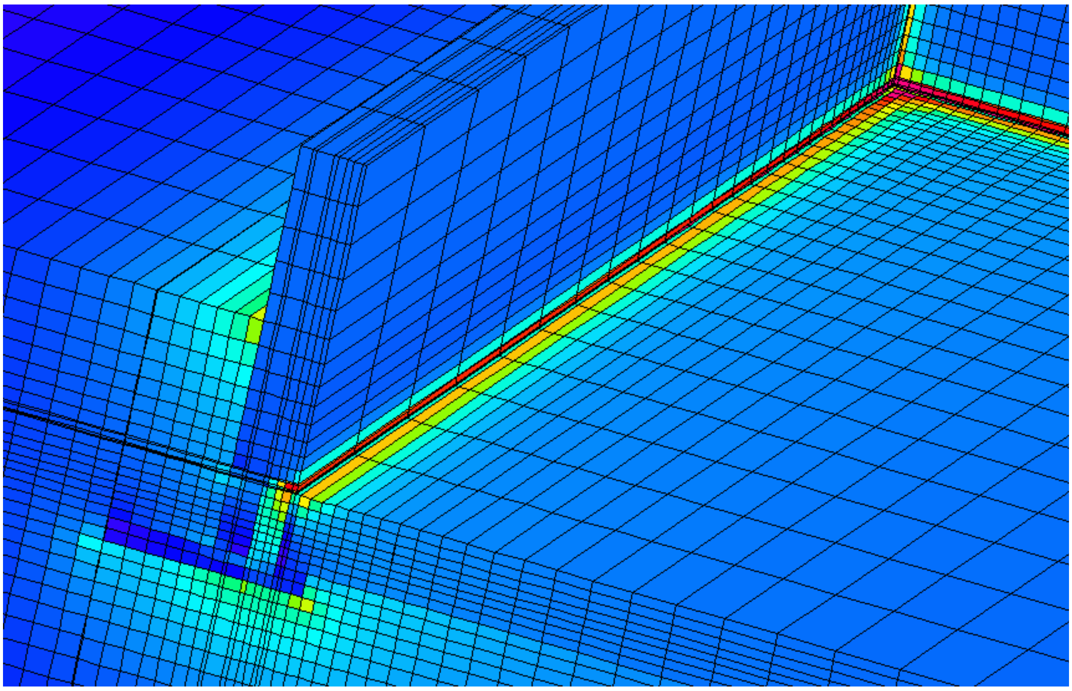

Thermal bridges at foundations

Evaluation of heat calculation methods

Master's Thesis in the Master's Programme Structural Engineering and Building Performance Design

HANNES NYBERG

Department of Civil and Environmental Engineering
Division of Building Technology
Building Physics
CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2011
Master's Thesis 2011:146

MASTER’S THESIS 2011:146

Thermal bridges at foundations

Evaluation of heat calculation methods

Master’s Thesis in the Master’s Programme Structural Engineering and Building Performance Design

HANNES NYBERG

Department of Civil and Environmental Engineering
Division of Building Technology
Building Physics
CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2011

Thermal bridges at foundations
Evaluation of heat calculation methods

Master's Thesis in the Master's Programme Structural Engineering and Building Performance Design
HANNES NYBERG

Examensarbete 2011:146
Chalmers tekniska högskola
Department of Civil and Environmental Engineering
Division of Building Technology
Building Physics
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
Example of 3D-analysis of thermal bridges in a basement wall-floor junction, made in HEAT3.

Chalmers Reproservice
Göteborg, Sweden 2011

Thermal bridges at foundations
Evaluation of heat calculation methods

Master's Thesis in the Master's Programme Structural Engineering and Building Performance Design
HANNES NYBERG
Department of Civil and Environmental Engineering
Division of Building Technology
Building Physics
Chalmers University of Technology

ABSTRACT

As the need of low-energy buildings and plus-houses increases in Sweden, the importance of knowing a building's energy consumption increases as well. When looking at a building's total energy consumption, one needs to know the heat exchange between the building and its environment. When calculating a building's heat exchange with the ground mainly two standards are used; SS-EN ISO 13370:2007 which explains heat loss via ground, and SS-EN ISO 10211:2007 that explains linear thermal bridges along building perimeters. These two standards together describe methods of doing 2D-simulations of wall-floor junctions, and describe how those results can be applied for 3D-cases. Since there are several calculation methods described in these standards but no recommendation on which one to use, and since some descriptions are quite open for interpretation, engineers using them have encountered problems with results varying up to 60%.

This report includes a guideline and describing document for other engineers, including calculation instructions explaining the methods used and a parameter study to show what influence different parameters have on the calculation results. Four different details of buildings' wall-floor junctions have been studied in HEAT2 (2D-simulations) and HEAT3 (3D-simulations) to verify that the methods work in different cases.

Catalogues where the Ψ-value of different construction details (their ability to transfer heat between indoors and outdoors via construction elements) is listed may include data such as the thickness of a floor slab or the U-value of the wall construction. There are several other parameters that can significantly affect the Ψ-value, such as material of the ground or the size and shape of the floor slab.

When comparing the results from 2D-simulations and applying them to 3D-cases with the different methods described, the results are good for slab-on-ground details (varying up to nearly 5%). When increasing the size of the slab, increasing the characteristic dimension of the slab by 50% increases the deviation of the results with up to over 10%.

Key words: Thermal bridge, heat loss calculation, HEAT2, HEAT3, ISO 10211:2007, ISO 13370:2007

Contents

Preface

This work has been done first and foremost as a guideline, a helping document, to support engineers analysing heat transfer between a building and the ground. It is a complementary document to support standards SS-EN ISO 13370:2007 and 10211:2007, but can also be used separately by users familiar with heat transfer and building physics.

The idea for this guideline has come from engineer and building physician Sonja Kildishev, who has also been an extremely helping and supporting supervisor for this work to be formed in a useful and understandable way. The idea has grown from problems that Sonja and other engineers have run into when trying to calculate building's ability to transfer heat to the ground, referred to via U- and Ψ–values and heat transfer coefficients.

Pär Johansson, graduate student at the Division of Building Technology at Chalmers University of Technology and second supervisor of this work, has together with Sonja and I worked out ideas for this work to be useful both to professional engineers and as a thesis work at Chalmers. He has also provided helpful knowledge, ideas and last but not least critical and constructive guidance for this work.

Examiner of this work is Carl-Eric Hagentoft, professor in building physics at the same division. Since the standards which this work has been developed for are based partly of Carl-Eric's work, he has also been a helpful and very useful source of knowledge and discussion for this work. He has also initiated for me to join a larger meeting between professional companies in building material industry and public institutions in the same area; this has helped clarifying the problems engineers have using the mentioned standards.

The work is based largely on calculations and simulations done in heat loss software HEAT2 and HEAT3 for four different construction details. Through discussions with S. Kildishev, guidelines to perform some of the calculations in the mentioned standards have been developed in written and illustrated form, to be as pedagogical as possible.

As last words, thanks to the engineers and researchers who have all been polite and helpful providing answers and discussion, and again many thanks to Kildishev and Johansson for their patience and support.

Göteborg December 2011

Hannes Nyberg

Notations

Roman upper case letters

A	Surface area	[m]
B'	Characteristic dimension of a building's floor	[m]
H	Heat transfer coefficient of a component or object	[W/K]
L_{2D}	Thermal coupling coefficient derived from 2D-simulation	[W/m·K]
$L_{2D,a}$	Thermal coupling coefficient derived from 2D-simulation, specifically for ground and floor	[W/m·K]
$L_{2D,wall}$	Thermal coupling coefficient derived from 2D-simulation, specifically for wall	[W/m·K]
L_{3D}	Thermal coupling coefficient derived from 3D-simulation	[W/K]
P	Perimeter of building	[m]
Q	Heat flow rate	[W]
R	Thermal resistance	[m^2·K/W]
R_{se}	Outdoor/exterior surface resistance	[m^2·K/W]
R_{si}	Indoor/interior surface resistance	[m^2·K/W]
T	Temperature	[K]
T_e	Outdoor temperature	[ºC]
T_i	Indoor temperature	[ºC]
U	Thermal transmittance	[W/m^2·K]

Roman lower case letters

d	Length of wall, floor etc	[m]
h	Height of object/element	[m]
l	Length of object/element	[m]
q	Heat flux (heat flow rate per area or per length)	[W/m^2] or [W/m]
t	Thickness of wall, floor etc	[m]

Greek upper case letters

Δ	Delta, difference or linear change of a parameter	[-]
Σ	Sigma, sum of magnitudes such as surfaces, lengths etc.	[-]

Greek lower case letters

α	Alpha, surface heat transfer coefficient	[W/m^2·K]
λ	Lambda, heat conductivity of a material	[W/m·K]
χ	Chi, point thermal transmittance	[W/K]
ψ	Psi, linear thermal transmittance	[W/m·K]

Glossary

Adiabatic boundary condition [-]
No heat transfer occurs through that specific boundary

Boundary condition [-]
Thermal condition (temperature, heat flux and thermal resistance) at the outer limit of a geometric model/detail

Building envelope [-]
Parts of a building (walls, roof, floor, windows etc.) that together creates a shell separating indoor and outdoor climate from each other

Rate of heat flow [W] or [J/s]
The exchange of heat energy between areas or volumes

Heat flux [W/m] or [W/m^2]
The intensity of heat flow e.g. heat flow per length or per area

Isotropic resp. anisotropic properties [-]
Similar resp. different material properties in different directions

Heat transfer coefficient [W/ΔK]
Over-all ability of a component to transfer heat

Perimeter [m]
Total length surrounding an area, e.g., windows, floors etc.

Steady state heat flow [-]
Heat flow when system is assumed to be in balance, i.e., the temperature of, and heat transfer between, objects and fluids in the system are constant

Thermal bridge [-]
Part of a construction with significant increase of heat transfer compared to surrounding construction

Thermal coupling coefficient [W/m·K] or [W/K]
The heat flow of an object/element divided by the temperature difference over it; derived through numerical calculation

Thermal conductivity [W/m·K]
Ability of a material to conduct heat

Thermal transmittance [W/m^{2}K]
Ability of an object to transfer heat perpendicular to its surface

Thermal transmittance, linear [W/m·K]
Ability of a component to conduct heat perpendicular to its length

Thermal transmittance, point [W/K]
Ability of a component to conduct heat from a certain point

Transient heat flow [-]
Heat flow before a system is assumed to be in balance, i.e., the temperature of and heat transfer between objects and fluids in the system are still changing

1 Introduction

1.1 Background

When looking at the ground floor or basement of a building, there is a heat exchange between the building and the surrounding ground. To instruct on how to calculate this heat exchange there are international standards, or packages of rules and guidelines that need to be used to make sure that engineers from different countries or companies get comparable results.

For thermal bridges at foundations mainly two standards are used in combination: SS-EN ISO 13370:2007 for calculating heat transfer from buildings through ground, and SS-EN ISO 10211:2007 for calculating and defining thermal bridges and building elements ability to transfer heat.

When using these standards, engineers have found difficulties interpreting several of the formulas and descriptions, since they lack specifications and can be interpreted in several ways. The procedures for calculating heat loss at a wall-floor junction at building corners are not described extensively enough which may lead to severely deviating calculation results. SS-EN ISO 10211:2007 also explains two partly different methods for this kind of calculation, methods which's results has turned out to vary significantly.

For research, shorter interviews have been done with engineers and researchers at a few companies and institutions. While a couple of them seem to have had little problems with their calculations, one has found several ambiguities with the standards which have resulted in very varying calculation results. Another company/institution experiences lack of time and resource for the specific calculations and instead uses a certain safety margin in their results.

A workshop has taken place in Gothenburg in March 2011, including both Swedish and Norwegian companies (e.g. WSP Group, Sundolitt AB and Jackon Isolering) and institutions (SP and SINTEF Byggforsk) working with construction and thermal performance of floor construction. One purpose of this workshop was to spread information on calculation of U- and ψ-values among companies, and discuss means of spreading this information within the construction sector.

A few written works about calculation of thermal performance has also been studied. In Akander (1995) explains the general idea of and problematic with discretisizing wall elements to perform Finite Element Analyses (FEA). He also discusses the problematic of analysing two-dimensional details compared to the simpler calculation of one-dimensional heat flow through, in this case, walls.

Staelens' (1988) thesis includes step-by-step instructions on calculating two-dimensional construction details by hand. Though this hand-calculation method is not used in this report, Staelens provides helpful discussions on defining thermal bridges and the thermal bridge's influence on an element's overall thermal performance.

Konieczny (2005) exemplifies how the thermal performance of several building components can be summed up into one coefficient, something that is also used in this thesis and the ISO-standards studied.

In his thesis, Blomberg (1996) discusses discretization and numerical calculations for constructions and the ground below. Examples in his thesis regarding three dimensional analysis of building corners have been studied to give an idea of how discretization can work for similar analyses in this thesis.

Rantala’s (2005) thesis discusses and performs numerical calculations regarding assumed temperature lines in the subsoil, something that is mentioned but not used in this report.

Wetterlund (2010) describes in short the main steps needed to calculate the thermal performance of floor slabs and their corners; the same principles are used in this report.

1.2 Purpose

The main purpose of this thesis is to specify, analyze and verify the specific calculation methods used in SS-EN ISO 13370:2007 and SS-EN ISO 10211:2007 to calculate heat loss to the ground. At the same time the thesis should function as a guide to support engineers calculating heat loss to ground. The purpose of the guide is to minimize the spread and error of the results, leaving little room for misinterpretations. Heat software calculations will be done in order to find out what parameters are most critical for correct results. The calculation results will also, in some degree, show whether or not simplifications and formulas in the standards are correct or appropriate.

1.3 Method

To learn about calculation methods used in the studied standards, interviews are made with users and authors of the standards. Background studies are made through literature from University libraries (Chalmers University of technology, Royal Institute of Technology) and browsing and reading through earlier academic thesis made on heat loss calculations. Research studies and seminar papers are also included in the background research to find problems and questions occurring when using the standards mentioned above. Heat calculations are done in HEAT2 and HEAT3, and illustrations are made in AutoCAD and MS Paint. Simpler calculations are done in Microsoft Excel.

1.4 Limitation

Calculations will consider heat losses only. The calculations only consider steady state, which means that thermal heat capacity of materials will not be taken into account. The calculation methods studied only consider those mentioned SS-EN ISO 13370:2007 and SS-EN ISO 10211:2007, describing the heat transfer between a building and the ground. The details studied only consider slab on ground and in some degree heated basements.

2 Theory of heat loss calculation

As a result of ceasing energy sources, increased greenhouse effect and increasing cost of energy used for e.g. heating of buildings, there is also an increasing demand for buildings and houses with low or no heating demand (Passive houses, low-energy houses, plus-energy-houses etc.).

For residential buildings in colder climates, there is most often a need to keep heat inside a building. This is in order to keep a comfortable indoor climate with a comfortable air temperature. To be able to design a building's need of heating or cooling energy, the designer needs to understand all the energy transfers occurring through the building envelope.

In the equations used to describe these energy transfers, there are several factors to take into account. Examples are rate of ventilation, air tightness of the building envelope (e.g. roof, walls and floor), the building's envelope's ability to transfer heat between indoor and outdoor climate, energy gains from solar radiation and internal gains etc.

It is the building envelope's ability to transfer heat, measured in [W/K] that is of interest in the calculations used in this report. The calculations and methods mentioned in this report focuses mainly on heat loss to the ground, i.e., heat transfer between indoor environment and outdoor environment through floor, ground and basement walls.

To be able to calculate the thermal performance of walls, floors etc. one first needs to know the basic concepts of heat transfer mechanisms, i.e., the different ways for heat energy to move between areas with different temperatures.

