveground buildings with the same function are exposed to fluctuating air temperatures throughout the year and therefore require more energy in order to maintain the indoor temperature set. The practical potential to build these types of buildings underground might be limited, since the vast majority of buildings require a comfortable temperature to live in. This indicates that buildings with other indoor temperature requirements might beneficially be brought underground in other parts of the world. The materials of the building envelope for both aboveground as underground buildings are of importance for the energy savings potential. Concrete underground buildings always result in higher energy savings then when steel sheet pile retaining walls are used. Adding underground isolation, which is currently not common practice, results in a significant higher energy savings potential especially when the indoor temperature lies further from the soil temperature. This can increase the practical potential of underground building, since spaces at living room temperature becoming interesting to bring underground now as well. The increasing energy efficiency measures for aboveground construction materials reduce the potential energy savings when comparing aboveground with the underground. Buildings built deeper than 15 meters underground experience no influence from the aboveground temperature fluctuations and achieve therefore higher energy savings potentials. These results are an indication for the potential energy savings achievable and give insight in what kind of conditions maximal energy savings potential can be reached and which situations are less favourable. Many assumptions had to be made to come to these first results. For every specific location, additional research is needed to determine the actual energy savings potential.

Not only energy can be an incentive when deciding to build underground. Population growth and urbanization create pressures on the aboveground land. Building underground could alleviate this effect. However, currently no regulations exist for (large scale) underground construction. By regulating and stimulating for example system scale underground building projects, energy can potentially be saved and negative impacts on the soil can be avoided. Next to this, many other factors come in play when considering underground construction. Life cycle costing analysis can provide important insights in order to make deliberate considerations on aboveground and underground construction, or a combination of both. More research is in addition needed to analyse the effects of buildings interacting underground; heat exchangers could lead to additional benefits. In turn, this could be an anticipation strategy for the continuous population growth, the increasing wealth and to reduce urban population pressures on land use and can in this way increase the quality of city life in a sustainable manner.

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Appendix A – Impact of groundwater flow on heat transfer

An important feature one encounters when constructing underground is groundwater flow. Since this is a complex phenomenon, models are developed specially for this purpose. It is therefore important to consider whether the groundwater flow matters in for the system described. It can be said that the energy required to heat up volume of water displaced in a day is the extra energy needed as compared to a stationary situation (without groundwater flow). In the model, the building is 10*10 meter, assuming a water volume of that size (neglecting the somewhat bigger sphere in which energy transfer takes place) the relative water displacement can be calculated.

Groundwater flow is in the Netherlands quite low, at some places only 1 meter per year, while in more sandy locations this can increase to 10 meter per year[30]. Figure 26 shows how the displacement of water volume is projected. It must be said that in reality the water will flow around the obstacle, the building, this means that the water travels along a longer path and thus is longer in contact with the (heated) building. Therefore this 'back of the envelope' calculation is on the conservative side.

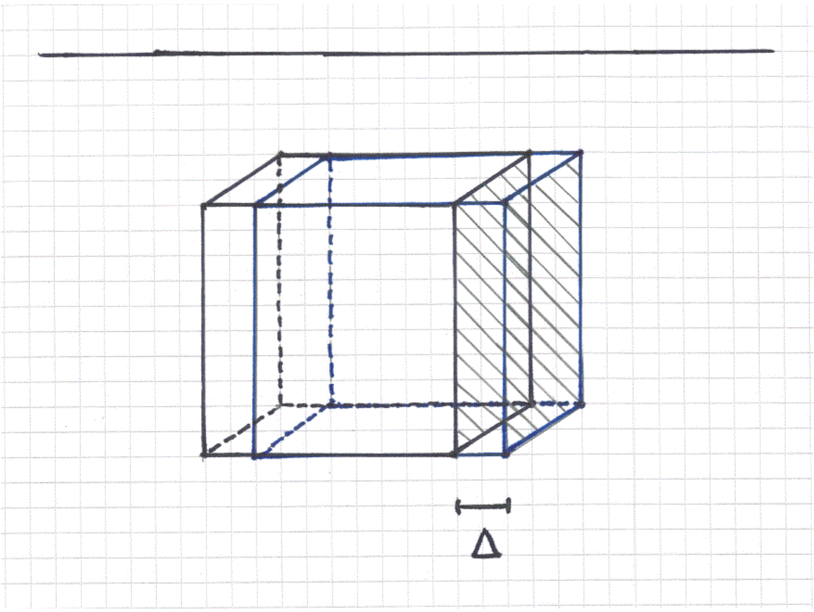

Figure 26, visualisation of the method used to make a 'back of the envelope' calculation for groundwater flow.

Table 21 shows the relative water displacement per day and in addition gives insight in the amount of energy needed to heat the replaced water.

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[30] G.Oude Essink, personal communication June 13th, 2013.

Table 21, relative importance groundwater flow for the model.

Volume		
Length building [m]	10	10
Flow rate [m/yr]	1	10
Displacement [m/day]	0.00274	0.0274
Porosity[31]	0.45	0.45
Frontal area*porosity [m^2]	45	45
Volume displaced [m^3/day]	0.1232	1.232
Relative water displacement [%]	0.0027	0.027
Heat		
ρ_{water} [kg/ m^3]	1000	1000
M [kg]	123.3	1232.4
c_{water} [kJ/kg•K]	4.18	4.18
T_{water} [K]	283	284
T_{indoor} [K]	291	293
ΔT [K]	8	282
Q[32] [MJ]	4.12	41.2
[kWh]	1.14[33]	11.44

In this example an indoor temperature of 20 °C is used, though in the model this is altered between 4 and 18 °C. Selecting these temperatures result in lower temperature differences and is thus not in conflict.