2.1 Heat transfer mechanisms

Heat energy, usually defined in Joule [J], is a quantity that transfers between different areas or volumes, from a warmer to a colder one due to temperature difference between them. This is because materials seek to even out their temperature differences. The heat loss of a building can be measured both in quantity, Joule [J], and power, Watts [W] or Joule per second [J/s]. It can be transferred in three ways: through **conduction**, **convection** and **radiation**.

2.1.1 Conduction

Conduction refers to the heat flow through materials, depending on the materials' ability to conduct heat. The heat flow through an object, e.g., a wall or a floor, in form of conduction depends on three parameters: the material's heat conductivity, i.e., its ability to transfer heat; the objects geometry, e.g., a wall's thickness; and the temperature difference throughout and around the object. The use of these parameters is described in **Fourier's law of heat conduction**, see equation (2.1).

$$q = -\lambda \cdot \frac{\Delta T}{d} \qquad [W] \qquad (2.1)$$

Where:

q is the heat flux (heat flow rate per area) through the material in one direction [W/m^2]
λ is the material's thermal conductivity [W/(m·K)]
ΔT is the temperature difference over the object [K]

Materials' heat conductivity can be temperature dependant, i.e., with increasing temperature the heat conductivity also increase. Normally though, a material's heat conductivity is assumed constant when calculating a building envelope's heat conductance. Figure 2.1 shows a principal sketch of how heat transfers through a wall layer of insulation with certain heat conductivity.

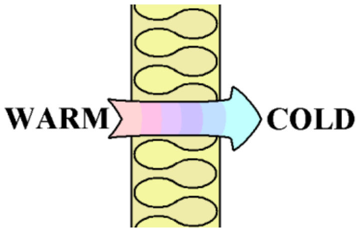

Figure 2.1 Example of heat transfer through insulation via heat conduction.

2.1.2 Convection

Convection is the movement of a fluent medium, i.e., a liquid or gas. Heat transfer through convection is when the medium is heated up, moves to a colder surface (either by itself, natural, or by external forces, forced) and then releases its heat onto the colder surface (Hagentoft, 2009).

Natural convection happens when there is a temperature difference in an volume of fluid which thereby crates a difference in density between warmer and colder volumes. The density difference causes the warmer fluid to rise and colder to sink, and there by creates a motion. An example of heat transfer via convection is when warm air rises because of its decreasing density. As soon as the air releases its heat onto a surface, the density increases again and the air sinks (Petersson, 2004), see Figure 2.2.

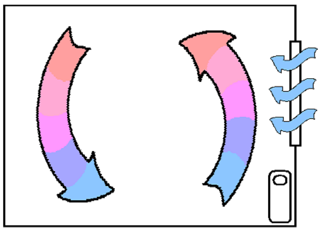

Figure 2.2 Forced convection in a room.

This phenomenon is used to prevent/decrease cooling sensations from colder windows by installing a radiator underneath it. When the radiator heats up the air, it rises and creates an air curtain in front of the window. This rising effect driven by buoyancy is called "stack effect". In addition to the air curtain, the rising air also creates a circulation of air in the room. This happens when the air is cooled down by cold surfaces further away in the room and thereby becomes denser. Air with higher density is heavier than air with low density, and therefore sinks because of gravity.

Another example of convection is when wind increases the heat exchange of ambient air and a surface, such as air flow caused by wind that increases heat exchange under a suspended floor, see Figure 2.3.

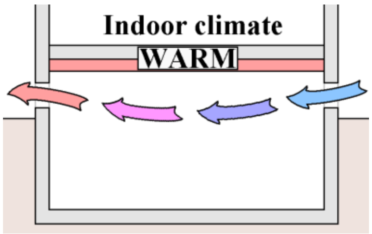

Figure 2.3 Simplified example of natural convection through crawl space.

The magnitude of heat transfer through convection depends on the size of the surface area, the velocity of the medium, and the medium's heat capacity, i.e., its ability to store heat.

2.1.3 Radiation

Radiation is basically heat transferred between surfaces via electromagnetic waves. The larger the temperature difference between the surfaces (in calculations defined in Kelvin [K]), the larger the surfaces and the more direct they face each other (defined through a viewing factor between 0 and1), the more heat will be transferred through radiation. How much of the radiation that is absorbed on a surface depends on that surface's emissivity, i.e., its ability to emit heat through radiation.

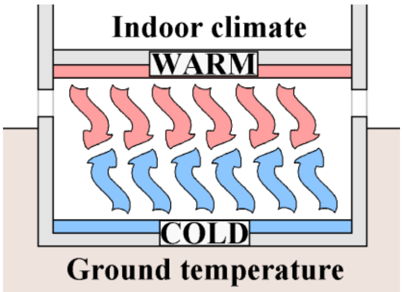

Figure 2.4 Radiation heat exchange between ground and suspended floor in a crawl space.

Figure 2.4 illustrates heat exchange between a suspended floor and basement floor. The radiation exemplified in this figure is not included in the calculations in this thesis.

2.2 Thermal transmittance

Once the basic mechanics of heat transfer are known, it is possible to calculate an object's ability to transfer heat between two climate environments. Depending on what kind of object is of interest (walls, nails, window frames etc.) this heat transfer ability can be defined in several ways:

Areas, such as walls, floors, windows etc are denoted with ***U*-values**, also referred to as simply **thermal transmittance** [W/m²K]. The U-value is multiplied with the area of corresponding element to find overall heat transfer ability, its $U \cdot A$-value [W/K].

For junctions, window frames, edge beams and other linear details, a ***Ψ*-value** (psi) is used, called **linear thermal transmittance** [W/m·K]. The Ψ-value is multiplied with the length of corresponding element to find overall heat transfer ability, its $\Psi \cdot l$ –value [W/K].

Three-dimensional corners, connectors and other point details are denoted ***χ*-values** (chi), also called **point thermal transmittance** [W/K].

When looking at objects consisting of several elements with different transmittances, it might be more convenient to use a heat **transfer coefficient *H*** [W/K], see equation (2.2). The heat transfer coefficient H is used in SS-EN ISO 13370:2007 when looking at a building's total heat transfer to the ground and is there referred to as H_g.

$$H = \sum U \cdot A + \sum \psi \cdot l + \sum \chi \qquad \left[\frac{W}{K}\right] \qquad (2.2)$$

Where:

H is the object's total heat transfer coefficient [W/K]
U is the thermal transmittance for each element with a surface area [W/m²K]
A is the surface area for each of those elements [m²]
ψ is the linear thermal transmittance for each element where only its length is considered [W/m·K]
l is the length for each of those elements [m]
χ is the point thermal transmittance for each element where only its position is considered [W/K]

See Figure 2.5 for a better understanding how the total heat transfer coefficient of a wall with balcony, window and door is calculated. Note that only a few components of the total heat transfer ability are exemplified here.

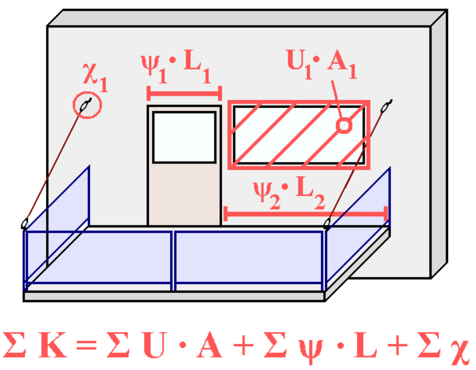

Figure 2.5 Example on where to use different thermal transmittances.

The connections where the balcony is suspended usually get a χ-value when calculating heat loss from indoors to outdoors. The attachment of the balcony slab can be considered having either a linear or point transmittance depending on the type of connections to the wall. Installation (frames, sealing etc.) of windows and doors can also be calculated by using a ψ-value, but are sometimes instead included in the window's U-value. Windows and walls are usually calculated with U-values that include the effect of framing.

When an object's heat transfer coefficient H or an elements $U \cdot A$-, $\Psi \cdot l$- or χ-value is known, it may be multiplied with the temperature difference ΔT [K] between its two environments, e.g., indoor air and outdoor air, to obtain the heat flow rate Q [W] through the object, e.g., the building envelope. If the indoor air is warmer than outdoor air, this heat exchange is considered a heat loss of the building. See equation (2.3) for the definition of this calculation.

$$Q = H \cdot \Delta T \qquad [W] \qquad (2.3)$$

Where:

Q is the heat flow rate through the object [W]
H is the heat transfer coefficient of the object [W/K]
ΔT is the temperature difference through the object [K]

Equation (2.3) can also be used the other way around, to find an object's ability to transfer heat by dividing the simulated heat flow rate through it with the known temperature difference, see equation (2.4). Note that when the heat transfer ability is calculated through a simulation, it is referred to as thermal coupling coefficient L_{3D}, which can be compared to H in equation (2.3).

$$L_{3D} = \frac{Q}{\Delta T} \qquad \left[\frac{W}{K}\right] \qquad (2.4)$$

Where:

L_{3D} is the thermal coupling coefficient derived from a 3D-simulation [W/K]

Know that most simulations discussed and explained in this report are two-dimensional, looking at a cross section. The units used are therefore described per meter depth of the section, and instead of L_{3D} [W/K], L_{2D} [W/m·K] is used.

This calculation method is a key technique in this report. By dividing a calculated heat flow Q from a heat transfer simulation with its known temperature difference ΔT, Ψ- and U-values can be calculated. This is mentioned more throughout Chapter 3.

2.3 Calculating thermal transmittance and thermal resistance

To find the thermal transmittance of e.g. a wall, one first needs to find the thermal resistance of the materials in the object by using equation (2.1) mentioned in Chapter 2.1.1. This equation can be developed further by re-defining the parameters, see equation (2.5).

$$\lambda \cdot \frac{\Delta T}{d} = \frac{\lambda}{d} \cdot \Delta T = \frac{1}{R} \cdot \Delta T \qquad [W] \qquad (2.5)$$

Where:

R is the thermal resistance of a layer of material [m^2K/W]
ΔT is the temperature difference over the object/layer [K]

By dividing the thickness with the thermal conductivity of the material, the **thermal resistance *R*** of that layer of material is defined.

Between ambient air and surfaces of facades, ceilings, floors etc. there is minor heat transfer occurring due to both convection and radiation (Petersson, 2004). These are normally taken into account by adding an extra surface resistance R_{si} (internal surfaces) and R_{se} (external surfaces) to these surfaces, see Table 2.1 and Figure 2.6.

Table 2.1 Surface resistance for different cases.

Type of surface	Notation	Value [m^2K/W]
Outdoors	R_{se}	0.04
Indoors-ceiling	R_{si}	0.10
Indoors-wall	R_{si}	0.13
Indoors-floor	R_{si}	0.17
Ground	-	0

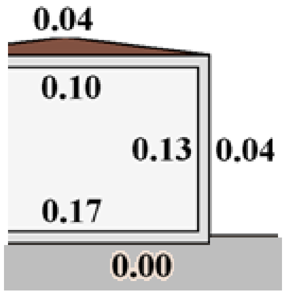

Figure 2.6 Locations of different values for surface resistance.

For internal surfaces this resistance is assumed different values for ceilings, walls and floors. The reason for this is that the different air movement at different surfaces causes the effect of convection to vary. On a horizontal floor surface for example the air stacks, which increases the thermal resistance between the floor and the room volume (Theoboldt, 2011). Sometimes the inverse of thermal resistance is used, and is then called surface heat transfer coefficient α [W/m^2K].

The total thermal resistance of a wall of the building envelope is the sum of the thermal resistance of all layers and the inner and outer surface resistance; see Figure 2.7 (not including surface resistances) and equation (2.6).

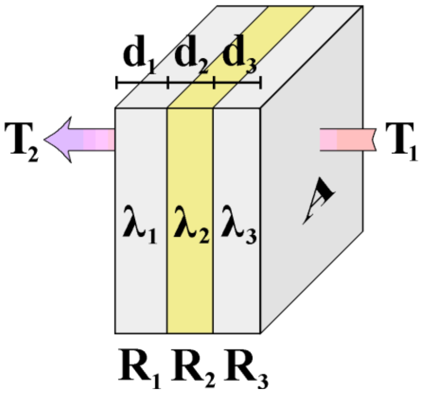

Figure 2.7 Total thermal resistance of several layers of material.

$$R_{wall} = R_{si} + \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \frac{d_3}{\lambda_3} + R_{se} \qquad \left[\frac{m^2K}{W}\right] \qquad (2.6)$$

Where:

R is the thermal resistance of a layer of material [m^2K/W]

The thermal transmittance U is the reciprocal of the total thermal resistance R, see equation (2.7).

$$U_{wall} = \frac{1}{R_{wall}} \qquad [W] \qquad (2.7)$$

Where:

R_{wall} is the thermal resistance of a layer of material [m^2K/W]
U_{wall} is the thermal transmittance of the wall [m^2K/W]

For floor on ground, the thermal performance (including the ground) is more complicated to derive since the direction of the heat flow in the ground might be difficult to anticipate. Those kinds of calculations may instead need numerical heat calculation software or specific calculation methods, described in SS-EN ISO 13370:2007.

Note that equation (2.6) applies only for the one-dimensional heat flow through a homogenous part of a wall. Geometrical and material changes in the wall what makes it irregular and non-homogeneous may contribute to the heat flow changing direction; this makes it inappropriate to assume the heat flow to be one-dimensional and complicates the calculation of the heat flow, making the above equations insufficient for deriving the total transmittance of the wall. For this reason, the thermal transmittance of walls is in this thesis calculated through numerical simulation, including smaller structural details.

2.4 Defining linear thermal transmittance

As long as a wall or roof is fairly consistent and homogenous, the heat flow through it can most often be assumed to be one-dimensional, i.e., the heat transfers straight through, perpendicular to the wall's surface. When a section of the wall or roof changes appearance however, either geometrically or in material, the heat flow pattern may change. Whether this change is significant or not is up to each user/engineer to decide. If it is, the heat flow can no longer be calculated by only using U-values. Instead these changes in heat flow pattern are regarded by including ψ-, and in some cases χ-values where the heat flow pattern changes.

There are several ways to obtain the linear thermal transmittance of a junction or part of a construction, either by hand (Staelens, 1988), with numerical methods (software calculations) or through catalogues with standard examples such as SS-EN ISO 14683:2007. According to SS-EN ISO 14683:2007 numerical calculations normally give results with an error of max 5%, while manual calculations and catalogue values are within 20% correct.

For geometrical changes of heat flow patterns, e.g. corners, it is of importance to define if a ψ-value refers to external or internal dimensions, since the two values can differ greatly.

In Figure 2.8, the external and internal dimensions are graphically defined for a wall-floor junction, the kind of detail that will be looked at throughout this report. According to SS-EN ISO 10211:2007, the difference of external and internal dimensions for the wall and floor is the wall thickness w and floor height h_f above ground respectively. Note though that for some countries or instances (e.g. Passive House Institute in Germany, PHI) the external measures reach down to the lower side of the corner, underneath ground level (Kildishev, 2011). Both ISO 10211's and PHI's definitions of external dimensions are illustrated in Figure 2.8.

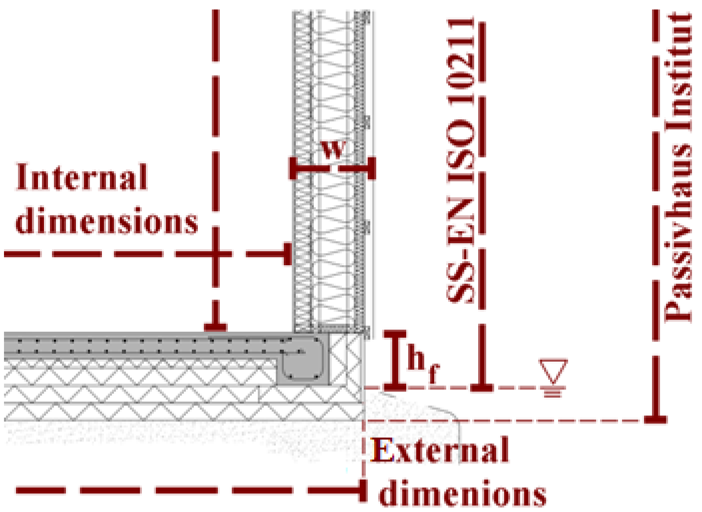

Figure 2.8 Definition of external and internal dimensions on a wall-corner junction.

When using **internal** dimensions, the corner element (seen in mid-dark/orange markings in Figure 2.9) is excluded from the wall and floor elements, which both can be calculated through U-values. That corner is instead defined with a ψ-value. Note that the wall and floor are slightly separated in Figure 2.9 to show that there are three heat transferring elements, one for the wall above the corner, one for the floor within the wall boundaries, and one for the corner element.

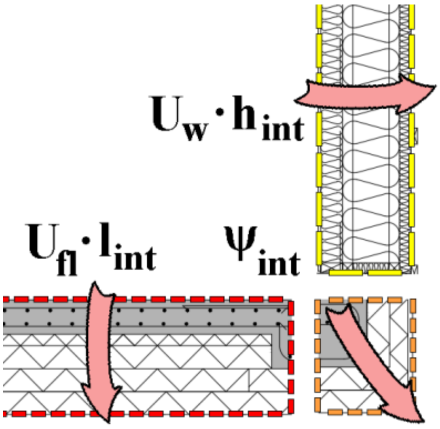

Figure 2.9 The heat transfer ability of the wall, floor and corner of a junction, derived from internal dimensions.

If using **external** dimensions on floor and wall (see Figure 2.10), both the wall's $U{\cdot}h$-value and the floor's $U{\cdot}l$-value will include the corner element. Since the floor and wall elements are overlapping each other in this method, the total heat transferring elements will include more materials than there actually is in the construction. For this reason the ψ-value might become negative.

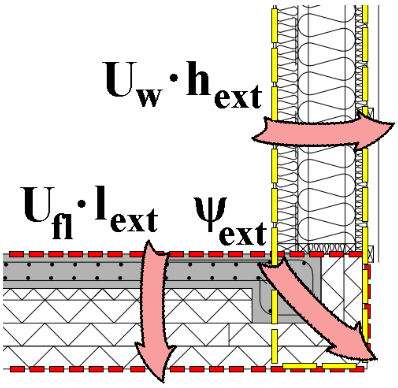

Figure 2.10 The heat transfer ability of the wall, floor and corner of a junction, derived with external dimensions.

There is a third way to define dimensions called **overall internal dimensions.** These dimensions do not separate floors and rooms but include the thicknesses of partition walls and floors (other than the bottom/basement floor). Since this report focuses on wall-ground junctions however, this way of defining dimensions will give similar results as of using only internal dimensions.

2.5 Thermal bridges in a construction

If an irregularity in the building envelope contributes to a significant increase of heat transfer compared to the surrounding elements, it may be referred to as a **thermal bridge**. Since a thermal bridge is often found in junctions between areas, in linear structural elements or in connectors, their thermal impact can often be described through a ψ- or χ-value.

According to Passive House Institute, PHI, a building can be considered **thermal bridge free** if the sum of these values, calculated for **external** dimensions, is below zero (Passive House Institute, 2011), see equation (2.8).

$$\sum \psi \cdot l + \sum \chi < 0.00 \qquad \left[\frac{W}{K}\right] \qquad (2.8)$$

Where:

$\sum \psi \cdot l + \sum \chi$ is the sum of all linear and point conductances in a building envelope [W/K]

PHI also has a simplified criterion for linear thermal transmittances, see equation (2.9). If this criterion applies, the first criterion most often applies as well. If not, the thermal bridges can be seen as negligibly small.

$$\psi < 0.01 \qquad \left[\frac{W}{m \cdot K}\right] \qquad (2.9)$$

Where:

ψ is the thermal transmittance [W/m·K]

3 Calculating heat loss to the ground

The type of heat transfer treated in this report is mainly through elements separating indoor and outdoor environment via the ground, i.e., through ground, basement walls and floor. The total heat transfer ability of these parts are defined in SS-EN ISO 13370:2007 as the **steady-state ground heat transfer coefficient H_g** in equation (3.1) for slab on ground and equation (3.2) for basements. In SS-EN ISO 13370:2007 these are referred to as equation (1) and (16) respectively.

$$H_g = A \cdot U_g + P \cdot \psi_g \qquad \left[\frac{W}{K}\right] \tag{3.1}$$

$$H_g = A \cdot U_{bf} + P \cdot \psi_{bg} + z \cdot P \cdot U_{bw} \qquad \left[\frac{W}{K}\right] \tag{3.2}$$

Where:

H_g is the steady state ground heat transfer coefficient [W/K]
A is the surface area of the floor/basement floor [m^2]
U_g is the thermal transmittance of the floor slab and ground [W/m^{2}K]
P is the perimeter of the floor [m]
ψ_b is the linear thermal transmittance of the wall-floor junction above ground [W/m·K]
U_{bf} is the thermal transmittance of the basement floor [W/m^{2}K]
ψ_{bg} is the linear thermal transmittance of the basement's wall-floor junction [W/m·K]
z is the depth of the basement floor [m]
$z \cdot P$ is the total area of the basement walls [m^2]
U_{bw} is the thermal transmittance of the basement walls [W/m^{2}K]

Figure 3.1 gives a graphical example of what equation (3.2) defines when using internal dimensions.

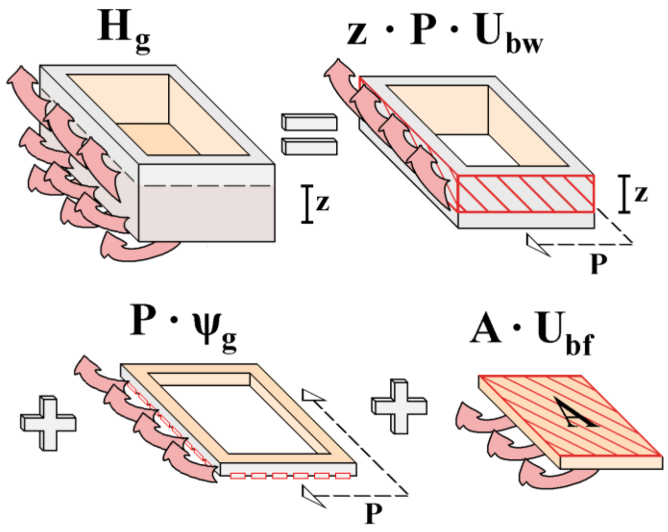

Figure 3.1 Graphical explanation of equation (3.2).

In the figure the envelope of a basement is separated into part with somewhat simplified heat flow (illustrated only for ones side of the basement). A smaller upper part of the basement wall, seen in pale grey, lies above ground level (illustrated with dashed dark line surrounding the building) and is therefore not included in the calculations of heat loss to the ground.

For the heat transfer ability of the basement wall $z \cdot P \cdot U_{bw}$ only the homogenous part of the wall below ground (not including the junction corner) is included. The junction corner is instead included in the ψ_g-value, which is multiplied with the perimeter P. All floor area within the walls is included in $A \cdot U_f$.

The rest of this chapter explains the basics of the two standards ISO 10211 and 13370, and the most important parameters and assumptions needed make these calculations with the necessary heat loss simulations.

3.1 SS-EN ISO 10211:2007 and SS-EN ISO 13370:2007

SS-EN ISO 10211:2007 gives instructions on how to calculate thermal bridges (ψ- and χ-values) in construction details in the building envelope. A user of this standard can together with heat calculating software analyse simpler two- or three-dimensional construction details, define their boundaries, simplify smaller repeating irregularities within them and find their linear or point thermal transmittance.

This standard also includes a sub-chapter with instructions on calculating ψ-value for wall-floor junctions above ground via two different methods, method A and B. The idea of that method is to, via two-dimensional numerical analyses with heat calculation software, find ψ_g-value which can then be used to find H_g. Know that exact calculation instructions for finding the Ψ_g–value basement wall-floor junctions (referred to as Ψ_{bg}-value in equation (3.2)) is not included in this standard; only the procedure for calculating Ψ-values for junctions above ground (Ψ_g) is.

SS-EN ISO 13370:2007 instructs on calculating the U-value of the building floor and the ground underneath, whether it is a slab on ground, heated or unheated basement or a suspended floor. Included in those descriptions is also formula calculation of thermal transmittance of basement walls. This standard also defines H_g, mentioned earlier in this chapter.

3.2 Analysing a wall-floor junction

To do a wall-floor junction analysis based on SS-EN ISO 10211:2007, the user looks at a cut-off lower part of a building's wall-floor corner facing outdoors, see Figure 3.2.

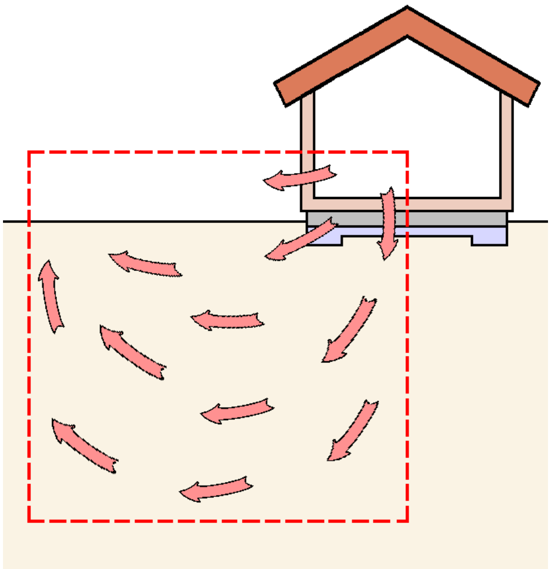

Figure 3.2 A simplified section of the analysis cut of a wall-floor junction, including an estimated heat flow pattern.

The part of the building used for a 2D-analysis is marked with a red dashed square in this figure. Note that this part normally includes an even larger part of the ground; this figure is merely a simplification. There are rules explained further into Chapter 3 in this report on how to do this cut. For this figure, where the indoor environment is assumed warmer than outdoors, the heat flow is illustrated through arrows.

The main idea of using SS-EN ISO 10211:2007 for 2D-analyses is to analyse a whole corner section and then separate the different heat transferring elements in order to find the linear thermal transmittance (ψ_g-value of the junction). The main separated elements are illustrated through heat flow arrows in Figure 3.3 and described in equation (3.3).

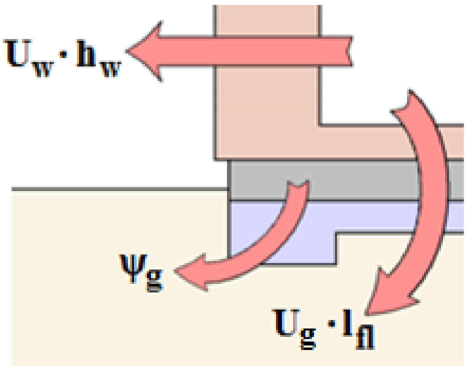

Figure 3.3 The three main heat transferring elements in a wall-floor junction.

$$L_{2D} = U_w \cdot h_w + \Psi_g + U_g \cdot l_{fl} \qquad \left[\frac{W}{m \cdot K}\right] \qquad (3.3)$$

Where:

L_{2D} is the thermal coupling coefficient for the whole analysed detail [W/m]
U_w is the thermal transmittance of the wall [W/m]
h_w is the internal height of the wall [W/m]
Ψ_g is the linear thermal transmittance of the corner [W/m]
U_g is the thermal transmittance of the floor and ground [W/m]
l_{fl} is the internal length of the floor [W/m]

In SS-EN ISO 10211:2007 equation (3.3) is expressed in another order and with slightly different parameters for calculating the ψ-value of the junction's corner, see equations (3.4), (3.5) and (3.6) below.

$$\psi_g = L_{2D} - U_w \cdot h_w - 0.5 \cdot B' \cdot U_g \qquad \left[\frac{W}{m \cdot K}\right] \qquad (3.4)$$

$$\psi_g = L_{2D} - U_w \cdot \left(h_w + h_f\right) - 0.5 \cdot (B' + w) \cdot U_g \qquad \left[\frac{W}{m \cdot K}\right] \qquad (3.5)$$

$$\psi_g = L_{2D} - U_w \cdot h_w - L_{2D,a} \qquad \left[\frac{W}{m \cdot K}\right] \qquad (3.6)$$

Where:

h_f is the floor height above ground [m]
B' is the characteristic dimension of the floor [m]
w is the thickness of the wall [m]
$L_{2D,a}$ is the thermal coupling coefficient of the floor and ground [W/K]

These equations represent two slightly different methods for calculating the ground's thermal transmittance, method A (equation (3.4) and (3.5)) and method B (equation (3.6)). For both methods L_{2D} is calculated through simulations with heat calculation software. For method A though, U_g is calculated with a formula, while method B needs another heat loss simulation to find $L_{2D,a}$.

Thermal coupling coefficient $L_{2D,a}$ represents the heat transferring ability of the floor and ground, but excluding any heat transfer through the wall and corner of the junction. For this to be calculated the wall and corner construction are eliminated for a heat transfer simulation and the floor is raised above ground. This leaves only a uniform floor slab with insulation on ground. This procedure is explained more thoroughly in Chapter 0 in this report.

Calculation procedure of the **wall's thermal transmittance U_w** is not explained in ISO 10211; the standard only mentions that U_w shall be derived in the same way as in the numerical calculation. The procedure of calculating $U_w \cdot h_w$ has instead been used from Wetterlund (2010). This procedure uses the same wall detail as used when analyzing the whole detail to find L_{2D}. By cutting out the wall from that detail and assuming no heat transfer through its top or bottom, $U_w \cdot h_w$ is derived. Since it is derived from computer analysis though, one might find it more correct to denote it a thermal coupling coefficient, such as $L_{2D,wall}$. In Appendix B. it is referred to as $L_{2D,wall}$. This procedure is described more thoroughly in Chapter 0 in this report.

The **characteristic dimension B'** of a floor, used in equations (3.4) and (3.5), is explained in SS-EN ISO 13370:2007 Chapter 8.1, equation 2. It is also used and needed in SS-EN ISO 10211:2007 since it determinates the size of the simulation detail used to calculate a wall-floor junction's Ψ_g–value. It is of importance that a correct value of B' is used, since it affects the size of the ψ_g-value, as shown later on in Chapter 4. It is defined as the floor area divided by half of its external perimeter, see equation (3.7).

$$B' = \frac{A}{0.5 \cdot P} = \frac{b \cdot c}{b + c} \qquad [m] \qquad (3.7)$$

Where:

B' is the characteristic dimension [m]
A is the ground-floor area of the floor slab [m^2]
P is the external perimeter of the floor slab [m]
b, c are the external measures of the floor slab [m]

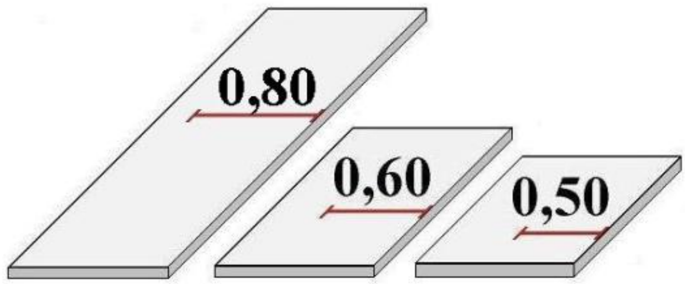

Figure 3.4 Examples of the value of B' on three different slabs with similar width but with different lengths.

Figure 3.4 shows examples of B' for three different 8 m wide floor slabs with the lengths 32, 12 and 8 m. B' is marked with a red/ dark line to compare with the actual width, and the quota of B' and the actual width is numbered on each slab.