To put this in perspective, the heat needed to heat up the water again is weighted against the energy use of a building. In the Netherlands, an average dwelling consumes 34 GJ of district heating per year[34], which results in about 26 kWh per day. Though this heat is used for both space heating and warm water, the space heating is far more dominant than warm water usage. So, the actual energy use for space heating is somewhat lower than 26 GJ, and thus the relative energy used to heat up the displaced water volume might be somewhat bigger. On the other hand, the dimensions of a typical Dutch dwelling in the case of a 1m/yr flow rate, the energy needed compared to district heating is 1.14% and in the case of a flow rate of 10m/yr this is 11.4%. The relative water volume displaced is low for low ground water flows and thus justifies the fact that the groundwater flow can be neglected at these locations and to consider the soil as a static entity. However, when translating this to the energy consumed, the 10 m/yr flow rate does have a considerable impact. Therefore, care should be taken when heat loss calculations are made for underground constructions in sandy regions and regions with high overall groundwater flow.

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[31] G. de Lange, personal communication June13th, 2013.

[32] Q = m*c*ΔT

[33] *"Porosity refers to that part of a soil volume that is not occupied by soil particles or organic matter."* (http://ecorestoration.montana.edu/mineland/guide/analytical/physical/porosity.htm)(in this case it is occupied with water, but air or other gasses can also be present)

[34] From (http://www.milieucentraal.nl/themas/energie-besparen/gemiddeld-energiegebruik-in-huis)

Appendix B – Ventilation effect on potential energy savings

Ventilation

In this research ventilation is not yet taken into account. However, ventilation does have an influence on the room temperature and therefore the heat loss of the building. A building can be naturally ventilated or mechanically. The type of ventilation system strongly influences the energy use (Sherman & Nance, 1997). So do the occupation density (El Mankibi, 2007) and the function of the building. Car parks need a higher ventilation rate to dilute the vehicle emissions. Since this research focusses on the differences between above -and below ground, it is important to consider the influence of ventilation rates. For an aboveground residential building, a ventilation rate of once an hour might suffice. Though, offices might be ventilated more times within an hour. For underground car parks several studies are available. From these can be ascertained that the ventilation rate varies strongly. It ranges from once every two hours to 13 times an hour[35]. There is a lack of scientific data on ventilation rates for other types of underground buildings.

Next to this, it is important to realize that ventilation is often combined with the heating and cooling installation of the building and it is therefore difficult to determine what amount of energy is purely used for ventilation (and which part of the total energy consumption can be assigned to indoor-outdoor temperature differences). For these reasons additional research must be carried out to determine the effect on energy consumption and heat losses due to the ventilation of underground (and aboveground) buildings. In general it can be assumed that underground buildings need more mechanical ventilation than aboveground buildings, though this might not be the case for buildings in which the indoor climate is already strongly regulated in the aboveground situation. Therefore, the results must be interpreted with care in the sense that it are only general results and each specific building must be analysed separately.[36]

One way to get a feeling of the impact of ventilation is to use a simple formula from Blok (2009).

$$Q_v = c_p * N * V * \rho * DD * \frac{24h}{day} \qquad \text{Formula [8]}$$

Where:

Q_v = annual heat loss from ventilation [kJ]
c_p = specific heat of air [kJ/kg•K]
N = ventilation rate [h^{-1}]
V = air volume inside the building [m^3]
ρ = specific mass of air [kg/m^3]
DD = number of degree days

From a modelling perspective, this can be perceived as refreshing the whole volume of air, with the same volume of air from outside which thus has the outside temperature. Of course, in real life cases heat exchangers will be put in place to handle ventilation as efficient as possible, so this estimate is conservative. The heat loss through transmission is calculated per square meter, therefore the research unit for ventilation will be cubic meter, since it handles volumes. In this way, the answers (in MJ) can be added (if desired).

The concrete simulation at 18°C will be used as illustration of the ventilation effect. The following values are used in the equation (Table 22).

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[35] Taken from Yaziz & Yen (1989), Chow (1995), Chan et al. (1998) and Chan & Chow (2004).

[36] This not only applies for ventilation, but soil characteristics and aboveground temperature as well.

Table 22, ventilation effect.

	Aboveground	Underground
c_p [kJ]	1	1
N [h^{-1}]	1	3, 5 or 10
V [m^3]	1	1
ρ [kg/m^3]	1,2	1,2
DD	2909	2909
Q_v [kJ]	3490,8	10472,4
Q_v [MJ]	3,4908	10,4724

Q_v was then added to the aboveground and underground heat losses and the same energy savings potential calculations were performed. Here, only the results after five years are shown, all results can be found below. As can be deduced from Table 22, it was assumed that the ventilation rate for underground buildings is three, five or ten times higher then for the aboveground building. This resulted in the following cumulative energy savings for different ventilation rates (Table 23).

Table 23, cumulative potential energy savings for different ventilation rates (N=3, 5 and 10).

Compared to a:	savings year 5 with ventilation rate of 3 times per hour [%]	savings year 5 with ventilation rate of 5 times per hour [%]	savings year 5 with ventilation rate of 10 times per hour [%]
Typical wall	23.5	22.0	18.2
2013 wall	14.2	12.5	8.3
2015 wall	-19.2	21.5	-27.4

From this can be seen that the addition of ventilation, albeit in a simple manner, still indicates potential energy savings of the same order.

All tables:

Ventilation rate of 3 times per hour.

Table 24, annual energy loss through ventilation (N=3).

	aboveground	underground
Cp [kJ]	1	1
N [h^{-1}]	1	3
V [m^3]	1	1
Rho [kg/m^3]	1,2	1,2
DD	2909	2909
Qv [kJ]	3490,8	10472,4
Qv [MJ]	3,4908	10,4724

Table 25, underground energy losses including ventilation (N=3).

time [d]	Q [MJ/m^2]
365	125,0
730	194,4
1095	252,2
1460	304,0
1825	352,8

Table 26, total potential energy savings (N=3).

Compared to a:	Total savings year 1 [%]	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	-35.5	-5.4	8.9	17.6	23.5
2013 wall	-51-9	-18.1	-2.2	7.6	14.2
2015 wall	-111.1	-64.2	-42.0	-28.4	-19.2

Ventilation rate of 5 times per hour.

Table 27, annual energy loss through ventilation (N=5).

	aboveground	underground
C_p [kJ]	1	1
N [h^{-1}]	1	5
V [m^3]	1	1
Rho [kg/m^3]	1,2	1,2
DD	2909	2909
Q_v [kJ]	3490,8	10472,4
Q_v [MJ]	3,4908	10,4724

Table 28, underground energy losses including ventilation (N=5).

time [d]	Q [MJ/m^2]
365	132,0
730	201,4
1095	259,2
1460	311,0
1825	359,8

Table 29, total potential energy savings (N=5).