To calculate U_g with method A, it must first be known whether the floor insulation can be graded as well-insulated or less good insulated. To do this, another parameter is calculated, the **equivalent thickness d_t**.

$$d_t = w + \lambda\left(R_{si} + R_{floor} + R_{se}\right) \qquad [m] \qquad (3.8)$$

Where:

d_t is the equivalent thickness [m]
w is the total thickness of the wall [m]
λ is the heat conductivity of the soil/ground material [W/m·K]
R_{floor} is the thermal resistance of the floor construction [m^{2}K/W]
R_{si}, R_{se} are the thermal ground surface resistances of indoors and outdoors [m^{2}K/W]

If the user of SS-EN ISO 13370:2007 is uncertain of what the conductivity of the soil is, sand/gravel is to be assumed with a λ-value of 2 W/m·K (ISO 13370, Chapter 5.1). The floor insulation is then graded by comparing B' with d_t, see equations (3.9) and (3.10).

Well-insulated: $$d_t \geq B' \qquad (3.9)$$

Less insulated: $$d_t < B' \qquad (3.10)$$

Where:

d_t is the equivalent thickness of the floor and ground [m]
B' is the characteristic dimension of the floor slab [m]

The U_g-value of the floor and ground is the calculated according to what category it belongs to; see equations (3.11) and (3.12).

Well-insulated: $$U_g = \frac{\lambda}{0.457 \cdot B' + d_t} \quad \left[\frac{W}{m^2K}\right] \qquad (3.11)$$

Less insulated: $$U_g = \frac{2 \cdot \lambda}{\pi \cdot B' + d_t} \cdot \ln\left(\frac{\pi \cdot B'}{d_t} + 1\right) \quad \left[\frac{W}{m^2K}\right] \qquad (3.12)$$

Where:

λ is the thermal conductivity of the ground material [W/m·K]
B' is the characteristic dimension of the floor [m]
d_t is the equivalent thickness of the ground [m]

The procedure for calculating U_{bf} is very similar to that of U_g. The equivalent thickness is calculated the same way as in equation (3.8). U_{bf} is calculated very similar to U_g is, but also includes the depth z of the corner (the height difference of the top of the floor and the ground), see equations (3.13) and (3.14).

Well-insulated: $$U_{bf} = \frac{\lambda}{0.457 \cdot B' + d_t + 0.5 \cdot z} \quad \left[\frac{W}{m^2K}\right] \qquad (3.13)$$

Less insulated: $$U_{bf} = \frac{2 \cdot \lambda}{\pi \cdot B' + d_t + 0.5 \cdot z} \cdot \ln\left(\frac{\pi \cdot B'}{d_t + 0.5 \cdot z} + 1\right) \quad \left[\frac{W}{m^2K}\right] \qquad (3.14)$$

Where:

z is the depth of the basement floor [m]

In addition to U_{bf}, ISO 13370 also provides a formula for calculating the U-value of basement walls U_{bw}, see equation (3.15).

$$U_{bw} = \frac{2 \cdot \lambda}{\pi \cdot z} \cdot \left(\frac{0.5 \cdot d_t}{d_t + z} + 1\right) \cdot \ln\left(\frac{z}{d_w} + 1\right) \quad \left[\frac{W}{m^2K}\right] \qquad (3.15)$$

Where:

U_{bw} is the thermal transmittance of the basement wall and soil outside [W/m^{2}K]
d_w is the equivalent thickness for the basement wall [m]

Equation (3.15) uses the equivalent thickness for the basement walls d_w, see equation (3.16).

$$d_w = \lambda(R_{si} + R_{wall} + R_{se}) \qquad [m] \qquad (3.16)$$

Where:

R_{wall} is the thermal resistance of the basement wall and the ground outside

If $d_w < d_t$ then d_t is replaces by d_w in equation (3.15).

3.3 Boundary distances

Anywhere in a building envelope where a junction of different surfaces or elements appear, that part of the envelope can either be analysed in 2D or 3D in order to find the correct linear or point thermal transmittance, or it can be compared to similar details found in catalogues with already calculated results.

How much length of a wall, roof or floor that needs to be included in an analysis depends on the thickness of the elements included and the distance to other thermal bridges nearby. The distance to the cuts (or the "cut-off planes" as referred to in SS-EN ISO 10211:2007) is called minimum distance (d_{min}) and is the largest of 1 m and three times the thickness of that wall, roof or floor, see equation (3.17).

$$d_{min} = min\begin{cases} 3 \cdot t_{thick} \\ 1\ m \end{cases} \qquad [m] \qquad (3.17)$$

Where:

d_{min} is the minimum cut-off distance [m]
t_{thick} is the thickness of the element [m]

If another detail, e.g., a window or a wall-roof junction is closer than d_{min} from the studied detail, the cut-off plane is instead placed in the middle, in a symmetry line. See figure 3-1 for an example.

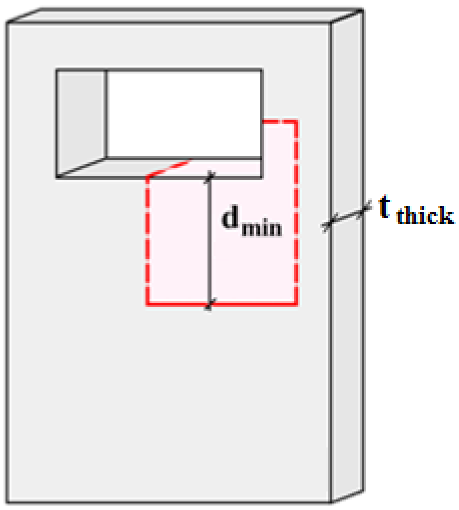

Figure 3.5 Example of where the cut-off planes are put for a 2D analysis of the lower right corner of a window opening.

Note that d_{min} in this case is only used below the window opening and represented by a continuous line. Anywhere else in the figure other junctions and details are too close, which puts the cut-off planes on the symmetry lines, represented by dashed lines.

For the kind of wall-floor junction analyses described in this thesis, d_{min} is only used when determining the height of the cut-off plane of the wall included in the junction. For the cutting of the floor in a wall-floor detail used in a heat loss simulation, B' is the main determinant. In a three-dimensional analysis the inner cut-off planes are in the middle of the slab's sides (0.5·b resp. 0.5·c), see equations (3.18) and (3.19).

$$d_{inner\ ,b} = 0.5 \cdot b \qquad [m] \qquad (3.18)$$

$$d_{inner\ ,c} = 0.5 \cdot c \qquad [m] \qquad (3.19)$$

Where:

d_{inner} is the distance from the wall to the inner cut-off plane [m]
b and c are the dimensions of the slab [m]

The cut-off planes below ground surface and outside the building are placed at a distance of the smallest of 2.5·b and 2.5·c, see equation (3.20).

$$d_{lower} = d_{outer} = \min \begin{cases} 2.5 \cdot b \\ 2.5 \cdot c \end{cases} \qquad [m] \qquad (3.20)$$

Where:

d_{lower} is the distance from the ground level to the lower cut-off plane (sub-soil) [m]
d_{outer} is the distance from the wall to the outer cut-off plane [m]

Equations (3.18), (3.19) and (3.20) are illustrated in Figure 3.6.

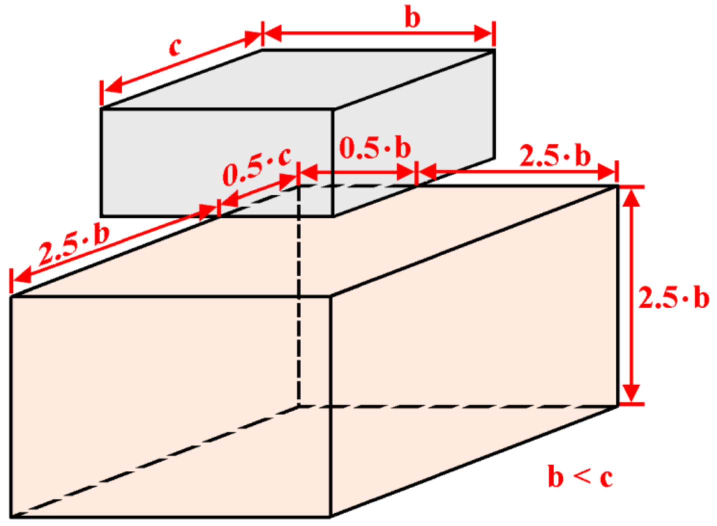

Figure 3.6 The placement of cut-off-planes in the soil (brown) around a corner of a building (grey) with the length c and width b. In this case b is smaller than c.

The height of the wall is defined with d_{min} as explained in equation (3.17).

For the distances to the cut-off planes for a two-dimensional analysis the standards is unclear. Chapter 5.2.4 in SS-EN ISO 10211:2007, including a table with the different distances for two- and three-dimensional analyses, suggests the cuts to be made according to the actual width of the analysed section (b or c in Figure 3.6).

Chapter 10.4 in SS-EN ISO 10211:2007 instead suggests the cuts to be made according to the floor slab's characteristic dimension B'. According to C-E Hagentoft (2011), who contributed to SS-EN ISO 10211:2007 and SS-EN ISO 13370:2007, B' is the correct dimension to use for two-dimensional analyses, and will therefore be used further on in this thesis.

When using the characteristic dimension B', the distances to the inner cut-off plane, d_{inner}, is 0.5·B', while for the lower and outer planes it is 2.5·B', see equations (3.21) and (3.22).

$$d_{inner} = 0.5 \cdot B' \qquad [m] \qquad (3.21)$$

$$d_{lower} = d_{outer} = 2.5 \cdot B' \qquad [m] \qquad (3.22)$$

Figure 3.6 illustrates these equations. Just as for a three-dimensional analysis, the height of the wall included is d_{min}.

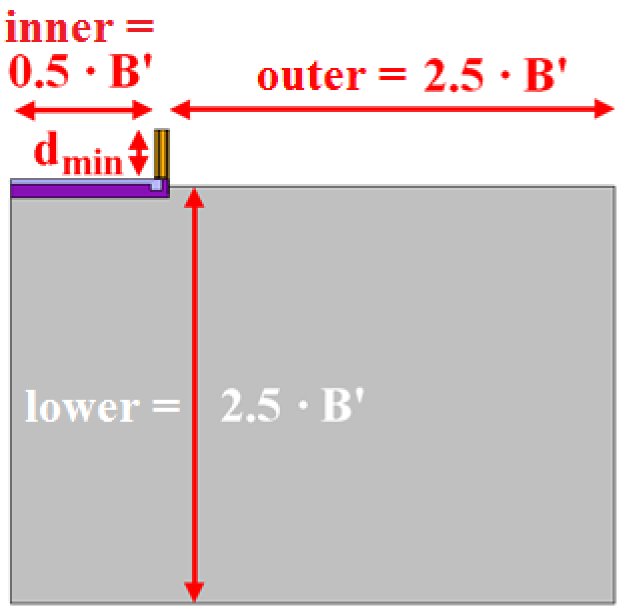

Figure 3.7 The distances to the cut-off planes for a two-dimensional analysis are shown in red arrowed lines.

According to Chapter 10.4.1 in SS-EN ISO 10211:2007, results calculated for a detail using a characteristic dimension B' of 8 m also applies for any slab with a B' larger than 8 m. This means that the dimensions of a detail do not need to be larger than for one of a characteristic dimension of 8 m. The accuracy of this statement is further looked into in Chapter 4.

3.4 Boundary conditions

When the boundary lengths and the size of the detail to analyze are known, the boundary conditions need to be correctly set. The boundary conditions for this report describe what the thermal conditions are at the boundaries of an analysis. For the analyses made in this report, those conditions can mean a constant room temperature, or an assumed constant heat flow at a certain depth of the ground.

In SS-EN ISO 10211:2007 and SS-EN ISO 13370:2007, the heat flow is always assumed to occur only between indoor and outdoor environment. By assuming a temperature of indoor and outdoor environment, the temperature-difference ΔT between those environments is known, and the detail's ability to transfer heat can be calculated by using equation (2.4), but using L_{2D} instead of L_{3D}. By assuming a temperature difference ΔT of 1 K, e.g. assuming 1°C indoors and 0°C outdoors, the thermal coupling coefficient L_{2D} and heat flow rate Q of a simulation will have the same magnitude (but with different units).

The assumption of heat exchanging only between indoor and outdoor air is not universally accepted however. As an example, some engineers assume a more or less constant temperature at a certain depth below the building, equal to the average annual outdoor temperature; this as a result of natural heat storage in the subsoil (Rantala, 2005 and Hagentoft, 2011).

A constant temperature in the sub-soil causes heat to exchange not only between indoor and outdoor, as in the assumptions in these standards, but also between above ground and the subsoil. With three different boundary temperatures (indoor, outdoor and subsoil), there will also be three different temperature differences ΔT (as illustrated in Figure 3.8), and thereby also three separate heat flows Q and thermal coupling coefficients L_{2D} (see equation (2.4)).

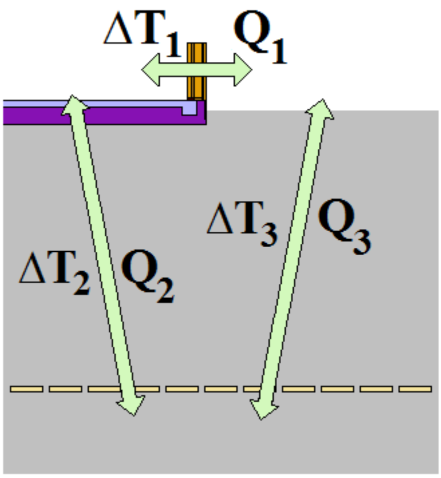

Figure 3.8 Illustration of the temperature differences and heat flows between indoors, outdoors and subsoil.

Figure 3.8 illustrates the three different temperature differences ΔT_1, ΔT_2 and ΔT_3 between indoor, outdoor and subsoil boundaries. The assumed constant temperature line is illustrated by a dashed line in the figure.

The main problem that occurs with these calculations is that the total heat flow Q obtained from heat simulation needs to be separated into the three heat flows that occur between each boundary, as illustrated in Figure 3.8. This separation of heat flows require some kind of weighting, which S. Rantala discusses in his report (Rantala, 2005).

Note that this report will only use the assumption of indoor and outdoor temperatures; the assumption of constant temperature in the subsoil is only mentioned as material for discussion in Chapter 6.

When performing a simulation according to SS-EN ISO 10211:2007, the inside of the wall and floor facing indoor air are assumed having indoor temperature, while the outside of the wall and the ground facing outdoor air are assumed having outdoor temperature. All other boundaries (including the upper cut of the wall) are assumed adiabatic, which means that no energy transfers through those boundaries in the analysis.

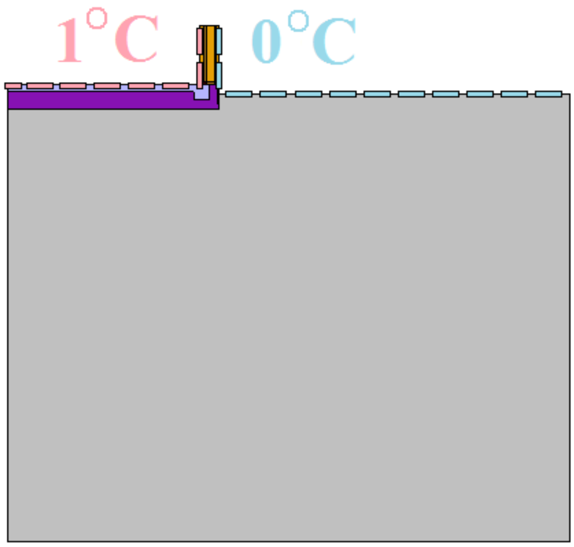

Figure 3.9 An example of temperature boundary conditions in a detail.

Figure 3.9 illustrates, with dashed lines, where to assume indoor and outdoor temperatures. Anywhere else, including top edge of the wall, adiabatic boundary conditions are assumed. Know that some of the soil in this figure has been cut out for this particular illustration, to show the junction more thoroughly.

3.5 Numerical calculation software

In order to find a somewhat correct value of the heat flow and thermal conductance of elements in two- or three-dimensional construction details, one normally needs some kind of numerical calculation software (it is possible to evaluate these values by formulas, but numerical calculation are more accurate). The software used for this thesis are HEAT2 and HEAT3, which both calculate the heat flow through materials by dividing a detail into cells and then solving the heat equations by means of explicit finite differences (Blocon, 2011).

In HEAT, the detail is built up in a pre-processor (see Figure 3.10) drawn with rectangles of chosen materials (properties of materials are changed in a material list). The coordinates of the rectangles can be put in manually if a reference point for the coordinate system is known (this point can also be put in manually), otherwise they are placed and modified with help from mouse pointer (putting in the coordinates manually is especially useful in HEAT3 for three-dimensional details, where keeping track of all objects in the detail can be tricky).

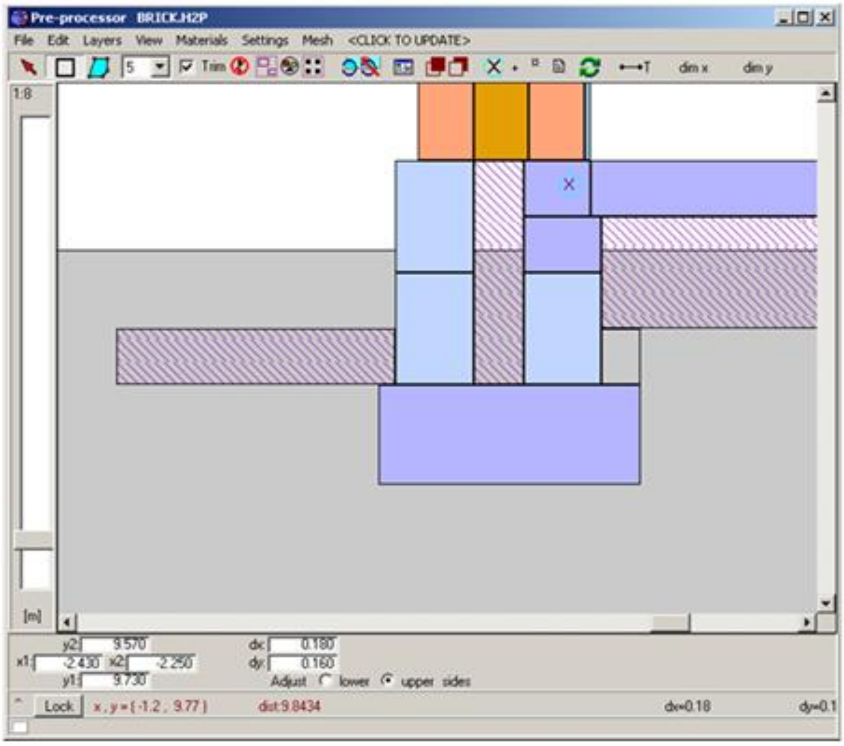

Figure 3.10 Detail seen in pre-processor in HEAT2.

Once the user is satisfied with a detail, it needs to be discretizised (divided into a mesh of cells). The user can in the pre-processor choose the density of the mesh and whether it should be concentrated around a point (expansion point) or evenly distributed. If the user doesn't set a density, 50·50 cells are automatically set. Since a cell can only be within one material, small details (boards, fillings etc.) will automatically get a finer mesh than larger details; see both details in Figure 3.11. A finer mesh normally gives more accurate results.

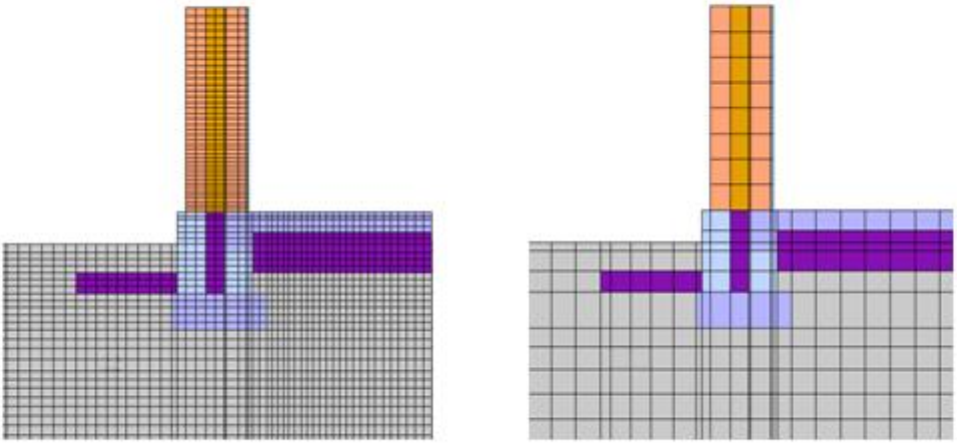

Figure 3.11 Mesh with (left) and without (right) expansion point at the room corner, seen through the post-processor for HEAT2. Both meshes are 200·200 cells large.

Figure 3.11 shows a cut-out of a wall-floor junction with the same number of cells but with and without expansion point. Both pictures are cut-outs, not showing most of the soil material. This might give the impression that the left picture, with a more dense mesh, has more cells; both pictures however are 200·200 cells large.

The right picture shows a mesh with evenly distributed cells; note though that at some areas the cells are automatically smaller because of unevenness of the material elements. The left picture, with a more dense mesh close to the building, has a sparser cell distribution further away from the building, which is not visible in this specific cut. This distribution is often more useful, since the most intense heat flow rate occurs around the building corner, which can be seen in simulation results in Figure 3.13.

Before a simulation can be done, the boundary conditions (temperatures and heat flows) of the detail need to be chosen. For HEAT2, each boundary is automatically given a boundary number, see Figure 3.13. Each boundary can then be given a boundary condition from an input-list, where the boundaries are defines manually. Each boundary not defined is automatically assumed adiabatic.

For HEAT3, the user instead creates volumes, similar to the material boxes used in a detail but with a boundary condition instead of material. These boundaries start where the material boxes end (such as the inner or outer surface of the wall). These boundaries can be seen as the air volumes that fill the indoor and outdoor cavities with different temperatures and surface resistances. All other surfaces that do not face a boundary condition are automatically assumed adiabatic.

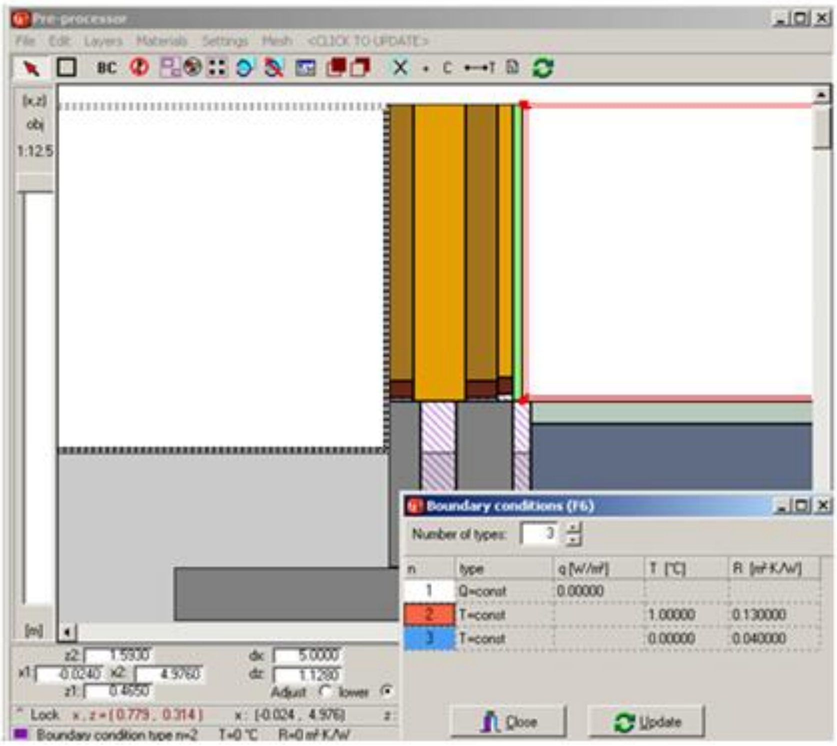

Figure 3.12 Boundary conditions in HEAT3.

Boundary conditions for indoors and outdoors in HEAT3 can be seen in Figure 3.12, where they are drawn with red and dashed lines for indoors and outdoors respectively. The boundary condition list is shown in the lower right hand corner.

Once the user is satisfied with a detail, its mesh and its boundary conditions, the user updates the detail into the post-processor where, after the heat simulation is done, the user can see heat flow and temperature patterns (heat flow seen in Figure 3.13).

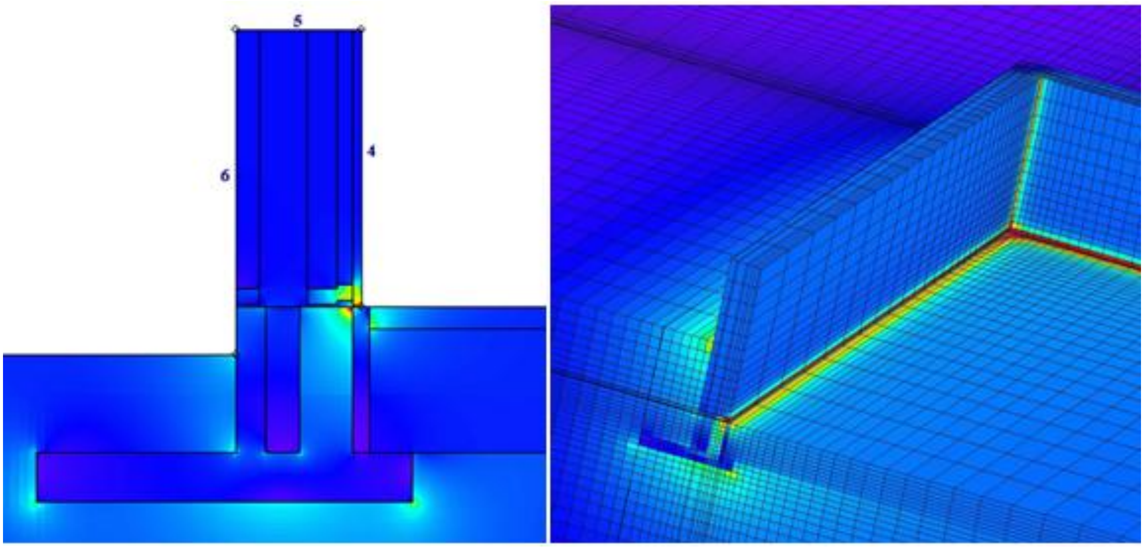

Figure 3.13 Heat flow for different simulated details in HEAT2 and HEAT3.

4 Parameter study

To compare the influence of changes of different parameters, a standard calculation has been done for four different cases/details, using both method A and method B (see equations (3.4) and (3.6) in Chapter 3.2) for calculating U_g. These standard calculations have been done thoroughly following the instructions of the standards and of Wetterlund (2010), with a relatively high cell density. These calculated Ψ-values are listed in Chapter 4.2. For each study where parameters have been varied (except the discretization study), the Ψ_g-value has been compared to that of the standard case. The results are then shown in percentage of deviation from the standard case. For all standard cases a characteristic dimension B' of 8 m has been used. When comparing results calculated with both method A and method B, the method used is written within bracket with the notation, e.g., Psi (A) when calculating the Ψ_g-value with method A.

The other purpose of this chapter is to verify the results achieved through suggested methods of two-dimensional analyses (HEAT2) against those of three-dimensional (HEAT3).

The results of each study have been documented in Microsoft Office Excel sheets seen in Appendix B; those results have then been translated into graphs with corresponding legends listed to the right hand side. For easier identification of which graph corresponds to which legend, the legends have been listed in the order the graphs appear for each study. Results are also listed in tables in each corresponding chapter.

Unless anything else is mentioned, the HEAT2 simulations are done with 400·400 cells while HEAT3 simulations are done with 75-150 cells (75·75·75 to 150·150·150 cells). The reason why not all HEAT3-simulations are done with 150 cells is that the simulation time for some of the details was very long; the number of cells were therefore reduced to reduce the simulation time.

Material data is obtained from the material list in HEAT2, SS-EN ISO 13370:2007 and literature used in Chalmers education (Hagentoft, 2009 and Petersson, 2004).

Table 4.1 Material list used for the parameter study.

Materials		
Cellular plastic	0.036	W/m·K
Mineral Wool	0.04	W/m·K
Gypsum Board	0.22	W/m·K
Isodrän	0.042	W/m·K
Concrete	1.7	W/m·K
LW Concrete 1600	0.8	W/m·K
Brick 6/19-hole	0.6	W/m·K
Leca block	0.205	W/m·K
Aercrete 1200 (Beam)	0.27	W/m·K
Aercrete 1800 (Carpet)	0.7	W/m·K
Aercrete 400 (Floor)	0.08	W/m·K
Plaster	1.0	W/m·K
Wood	0.14	W/m·K

Wood+MW 600/45	0.048	W/m·K
Aluminium	226	W/m·K
Soil materials		
Clay, silt	1.5	W/m·K
Sand, gravel	2	W/m·K
Homogenous rock	3.5	W/m·K

4.1 Details simulated

Four different details have been analysed to see if the results vary much between different parameters.

4.1.1 Detail 1: Simple timber-joist junction

This detail consists of a timber joist wall with mineral wool insulation and EPS facade, placed upon concrete slab with a thick corner beam, covered with EPS insulation underneath and outside.

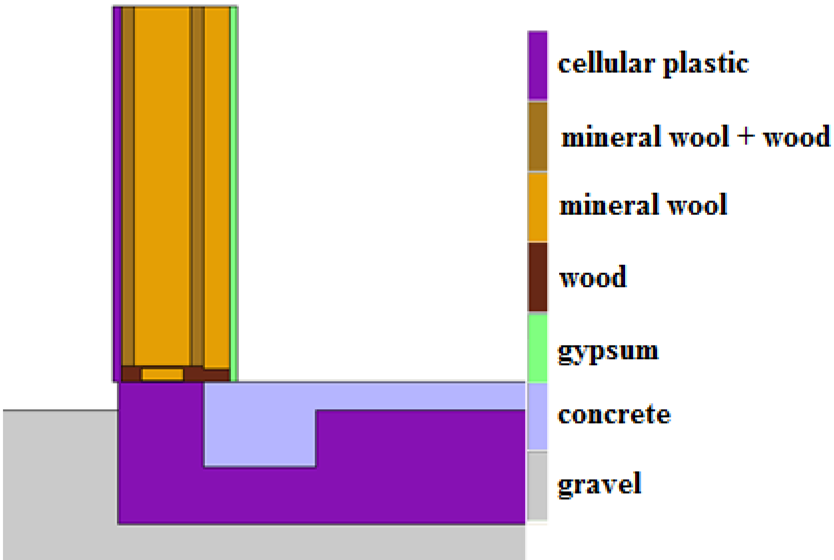

Figure 4.1 Detail 1, a relatively simple timber-joist junction on concrete floor with EPS floor insulation.

4.1.2 Detail 2: Sandwich wall on lightweight concrete

This sandwich wall (brick wall with mineral wool in-between) is standing on a concrete floor with partly lightweight concrete corner construction, with EPS insulation at the edge, underneath the concrete slab and outside the corner to prevent ground frost to reach the floor construction.