Compared to a:	Total savings year 1 [%]	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	-43.0	-9.1	6.4	15.7	22.0
2013 wall	-60.4	-22.4	-5.0	5.4	12.5
2015 wall	-122.9	-70.1	-45.9	-31.3	-21.5

Ventilation rate of 10 times per hour.

Table 30, annual energy loss through ventilation (N=10).

	aboveground	**underground**
C_p [kJ]	1	1
N [h^{-1}]	1	10
V [m^3]	1	1
Rho [kg/m^3]	1,2	1,2
DD	2909	2909
Q_v [kJ]	3490,8	10472,4
Q_v [MJ]	3,4908	10,4724

Table 31, underground energy losses including ventilation (N=10).

time [d]	**Q [MJ/m^2]**
365	149.4
730	218.8
1095	276.6
1460	328.5
1825	377.3

Table 32, total potential energy savings (N=10).

Compared to a:	Total savings year 1 [%]	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	-62.0	-18.6	0.06	11.0	18.2
2013 wall	-81.6	-33.0	-12.1	0.17	8.3
2015 wall	-152.4	-84.8	-55.7	-38.7	-27.4

Appendix C - Temperature sine

The aboveground temperature fluctuates throughout the year and takes the form of sine function. The general temperature sine function can be described as in formula 7.

$$T = T_g + a\sin(b(t - t_0)) \qquad \text{Formula [7]}$$

Where:
T = temperature in days from January first [K]
T_g = average year temperature
a = amplitude
b = period (2π/365.25, a period of one year)
t_0 = time at which the curve bends up.
(van de Moortel, 2007)

For the research, weather data from the KMNI are used. The long-term average temperature (1981-2010) was used to construct the sine function. This resulted in the following parameter (Table 33)

Table 33, data for temperature sine function based on weather station the Bilt (KNMI, 2011)

Parameter	Value
T_g	10.1
a	8.1
b	0.0172
t_0	106

To put this function in Comsol, it had to be rewritten to Kelvin and the time unit must omitted from the equation since Comsol only recognizes Kelvin as unit for a temperature. All in all, the final function used was:
T = 283.25+8.1*sin((t/3600/24106)/1[s]*0.017202424)283.25+8.1*sin((t/3600/24-106)/1[s]*0.017202424)

Appendix D – Potential energy savings

The cumulative potential energy savings graphs presented in the potential energy savings chapter are based on the tables presented in this appendix. For each assessed case (e.g. concrete, concrete with insulation etc.) the three temperatures (18,11 and 4°C) are presented. Each temperature comes with three tables. The first table (e.g. Table 34) provides the actual total energy losses (derived from the heat flux) at the end of each year. The second table (e.g. Table 35) provides extra information on the yearly savings potential, but is not presented in any graph. By deducting the energy losses at the end of the first year from the energy losses from the end of the second year, the energy lost in year two can be calculated. Negative savings imply that additional heat is needed in the underground situation as compared to the aboveground case.

The second table is actually used for the graphs in the potential energy savings chapter. Here, the cumulative potential energy savings are calculated. The values from the first table are compared against the energy losses in the aboveground situation, multiplied with the specific year of interest (as explained in box 2). This is done for all three temperatures and compared against the three aboveground wall profiles.

Concrete

Table 34, underground energy losses concrete building.

	T_{indoor} 18°C	T_{indoor} 11°C	T_{indoor} 4°C
time [d]	**Q [MJ/m^2]**	**Q [MJ/ m^2]**	**Q [MJ/ m^2]**
365	114.5	11.5	68.8
730	183.9	18.4	110.5
1095	241.7	24.2	145.2
1460	293.6	29.4	176.3
1825	342.3	34.3	205.6

Table 35, yearly potential energy savings at indoor temperature of 11°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	80.4	88.1	90.1	91.1	91.7
2013 wall	77.9	86.7	88.9	90.0	90.6
2015 wall	68.8	81.1	84.3	85.9	86.7

Table 36, total potential energy savings at indoor temperature of 11°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	84.3	86.3	87.5	88.3
2013 wall	82.3	84.5	85.9	86.8
2015 wall	75.0	78.1	80.0	81.4

Belonging to Figure 15

Table 37, yearly potential energy savings at indoor temperature of 4°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	18.1	50.4	58.7	62.9	65.2
2013 wall	7.6	44.1	53.5	58.2	60.8
2015 wall	-30.6	21.0	34.2	40.9	44.5

Table 38, total potential energy savings at indoor temperature of 4°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	34.2	42.4	47.5	51.1
2013 wall	25.9	35.1	40.9	44.8
2015 wall	-4.8	8.2	16.4	22.0

Belonging to Figure 15

Steel

Table 39, underground energy losses.

	T_{indoor} 18°C	T_{indoor} 11°C	T_{indoor} 4°C
time [d]	**Q [MJ/m^2]**	**Q [MJ/ m^2]**	**Q [MJ/ m^2]**
365	249.6	31.2	187.0
730	396.9	49.6	297.3
1095	520.0	65.0	389.7
1460	630.9	78.9	473.0
1825	735.3	91.9	551.0

Table 40, yearly potential energy savings at indoor temperature of 18°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	-181.2	-65.9	-38.8	-24.9	-17.7
2013 wall	-216.9	-86.9	-56.4	-40.7	-32.6
2015 wall	-348.0	-164.3	-121.1	-99.0	-87.5

Table 41, total potential energy savings at indoor temperature of 18°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	-123.5	-95.3	-77.7	-65.7
2013 wall	-151.9	-120.1	-100.2	-86.7
2015 wall	-256.2	-211.2	-183.1	-164.0

Not presented in any graph by itself, but contributes to the outcomes of the retaining walls

Table 42, yearly potential energy savings at indoor temperature of 11°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	46.8	68.6	73.7	76.4	77.7
2013 wall	40.0	64.7	70.4	73.4	74.9
2015 wall	15.2	50.0	58.2	62.4	64.5

Table 43, total potential energy savings at indoor temperature of 11°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	57.7	73.7	66.3	68.7
2013 wall	37.5	70.4	62.1	64.7
2015 wall	-7.1	58.2	46.4	50.1

Table 44, yearly potential energy savings at indoor temperature of 4°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	-122.6	-31.4	-10.0	0.8	7.2
2013 wall	-150.8	-48.2	-23.9	-11.8	-4.6
2015 wall	-254.6	-109.4	-75.2	-58.0	-47.8

Table 45, total potential energy savings at indoor temperature of 4°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	-77.0	-54.6	-40.8	-31.2
2013 wall	-99.4	-74.3	-58.6	-47.8
2015 wall	-182.0	-146.4	-124.3	-109.0

Not presented in any graph by itself, but contributes to the outcomes of the retaining walls

Retaining walls

Table 46, underground energy losses.

	T_{indoor} 18°C	T_{indoor} 11°C	T_{indoor} 4°C
time [d]	**Q [MJ/m^2]**	**Q [MJ/ m^2]**	**Q [MJ/ m^2]**
365	182.0	21.3	127.9
730	290.4	34.0	203.9
1095	380.9	44.6	267.4
1460	462.2	54.1	324.7
1825	538.8	63.1	378.3

Table 47, yearly potential energy savings at indoor temperature of 18°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	-105.1	-22.0	-1.9	8.3	13.6
2013 wall	-131.1	-37.5	-14.9	-3.2	2.7
2015 wall	-226.8	-94.5	-62.4	-46.0	-37.5

Table 48, total potential energy savings at indoor temperature of 18°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	-63.6	-43.0	-30.2	-21.4
2013 wall	-84.3	-61.2	-46.7	-36.8
2015 wall	-160.6	-127.9	-107.4	-93.4

Table 49, yearly potential energy savings at indoor temperature of 11°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	63.6	78.3	81.9	83.8	84.7
2013 wall	59.0	75.7	79.7	81.7	82.8
2015 wall	42.0	65.6	71.2	74.1	75.6

Table 50, total potential energy savings at indoor temperature of 11°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	71.0	74.7	76.9	78.5
2013 wall	67.3	71.4	74.0	75.8
2015 wall	53.8	59.6	63.2	65.7

Belonging to
Figure 16

Table 51, yearly potential energy savings at indoor temperature of 4°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	-52.3	9.5	24.4	31.9	36.2
2013 wall	-71.6	-2.0	14.8	23.2	28.1
2015 wall	-142.6	-44.2	-20.5	-8.5	-1.7

Table 52, total potential energy savings at indoor temperature of 4°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	-21.4	24.4	31.9	36.2
2013 wall	-36.8	14.8	23.2	28.1
2015 wall	-93.4	-20.5	-8.5	-1.7

Belonging to Figure 16

Concrete underground structure with insulation

	T_{indoor} 18°C	T_{indoor} 11°C	T_{indoor} 4°C
time [d]	**Q [MJ/m^2]**	**Q [MJ/ m^2]**	**Q [MJ/ m^2]**
365	52.2	6.5	39.1
730	85.6	10.7	64.2
1095	116.3	14.5	87.2
1460	145.3	18.1	109.0
1825	173.4	21.7	130.0

Table 53, yearly potential energy savings at indoor temperature of 18°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	41.2	62.4	65.4	67.3	68.3
2013 wall	33.8	57.6	61.0	63.2	64.3
2015 wall	6.3	40.0	44.8	48.0	49.5

Table 54, total potential energy savings at indoor temperature of 18°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	51.8	56.3	59.1	60.9
2013 wall	45.7	50.8	53.9	56.0
2015 wall	23.2	30.4	34.8	37.7

Table 55, yearly potential energy savings at indoor temperature of 11°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	88.9	92.9	93.4	93.8	92.6
2013 wall	87.5	92.0	92.6	93.0	91.7
2015 wall	82.3	88.6	89.6	90.2	88.2

Table 56, total potential energy savings at indoor temperature of 11°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	90.9	91.7	92.3	92.6
2013 wall	89.7	90.7	91.3	91.7
2015 wall	85.5	86.8	87.7	88.2

Belonging to
Figure 17

Table 57, yearly potential energy savings at indoor temperature of 4°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	53.4	70.2	72.6	74.1	74.8
2013 wall	47.5	66.4	69.1	70.8	71.7
2015 wall	25.8	52.5	56.3	58.7	60.0

Table 58, total potential energy savings at indoor temperature of 4°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	61.8	65.4	67.6	69.0
2013 wall	56.9	61.0	63.4	65.1
2015 wall	39.1	44.8	48.3	50.6

Belonging to
Figure 17

Steel with insulation

Table 59, underground energy losses.

	T_{indoor} 18°C	T_{indoor} 11°C	T_{indoor} 4°C
time [d]	**Q [MJ/m^2]**	**Q [MJ/ m^2]**	**Q [MJ/ m^2]**
365	99.5	12.4	74.6
730	192.6	24.1	144.4
1095	279.4	34.9	209.5
1460	361.0	45.1	270.8
1825	439.9	55.0	330.0

Table 60, yearly potential energy savings at indoor temperature of 18°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	-12.1	-4.9	2.2	8.0	11.1
2013 wall	-26.3	-18.2	-10.2	-3.6	-0.2
2015 wall	-78.6	-67.1	-55.8	-46.5	-41.7

Table 61, total potential energy savings at indoor temperature of 18°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	-8.4	-4.9	-1.7	0.9
2013 wall	-22.2	-18.2	-14.6	-11.7
2015 wall	-72.8	-67.1	-62.0	-57.9

Not presented in
any graph by itself,
but contributes to
the outcomes of
the retaining walls
with insulation

Table 62, yearly potential energy savings at indoor temperature of 11°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	78.8	80.2	81.5	82.6	83.2
2013 wall	76.1	77.6	79.2	80.4	81.0
2015 wall	66.2	68.4	70.5	72.3	73.2

Table 63, total potential energy savings at indoor temperature of 11°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	79.5	80.2	80.8	81.2
2013 wall	76.9	77.6	78.3	78.9
2015 wall	67.3	68.4	69.3	70.1

Table 64, yearly potential energy savings at indoor temperature of 4°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	11.2	16.9	22.5	27.1	29.5
2013 wall	-0.04	6.3	12.7	17.8	20.5
2015 wall	-41.4	-32.4	-23.5	-16.2	-12.3

Table 65, total potential energy savings at indoor temperature of 4°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	14.0	16.9	19.4	21.4
2013 wall	3.1	6.3	9.2	11.4
2015 wall	-36.9	-32.4	-28.4	-25.2

Not presented in any graph by itself, but contributes to the outcomes of the retaining walls with insulation

Retaining wall with insulation

Table 66, Underground energy losses.