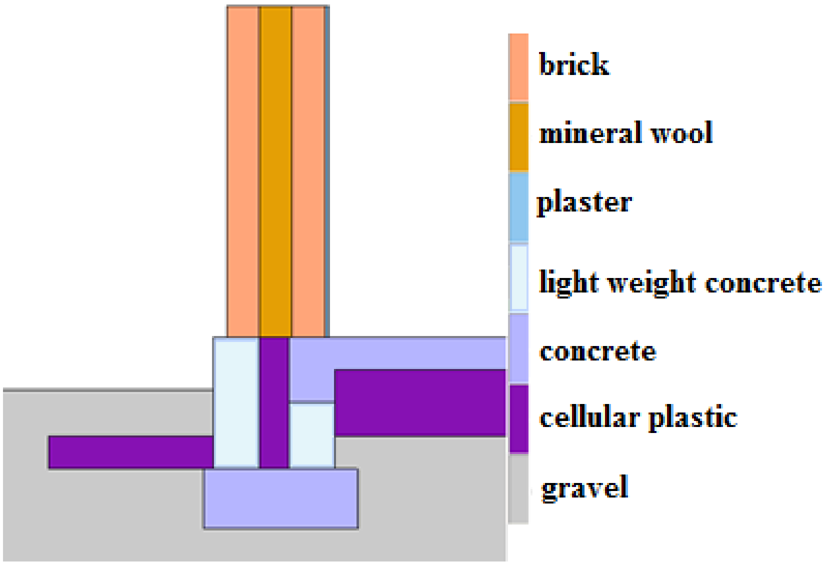

Figure 4.2 Detail 2, sandwich concrete wall on a lightweight concrete and concrete floor construction with EPS floor insulation.

4.1.3 Detail 3: Low-conductivity concrete

This construction uses a special low-conductive kind of concrete (λ=0.08-0.27 W/m·K for this detail, comparable with standard concrete, λ=1.7 W/m·K) (Aercrete, 2011). This concrete has three different strengths and conductivities for the floor slab, the floor carpet and the corner beam construction. Figure 4.3 shows the different kinds of Aercrete with different colours. With a low conductivity, the concrete serves both as construction material and as insulation. Some edge insulation is still used between the concrete elements. The specific property that this construction gets makes the results stand out somewhat compared to the other details.

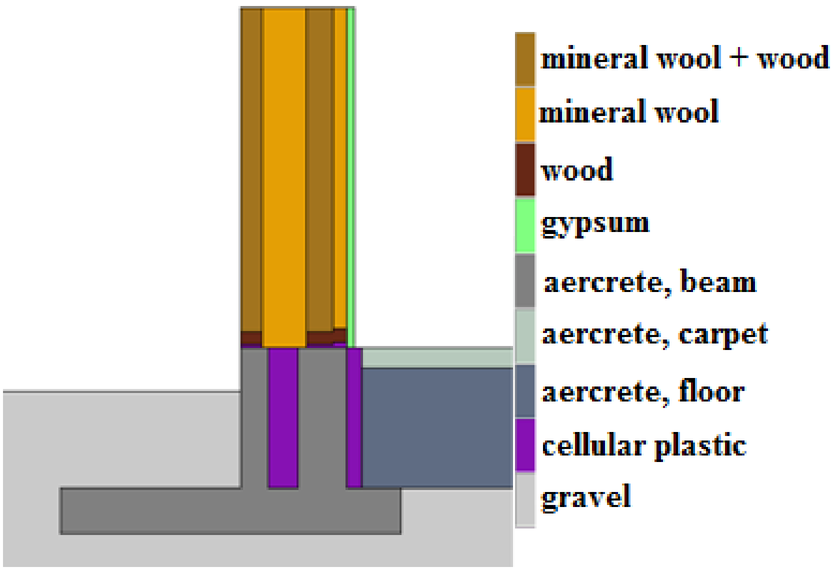

Figure 4.3 Detail 3, a concrete floor construction made up of three different low conductive concrete types.

4.1.4 Detail 4: EPS wall-floor junction

This detail has a similar slab construction as that of detail 1, but has a Leca-block wall with outer insulation partly of mineral wool and partly of cellular plastic and an Isodrän-board. Isodrän is a material that both thermally insulates and prevents water ingress (Isodrän, 2011). For these simulations however, it is only the thermal properties that are of interest.

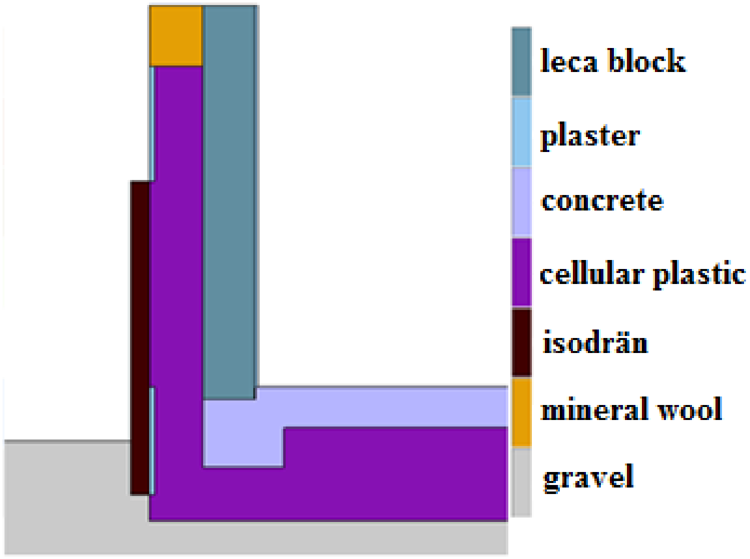

Figure 4.4 Detail 4, a concrete slab construction with Leca-block wall and EPS-insulation continuous under slab and outside wall.

4.2 Results from standard cases

Table 4.2 Calculated Ψ–values for standard cases for all four details with both method A and B.

Detail	Standard Ψ-value		Difference of A and B
	Method A	Method B	
1	0.087	0.082	+5.5%
2	0.234	0.220	+6.4%
3	0.052	0.035	+47.3%
4	0.091	0.085	+6.9%

Table 4.2 shows the calculated Ψ-values for the standard cases, with a comparison of the methods' results expressed in percentage of difference between method A and B. For details 1, 2 and 4, the methods show somewhat similar results, varying 5-7 percent. For method 3 however, the methods vary with almost 50 percent. This gives the impression that either one or both methods are unreliable. For this reason, one

might need a closer description or recommendation in the standard of which method to use. Such a large difference might also raise suspicion of whether or not the calculations have been done correctly. For the parameter study further on though, results are similar to those of the standard cases.

The results also show that Ψ–values can vary greatly between different details. Details 1 and 4, both having EPS-plastic covering the bottom of the whole floor construction, show similar results, around 0.08-0.09 W/m·K. Detail 3 has a lower Ψ-value than 1 and 4, which gives an indication that the low-conductive concrete works well together with vertical EPS-insulation. One might however discuss what parts of this junction detail that is most important for a low Ψ-value; the corner beam construction, the EPS-insulation or the floor construction (which for this detail also works as floor insulation).

Detail 2 has by far the highest Ψ-value of all details. Since the bottom of the floor is covered with EPS-insulation, and the wall-insulation continues down to the vertical edge EPS-insulation, one might conclude that the light weight concrete between the insulations works ineffectively to reduce thermal bridges.

4.3 Discretization

SS-EN ISO 10211:2007 mentions two rules for discretization of an analysis, one that involves a temperature factor that is not treated in this thesis, and one that says that doubling the number of auxiliary planes in a simulation should not influence the heat flow results more than 1 %. However, since the ψ_g-value is just a fraction of L_{2D} (5-22 % for the tested details), it should be relatively more vulnerable to changes.

Thermal coupling coefficients L_{2D} and $L_{2D,a}$ have been analysed for 25, 50, 75, 100, 150, 200, 300, 400, 600 and 700 cells (maximum number of cells for the software version of HEAT2 used for this thesis), both with and without an expansion point. When using an expansion point, it is placed in the most critical heat flow area of the detail, usually just below the inner corner of the connection. Each result is then compared to one which has double the number of cells, to see if the heat flow has increased more than 1 %. For this analysis, detail 1, 2 and 3 have been used.

The simulation time for the analyses has been recorded to see if there is a certain point where increasing the number of cells gets ineffective compared to the necessary accuracy of the results.

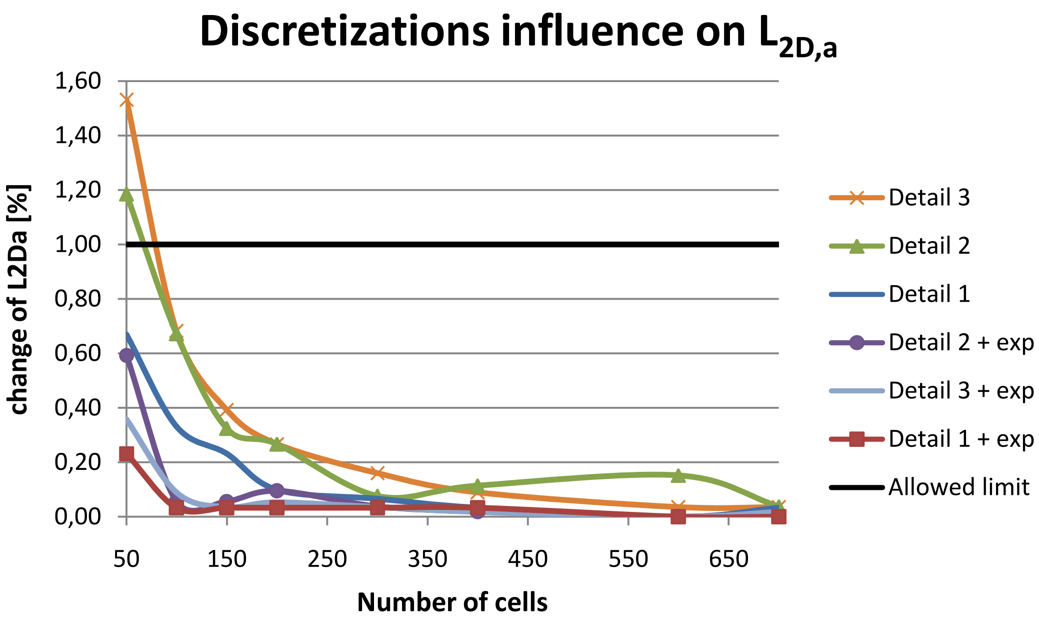

Figure 4.5 Discretization, with and without expansion point, of three different $L_{2D,a}$ details. 1%-limit is marked with thick line.

For the analysis of $L_{2D,a}$ (thermal coupling coefficient for floor and ground), subdividing the cells seems to have little influence on the results after about 250 cells, see Figure 4.5. The results of Detail 2 without expansion point deviates from that of the other details between 400 and 700 cells before reaching more stable behaviour. The reason for this can be that Detail 2 in HEAT2 has few thin/small material blocks, which makes the mesh relatively coarse if no expansion point is used.

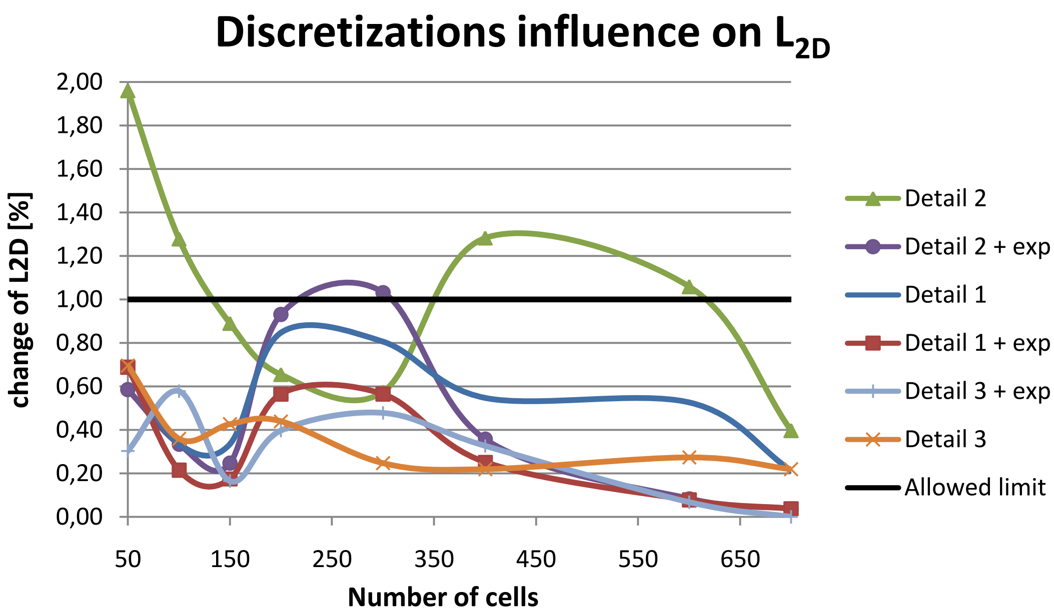

Figure 4.6 Discretization, with and without expansion points, of three different L_{2D}-details. 1%-limit is marked with thick line.

For L_{2D} (thermal coupling coefficient for whole detail), Detail 1 and 3 follow a similar pattern between 150 and 600 cells and never exceeds the 1%-limit within that interval. The L_{2D}–values of Detail 2 on the other hand is less stable, both exceeding the 1%-limit at different intervals. Especially the graph of Detail 2 without expansion point deviates from that of the other details. Note that Detail 2 without expansion point exceeds the 1%-limit at two points, which makes it less likely that the exceeding of the 1%-limit within the interval of 350 to 600 cells is an error in the simulation results, though this is still possible.

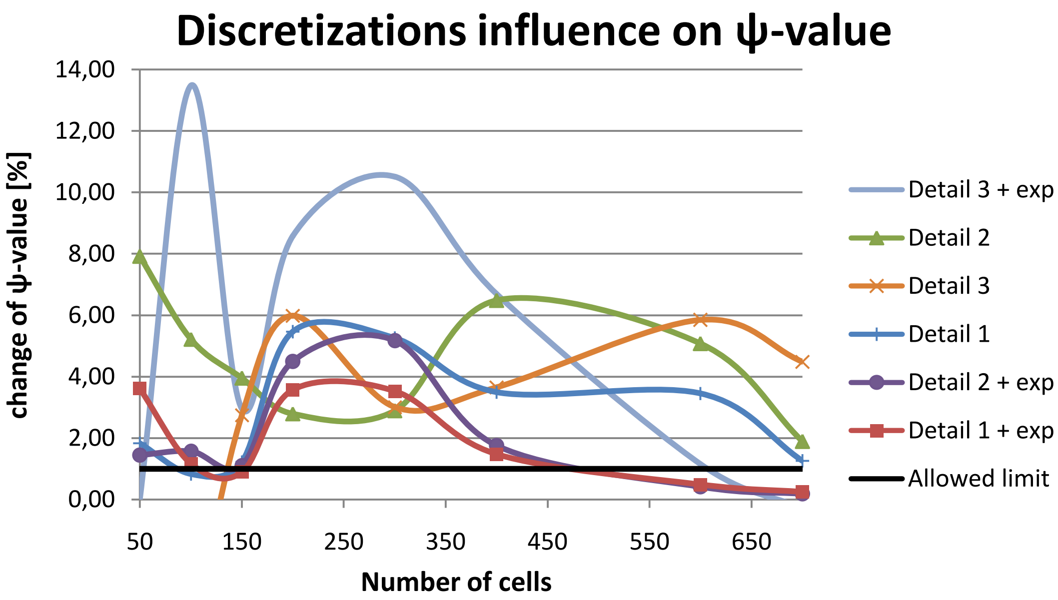

Figure 4.7 Relative change of ψ-value for three different details with and without expansion point. 1%-limit is marked with thick line.

As mentioned earlier, the Ψ_g-value is more sensitive to discretization, which is indicated in Figure 4.7. These numbers are results of subtracting the $L_{2D,a}$-results and the more or less constant wall transmittance $h_w \cdot U_w$ from the L_{2D}-results. The heat flow through the wall was very stable already at 25 cells for all three details, changing not more than 0.2% at most. This is not shown in any diagrams for this thesis, and is only mentioned here to further explain the behaviour of the Ψ-value.