	T_{indoor} 18°C	T_{indoor} 11°C	T_{indoor} 4°C
time [d]	**Q [MJ/m^2]**	**Q [MJ/ m^2]**	**Q [MJ/ m^2]**
365	75.8	9.5	56.9
730	139.1	17.4	104.3
1095	197.8	24.7	148.4
1460	253.2	31.6	189.9
1825	306.7	38.3	230.0

Table 67, yearly potential energy savings at indoor temperature of 18°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	14.6	28.8	33.8	37.7	39.7
2013 wall	3.7	19.7	25.4	29.8	32.1
2015 wall	-36.1	-13.5	-5.5	0.71	3.9

Table 68, total potential energy savings at indoor temperature of 18°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	21.7	25.7	28.7	30.9
2013 wall	11.7	16.3	19.6	22.1
2015 wall	-24.8	-18.4	-13.6	-10.1

Table 69, yearly potential energy savings at indoor temperature of 11°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	83.8	86.5	87.5	88.2	88.6
2013 wall	81.8	84.8	85.9	86.7	87.1
2015 wall	74.3	78.5	80.0	81.2	81.8

Table 70, total potential energy savings at indoor temperature of 11°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	85.2	85.9	86.5	86.9
2013 wall	83.3	84.2	84.8	85.3
2015 wall	76.4	77.6	78.5	79.2

Belonging to Figure 18

Table 71, yearly potential energy savings at indoor temperature of 4°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	32.3	43.5	47.5	50.6	52.2
2013 wall	23.7	36.4	40.8	44.3	46.1
2015 wall	-7.8	10.0	16.4	21.3	23.8

Table 72, total potential energy savings at indoor temperature of 4°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	37.9	41.1	43.5	45.2
2013 wall	30.0	33.7	36.3	38.3
2015 wall	1.09	6.2	10.0	12.7

Belonging to
Figure 18

Concrete with aboveground temperature sine (shallow subsurface)

Table 73, underground energy losses.

	T_{indoor} 18°C	T_{indoor} 11°C	T_{indoor} 4°C
time [d]	**Q [MJ/m^2]**	**Q [MJ/ m^2]**	**Q [MJ/ m^2]**
365	103.3	17.2	70.6
730	178.4	31.7	126.6
1095	250.6	47.0	182.1
1460	322.2	62.2	237.3
1825	394.5	77.7	292.8

Table 74, yearly potential energy savings at indoor temperature of 18°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	-16.3	15.4	18.7	19.3	18.6
2013 wall	-31.1	4.6	8.4	9.0	8.3
2015 wall	-85.3	-34.8	-29.6	-28.6	-29.7

Table 75, total potential energy savings at indoor temperature of 18°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	-0.5	5.9	9.3	11.1
2013 wall	-13.2	-6.03	-2.3	-0.16
2015 wall	-60.1	-49.9	-44.6	-41.6

Table 76, yearly potential energy savings at indoor temperature of 11°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	70.8	75.25	73.8	74.0	73.7
2013 wall	67.0	72.1	70.4	70.8	70.3
2015 wall	53.4	60.6	58.3	58.6	59.1

Table 77, total potential energy savings at indoor temperature of 11°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	73.0	73.3	73.5	73.5
2013 wall	69.6	69.9	70.1	70.2
2015 wall	57.0	57.4	57.8	57.8

Belonging to
Figure 19

Table 78, yearly potential energy savings at indoor temperature of 4°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	16.0	33.4	33.8	34.2	33.9
2013 wall	5.3	24.9	25.5	25.9	25.5
2015 wall	-33.9	-6.1	-5.4	-4.8	-5.2

Table 79, total potential energy savings at indoor temperature of 4°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	24.7	27.7	29.4	30.2
2013 wall	15.1	18.6	20.4	21.4
2015 wall	-20.0	-15.1	-12.5	-11.1

Belonging to
Figure 19

Concrete with insulation and aboveground temperature sine

Table 80, underground energy losses.

	T_{indoor} 18°C	T_{indoor} 11°C	T_{indoor} 4°C
time [d]	**Q [MJ/m^2]**	**Q [MJ/ m^2]**	**Q [MJ/ m^2]**
365	53.8	6.7	40.3
730	92.8	11.6	69.6
1095	131.5	16.4	98.6
1460	170.1	21.2	127.5
1825	208.9	26.1	156.7

Table 81, yearly potential energy savings at indoor temperature of 18°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	39.4	56.0	56.4	56.5	56.2
2013 wall	31.7	50.5	50.9	51.0	50.7
2015 wall	3.5	29.9	30.6	30.7	30.3

Table 82, total potential energy savings at indoor temperature of 18°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	47.7	50.6	52.1	52.9
2013 wall	41.1	44.3	46.0	47.0
2015 wall	16.7	21.3	23.7	25.0

Belonging to
Figure 20

Table 83, yearly potential energy savings at indoor temperature of 11°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	88.6	91.7	91.8	90.9	91.7
2013 wall	87.1	90.6	90.7	89.8	90.7
2015 wall	81.8	86.8	86.9	85.6	86.8

Table 84, total potential energy savings at indoor temperature of 11°C.

Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	90.1	90.7	90.9	91.1
2013 wall	88.9	89.5	89.8	90.0
2015 wall	84.3	85.1	85.6	85.8

Table 85, yearly potential energy savings at indoor temperature of 4°C.