All details with expansion point goes below the 1%-limit at a certain point; detail 1 and 2 after 500 cells and detail 3 after about 600 cells; other than that they exceed the 1%-limit. Note that the maximum allowed change of heat flow (or Ψ_g–value in this case) mentioned in SS-EN ISO 10211:2007 only applies for the results of one detail simulation, not a combined result from several simulations, e.g. the Ψ_g-value, see beginning of Chapter 4.2.

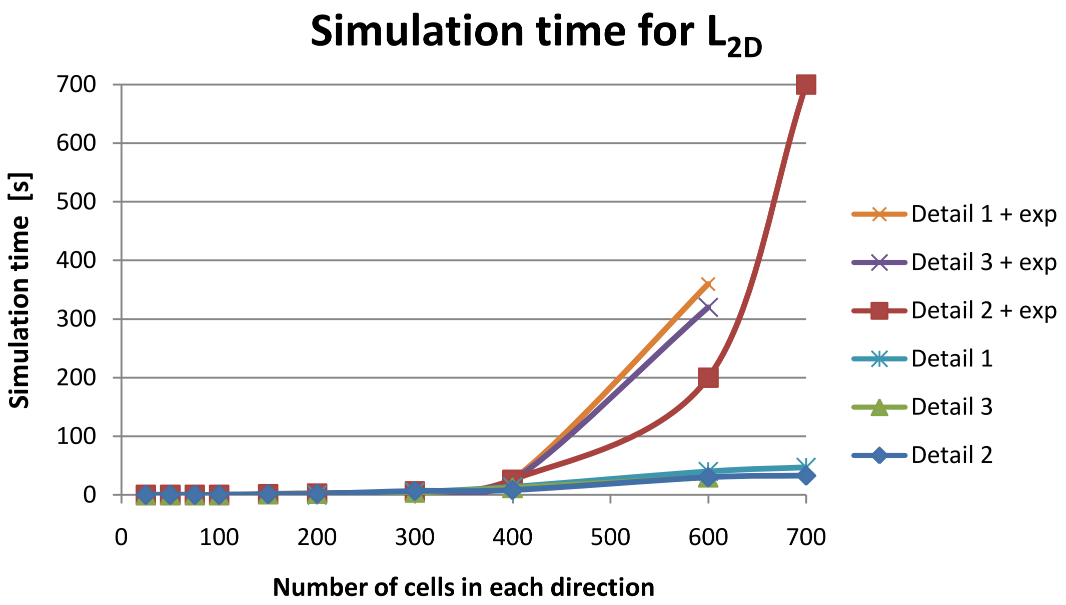

Figure 4.8 Simulation time for different degrees of discretization for Detail 2 and 3 with and without expansion points.

The simulation time has been recorded for the L_{2D}-analyses for all three details with and without expansion point. During the simulations, only Microsoft Word and Excel have been running simultaneously as HEAT. The computer used has a CPU of 2 Ghz and 2 GB working memory. Simulations longer than 20 minutes have been aborted due to lack of time; for this reason the results for Detail 1 and 3 with expansion points shown in Figure 4.8 are abruptly cut off at 600 cells.

The results in Figure 4.8 are somewhat similar from 25 to 350 cells; after that point the evenly distributed meshes (without expansion point) have a more stable increase of time while the concentrated meshes (with expansion point) have a significantly longer simulation time.

A few of the simulations made in HEAT3 have also been clocked, although the results are too few to show in this report. It should be mentioned that some of those simulations, made with relatively large meshes, have had very short simulation time when varying the shape of the floor slab to more oblong shapes. The reason for this is in this report unknown, but it can be discussed if this variation has anything to do with inconsistent performance of HEAT software.

4.4 Varying the size of the detail

This test is divided into two; in both tests the size of detail 1, 2 and 3 are changed by varying B' and thereby also the distance to the outer, lower and inner boundaries, since all of these distances are multiples of B'. The span of B' varies from 4 m to 12 m; this means that the outer (between wall and outdoor soil boundary) and lower (between ground and subsoil) distances vary between 10 m and 30 m, while the inner distance varies between 2 m and 6 m.

Test 1 varies only the outer and lower distances to see if all the soil recommended for a detail is needed (only a few percent of the detail consist of the building corner, the rest is soil). This test gives an indication of the importance of amount of soil used for a simulation. The test is done for *B'* of 4 m, 8 m and 12 m.

Test 2 varies all three distances that are affected by *B'* (outer, lower and inner boundary distance). By doing this, the simulation results show if the correct assumption of the size of the slab has any influence on the ψ_g-value, since *B'* is directly dependent on the floor slab size and shape. This test is done with *B'* of 4 m, 6 m, 8 m, 10 m and 12 m. If unclear what is meant with outer, lower and inner distances, see Figure 3.7 in Chapter 3.3.

The results for Test 1 are shown in Figure 4.9 and are also listed in Table 4.3.

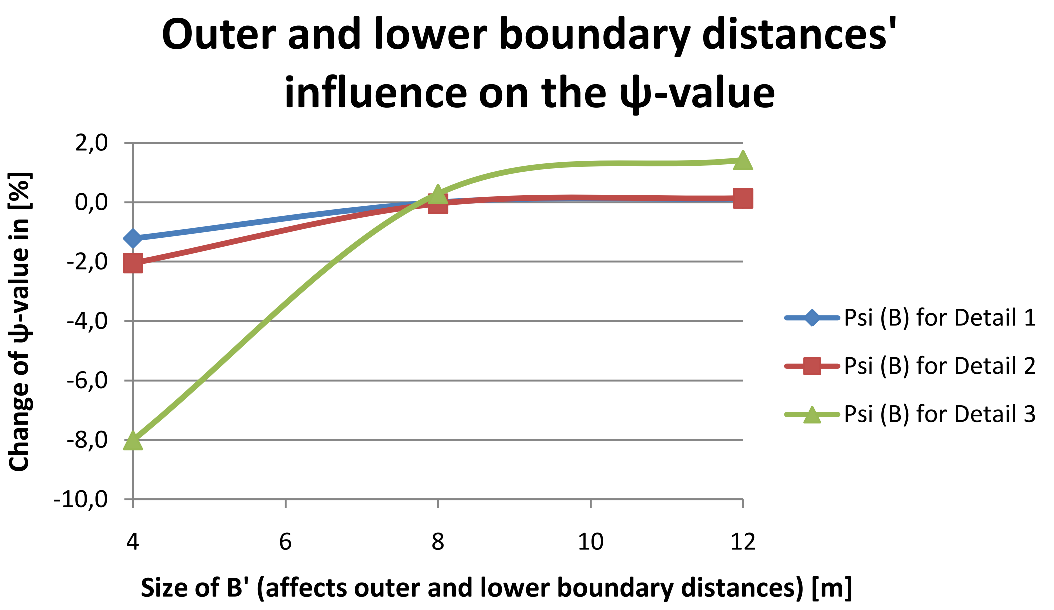

Figure 4.9 Change of ψ-value when changing outer and lower boundary distances, having the inner distance being fixed. The methods used are mentioned within brackets for each detail.

Table 4.3 Results of ψ-values when varying lower and outer boundary distances. Largest positive and negative values are written in bold.

Analysis	Detail	Ψ-value [W/m·K]		
		B'=4 m	Standard value	*B'*=12 m
Varying outer and lower boundary distances	1(B)	0.081 (-1.2%)	0.082	0.083 (+0.1%)
	2(B)	0.215 (-2.0%)	0.220	0.220 (+0.1%)
	3(B)	0.032 **(-8.0%)**	0.035	0.036 **(+1.4%)**

For Test 1, when varying just the outer distances, i.e., varying the amount of soil of the analysis, Detail 1 and 2 seems quite stable, changing only about 2% at *B'*=4 m. Detail 3 has a larger variation of -8% at *B'*=4 m to +1.4% at *B'*=12 m. All three results indicate that the ψ_g-value increases with a larger amount of soil used in the analysis, while it decreases with decreasing amount of soil.

Results from Test 2 are shown in Figure 4.10 and listed in Table 4.4.

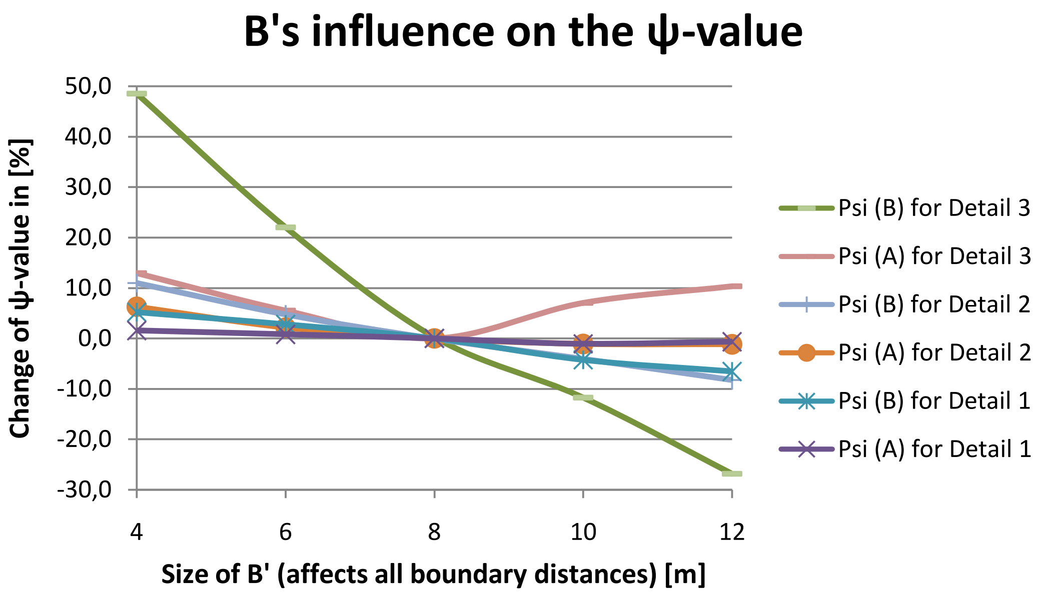

Figure 4.10 Change of ψ-value when changing the characteristic dimension B'. The methods used are mentioned within brackets for each detail.

Table 4.4 Results of ψ-values when varying all boundary distances. Largest positive and negative values are written in bold.

Analysis	Detail	Ψ-value [W/m·K]		
		B'=4 m	Standard value	*B'*=12 m
Varying all boundary distances	1(A)	0.088 (+1.6%)	0.087	0.086 (-0.6%)
	1(B)	0.087 (+5.2%)	0.082	0.077 (-6.6%)
	2(A)	0.249 (+6.3%)	0.234	0.231 (-1.2%)
	2(B)	0.244 (+11.0%)	0.220	0.202 (-8.3%)
	3(A)	0.058 (+12.9%)	0.052	0.057 (+10.4%)
	3(B)	0.052 **(+48.6%)**	0.035	0.025 **(-26.9%)**

The results of Test 2 show a quite different trend than that of Test 1. In this test the ψ_g-value of details with lower *B'* has a higher value (up to 48.6% higher), while for larger details (*B'*>8m) the ψ-value is more unpredictable, with both lower and higher values (-26.9% to +10.4%). As for Test 1, Detail 3 has a significantly larger variation than the first two details.

4.5 Varying the ground material

One can assume that a part of the heat that transfers through the junction corner (defined through the ψ_g-value) transfers through the ground. This assumption indicates that the ψ_g-value is more or less dependent on what ground material is used. For this study, all four details have been simulated using different λ-values for the soil, varying from 1 W/m·K to 5 W/m·K with 0.5 W/m·K step changes. For easier comparison, the λ-values for different types of soils that SS-EN ISO 13370:2007 recommends are marked with vertical dashed lines in Figure 4.11. These ground materials are all listed in Table 4.1 in the beginning of Chapter 4. The results of varying the grounds λ-value are shown in Figure 4.11 and are listed in Table 4.5

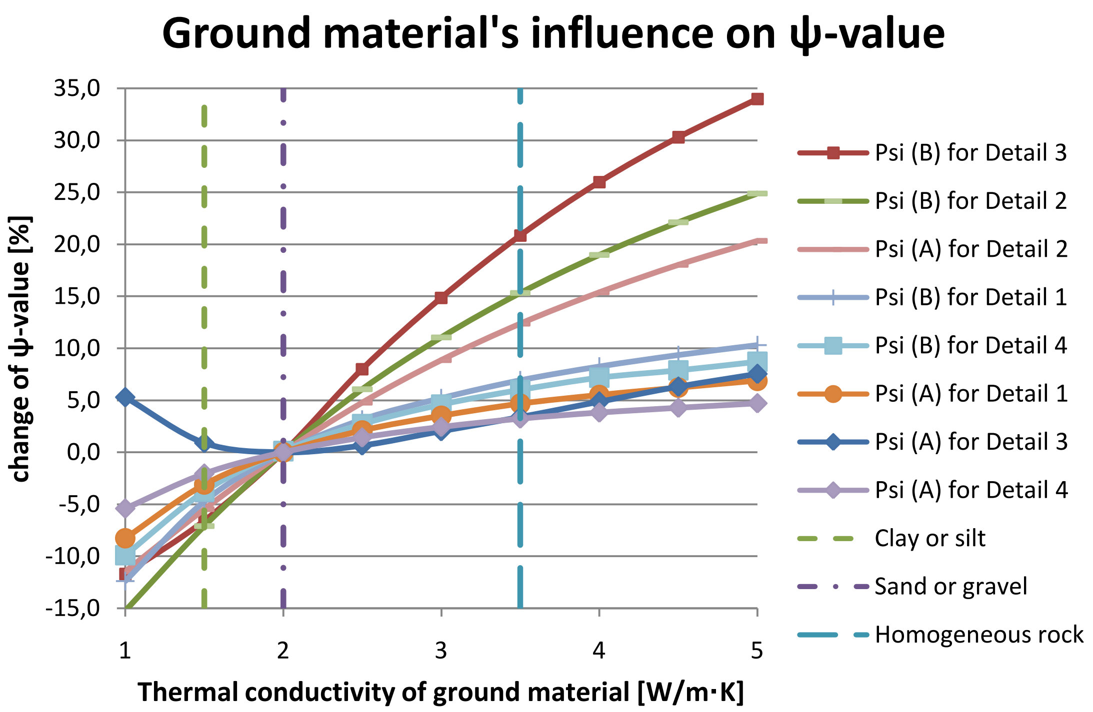

Figure 4.11 Relative change of ψ_g-value when varying type of soil for all four details with both method A and B. Recommended values for clay/silt, sand/gravel and rock are marked with vertical lines.

*Table 4.5 Results of ψ-values when varying the ground material's **λ**-value. Only the span of **λ** between 1.5-3.5 is mentioned here. Largest positive and negative values are written in bold.*

Analysis	Detail	Ψ-value [W/m·K]		
		If λ=1.5 W/m·K	Standard value	If λ=3.5 W/m·K
Varying type of soil material	1(A)	0.084 (-3.1%)	0.087	0.091 (+4.7%)
	1(B)	0.079 (-4.7%)	0.082	0.088 (+6.9%)
	2(A)	0.221 (-5.5%)	0.234	0.263 (+12.4%)
	2(B)	0.204 **(-7.1%)**	0.220	0.254 (+15.3%)
	3(A)	0.052 (+0.9%)	0.052	0.053 (+3.4%)
	3(B)	0.033 (-6.6%)	0.035	0.042 **(+20.9%)**
	4(A)	0.089 (-2.1%)	0.091	0.094 (+3.2%)
	4(B)	0.082 (-3.8%)	0.085	0.090 (+6.0%)

The results show a clear indication that different details are more or less dependent of correct input of the thermal conductivity of the soil. The result from Detail 3 (method A) clearly stands out from that of the other details, and indicates that the ψ-value can increase both with more and less conductive soil. These results (for λ of 1 W/m·K and 1.5 W/m·K) have been re-calculated several times to ensure that they are correct calculated.