Compared to a:	savings year 1 [%]	savings year 2 [%]	savings year 3 [%]	savings year 4 [%]	savings year 5 [%]
Typical wall	52.0	65.2	65.5	65.6	65.3
2013 wall	45.9	60.7	61.1	61.1	60.9
2015 wall	23.5	44.5	45.0	45.1	44.7

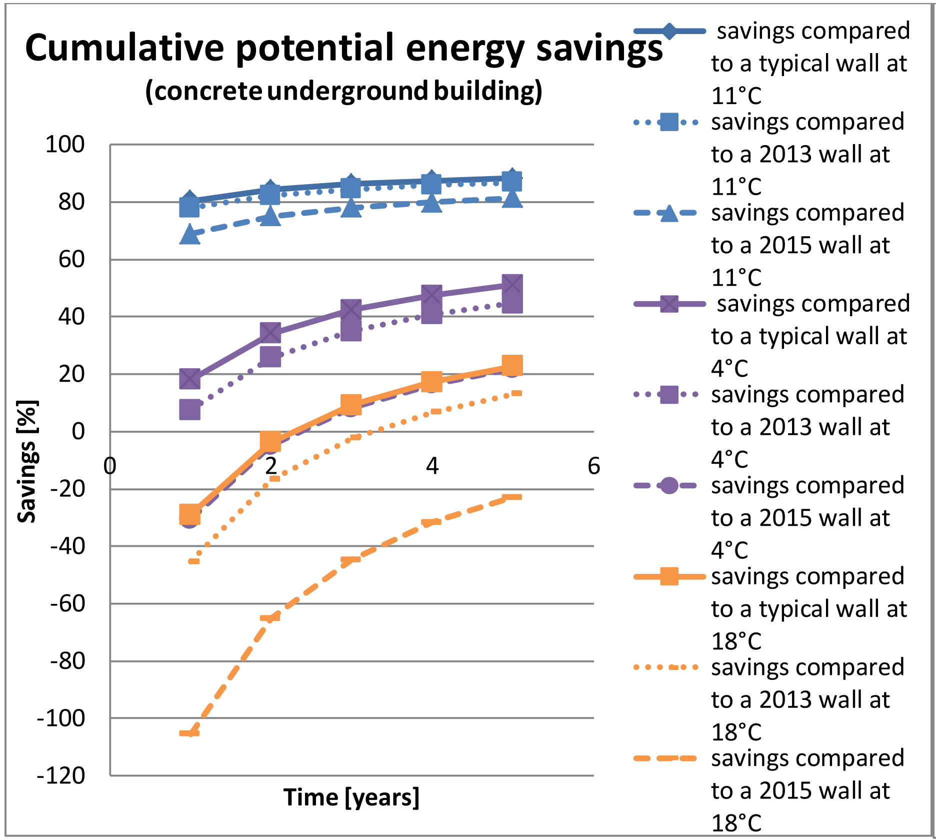
Table 86, total potential energy savings at indoor temperature of 4°C.

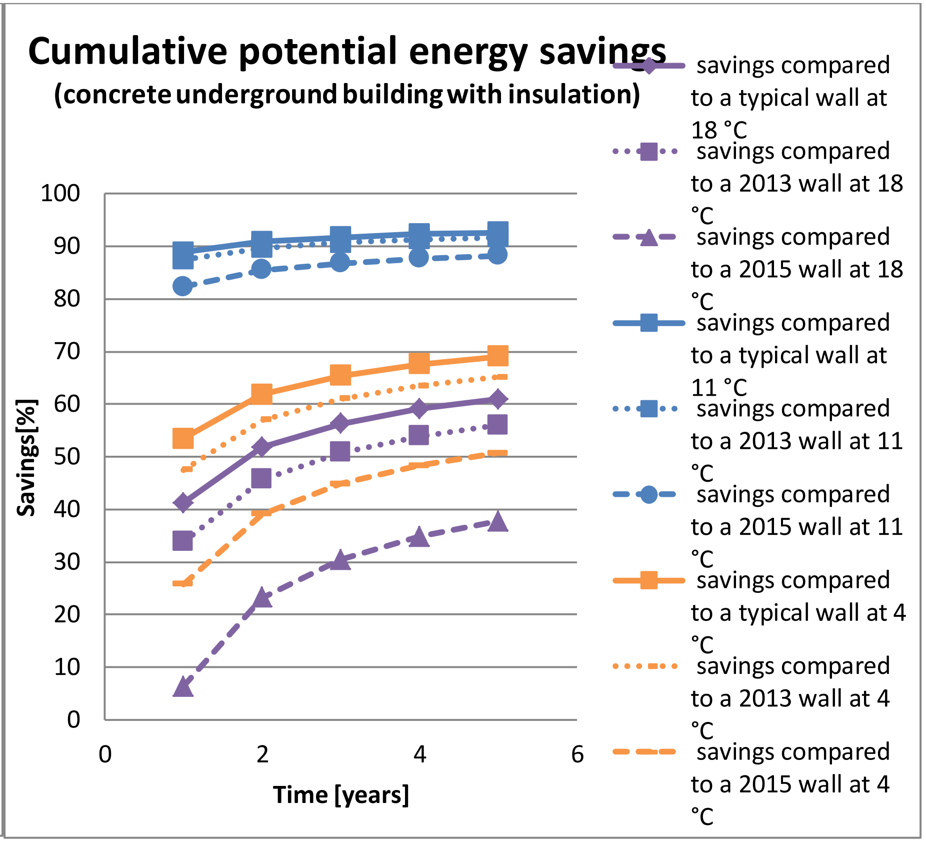
Compared to a:	Total savings year 2 [%]	Total savings year 3 [%]	Total savings year 4 [%]	Total savings year 5 [%]
Typical wall	58.6	60.9	62.0	62.7
2013 wall	53.3	55.9	57.2	58.0
2015 wall	34.0	37.7	39.5	40.6

Belonging to
Figure 20

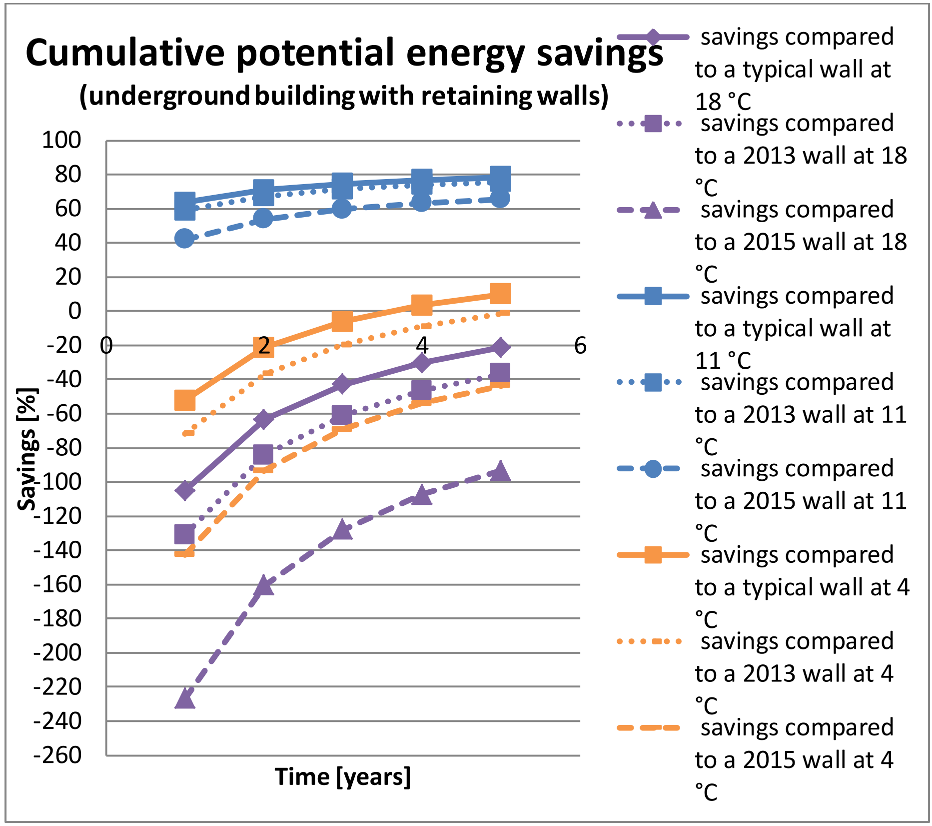
Appendix E - Cumulative potential energy savings (graphs for comparison)

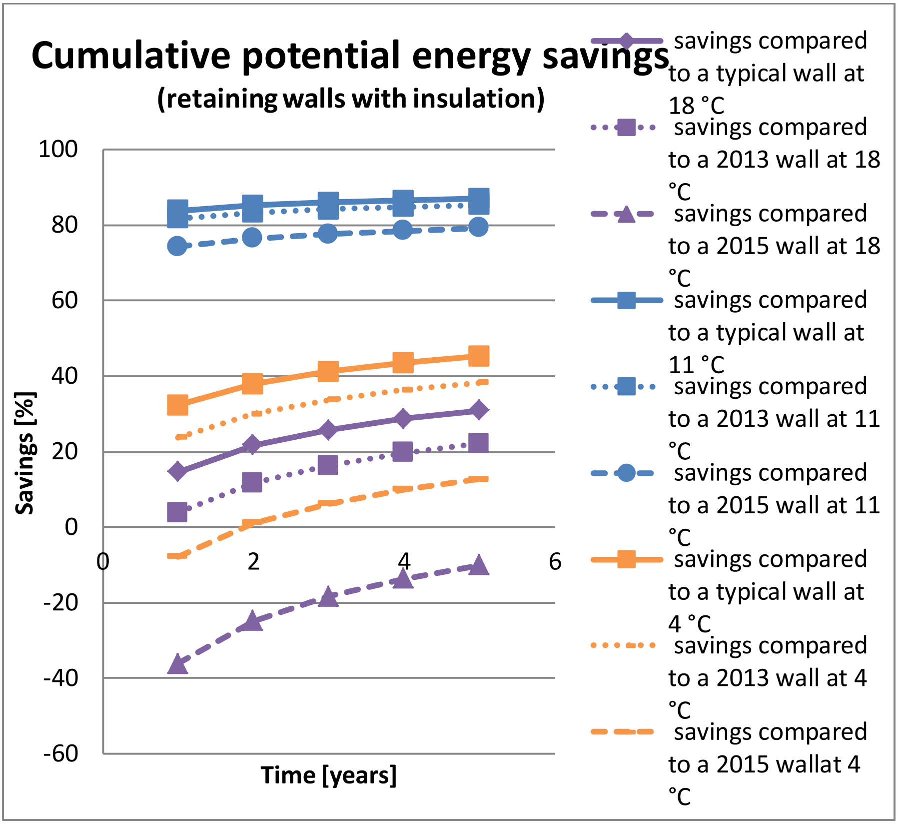
Concrete vs. concrete with insulation



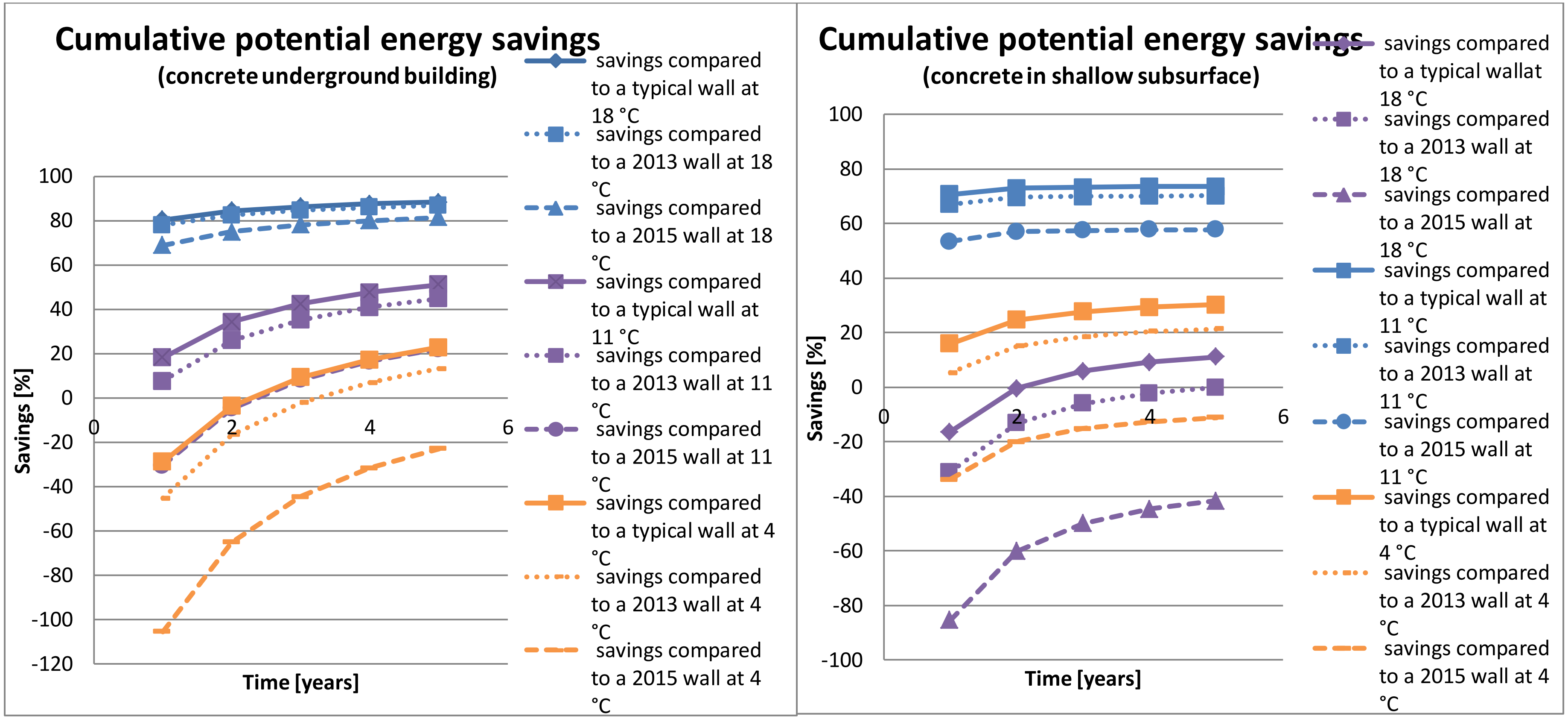


Retaining wall vs. retaining wall with insulation

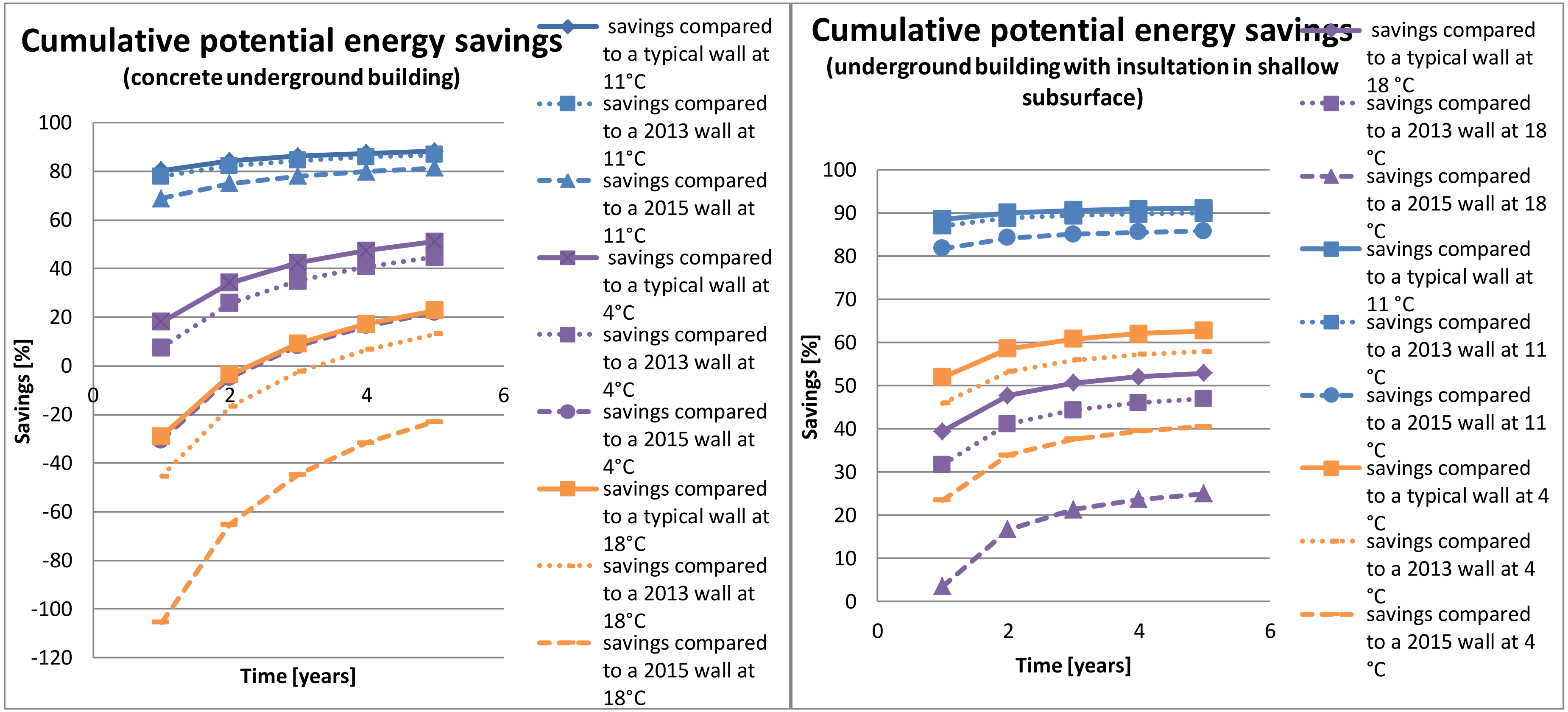




Concrete vs. concrete with seasonal temperature influence



Concrete vs. concrete with seasonal temperature influence and insulation



Difficulties mastered are opportunities won.

W.L.S. Churchill