As seen on the vertical axis of the diagram, the ψ_g-value can be strongly dependent on the soil material, varying from about -7.1% up to +20.9% between the recommended soil values (clay/silt and homogenous rock respectively) in this test.

4.6 Varying ground insulation

This analysis consists of two quite similar tests. Test 1 is to see the importance of correct thickness of ground insulation, which might not always be known for an engineer and can be difficult to find on an existing building. The test has been done by varying the thickness of the insulation below the slab and then compare the relative change of the ψ_g-value of the corner. The horizontal axis of the result diagram (Figure 4.12) shows the relative variation (around 80% - 120%) of the thickness of the ground insulation, to simplify the comparison between the different details. 100% relative insulation thickness is equal to the actual thickness used in the standard case for each specific detail. Since all details have different ground insulation thicknesses, a relative variation of the thickness (defined in %) is more consistent.

Test 2 is similar to Test 1 but instead varies the thermal conductivity of the ground insulation material. This variation is also done in relative values since Detail 3 uses different insulation materials with different λ-values than what is used in the other details. The horizontal axis of the result diagram (Figure 4.12) shows the relative variation of the thermal conductivity (around 80% - 120%) of the ground insulation, to simplify the comparison between the different details.

For Figure 4.12 and Figure 4.13, the horizontal axis represents an increasing thermal resistance of the ground insulation (increasing insulation thickness for Test 2 and decreasing thermal conductivity for Test 1).

For Test 1, the actual thicknesses used as parameter are listed, together with corresponding relative thickness, in Table 4.6.

Table 4.6 Minimum and maximum thicknesses of ground insulation used for Test 1, including standard thicknesses for comparison. Corresponding relative thicknesses are shown within brackets.

Detail	Min. thickness [m]	Standard thickness [m]	Max. thickness [m]
1	0.320 (80%)	0.400	0.480 (120%)
2	0.160 (80%)	0.200	0.240 (120%)
3	0.320 (80%)	0.400	0.492 (123%)
4	0.280 (80%)	0.350	0.420 (120%)

The results for Test 1 are shown in Figure 4.12 and are also listed in Table 4.7

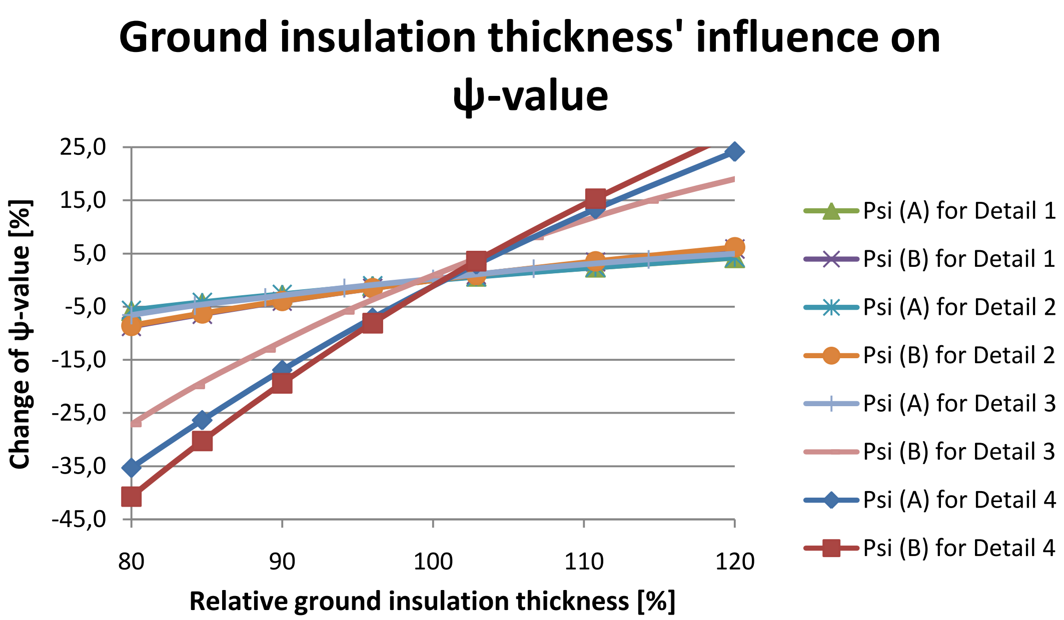

Figure 4.12 Relative change of ψ-value when varying the thickness of the ground insulation.

Table 4.7 Results of ψ-values when varying ground insulation's thickness. Largest positive and negative relative values are written in bold.

Analysis	Detail	Ψ-value [W/m·K]		
		Min. relative thickness	Standard value	Max. relative thickness
Varying insulation thickness	1(A)	0.082 (-5.8%)	0.087	0.091 (+4.1%)
	1(B)	0.075 (-8.7%)	0.082	0.087 (+5.8%)
	2(A)	0.221 (-5.7%)	0.234	0.244 (+4.2%)
	2(B)	0.201 (-8.6%)	0.220	0.233 (+6.1%)
	3(A)	0.048 (-6.6%)	0.052	0.054 (+5.5%)
	3(B)	0.026 (-27.1%)	0.035	0.042 (+21.1%)
	4(A)	0.059 (-35.3%)	0.091	0.113 (+24.1%)
	4(B)	0.050 **(-40.8%)**	0.085	0.108 **(+27.7%)**

For Test 1, all details have an increased ψ_g-value with an increasing thickness of the floor insulation. Detail 3 and 4 seem more sensitive to changes of the thickness. The ψ_g-value varies from -40.8% with the lowest thickness to +27.7% with the thickest insulation.

For Test 2, the actual λ-values used as parameter are listed, together with corresponding relative λ-value, in Table 4.8.

*Table 4.8 Maximum and minimum **λ**-values of ground insulation used for Test 2, including standard **λ**-value for comparison. Corresponding relative ψ-values are shown within brackets.*

Detail	Max. λ-value [W/m·K]	Standard λ-value [W/m·K]	Min. λ-value [W/m·K]
1	0.043 (118.1%)	0.036	0.030 (83.3%)
2	0.030 (118.1%)	0.036	0.030 (83.3%)
3	0.095 (118.8%)	0.080	0.065 (81.3%)
4	0.030 (118.1%)	0.036	0.030 (83.3%)

The results for Test 1 are shown in Figure 4.13 and are also listed in Table 4.9.

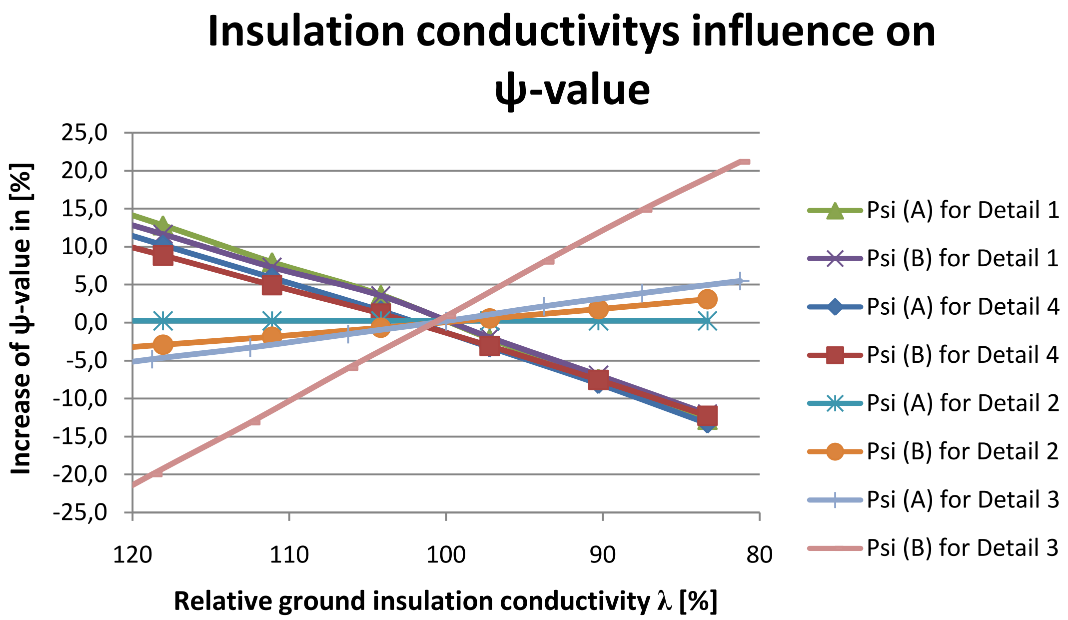

Figure 4.13 Change of ψ-value when varying the conductivity of the ground insulation.

Table 4.9 Results of ψ-values when varying ground insulation's ***λ****-value. Largest positive and negative relative values are written in bold.*

Analysis	Detail	*Ψ*-value [W/m·K]		
		Max. relative thermal conductivity	Standard value	Min. relative thermal conductivity
Varying insulation conductivity	1(A)	0.098 (+12.8%)	0.087	0.076 (-12.8%)
	1(B)	0.092 (-11.7%)	0.082	0.073 (-12.0%)
	2(A)	0.231 (-1.1%)	0.234	0.237 (+1.4%)
	2(B)	0.213 (-2.9%)	0.220	0.227 (+3.1%)
	3(A)	0.049 (-4.8%)	0.052	0.054 (+5.5%)
	3(B)	0.028 **(-20.0%)**	0.035	0.042 **(+21.1%)**
	4(A)	0.100 (+10.2%)	0.091	0.079 (-13.3%)
	4(B)	0.092 (+8.8%)	0.085	0.075 (-12.2%)

For Test 2, Detail 1 and 4 show very different behaviour than Detail 2 and 3, decreasing instead of increasing. The results are also much more spread out than for Test 1, varying from around -20% to +21.1% for detail 3 while the other details vary from +13.3% down to -12.8%. Note that all details have varying usage of the ground insulation with different solutions for the corner insulation, see Figure 4.1 to Figure

4.4. For detail 3, only the floor slab insulation has been included in the variation, since the other kinds of Aercrete-materials in the detail have different thermal conductivity.

4.7 Results of parameter study

For a more comprehensive overlook of the maximum variations (both positive and negative) of the Ψ_g-value for each of the parameter studies (see Chapters 4.4-4.6), they are listed in

Table 4.10.

Table 4.10 Change of ψ–value for each of the parameter studies.

Analysis	Largest negative change	Largest positive change
Varying outer and lower boundary distances	-8.0%	+1.4%
Varying all boundary distances	-26.9%	+48.6%
Varying type of soil material	-7.1%	+20.9%
Varying insulation thickness.	-40.8%	+27.7%
Varying insulation conductivity	-20.0%	+21.1%

The results from this study shows that the correct value of B' has the largest influence on the Ψ_g-value of all the parameters studied. Since the outer and lower distance seems to have relatively small influence on the Ψ_g-value as mentioned above, one might conclude that it is the inner distance (and thereby the size of the slab) used for the analysis that has this large effect on the results.

The correct thickness and thermal conductivity of the ground insulation both seem to affect the Ψ_g-value greatly (22-40 %). Both of these parameters can be difficult to determine for already existing constructions since the under-floor insulation might be unreachable without disassembling the floor construction.

The correct thermal conductivity of the soil material also seems to have some importance for the Ψ_g-value (7-20 %), while the correct amount of soil included in the analysis (determined by the value of B') seems to have little effect on the results (1.5-8 %).

4.8 Verifying methods for 2D analysis

All tests described so far in the report are done through two-dimensional analyses. However, it is also of interest to find out how close the results of the methods described in the standards are to those of a three-dimensional analysis using the same standards. The idea of the calculation procedure in SS-EN ISO 10211:2007, described throughout Chapter 3 in this report, is to find the ψ_g- and U_g-value of a two-dimensional detail and then apply those results for the whole perimeter of a building. These results are then supposed to represent the actual heat transfer ability of such a building. To confirm this, Detail 1 and 3 have both been detailed as three-dimensional details in HEAT3.

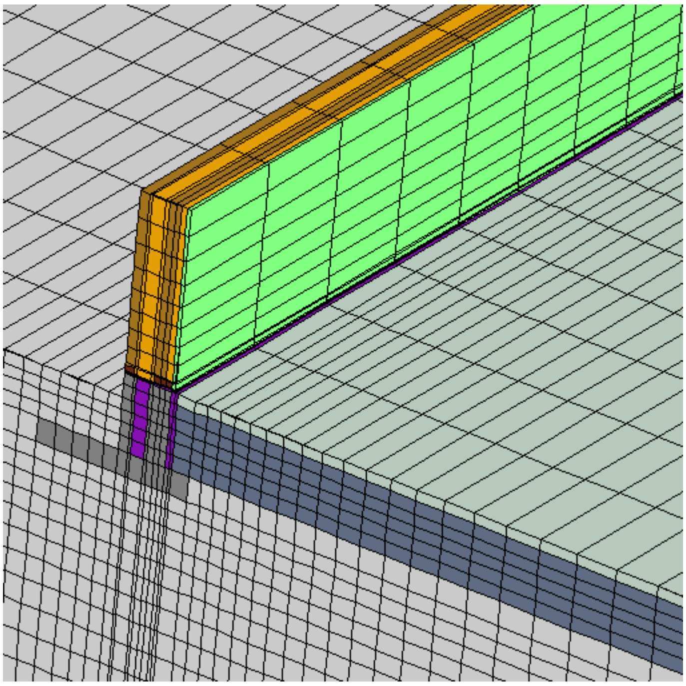

Figure 4.14 Example of Detail 3 in HEAT3.

For the three-dimensional analyses both detail analyzed has been detailed with three different slab shapes: 16x16 m², 12x24 m² and 10x40 m², each having a characteristic dimension B' of 8 m. The cuts have been made, as explained in Chapter 3.3, in the middle of the slab at a symmetry line and at a wall height of d_{min}.

Both details have also been simulated in a two-dimensional analysis, again with a B' of 8 m. Those results (including both method A and B) have then been applied as explained in equation (3.1) to derive the steady state ground heat transfer coefficient H_g. Since the three dimensional analysis has included walls above ground, the two-dimensional analysis needs to include them as well. Therefore, a wall heat transfer coefficient H_{wall} has been calculated by multiplying the $U_w \cdot h_w$-value from the two-dimensional analysis with the perimeter P of the building, see equation (4.1).

$$H_{wall} = U_w \cdot h_w \cdot P \qquad \left[\frac{W}{K}\right] \qquad (4.1)$$

Where:

H_{wall} is the wall heat transfer coefficient [W/K]
$U_w \cdot h_w$ is the wall's ability to transfer heat, obtained from 2D-analysis [W/m·K]
P is the building's perimeter [m]

The sum of H_g and H_{wall} may then be compared to the results of the three-dimensional analysis L_{3D}. To find the deviation of the results from the two-dimensional analysis in percent, both the results (2D and 3D) are compared to each other as written in equation (4.2). The deviation then gives an indication on how correct the results are.

$$Deviation = \left(\left(\frac{L_{3D}}{H_g + H_{wall}} \right) - 1 \right) \cdot 100 \qquad [\%] \qquad (4.2)$$

The results of equation (4.2) are shown in Table 4.11.

Table 4.11 Results from the 2D-3D verification, shown as deviation in percentage for slab on ground, see equation (4.2).

	16x16 m^2	12x24 m^2	10x40 m^2	24x24 m^2
Detail 1 (A)	-0.3%	2.1%	1.0%	-4.4%
Detail 1 (B)	-0.3%	1.2%	0.1%	-5.4%
Detail 3 (A)	1.4%	4.3%	2.1%	-8.1%
Detail 3 (B)	-0.8%	2.0%	-0.2%	-10.3%

This verification shows that the sum of the heat transfer coefficients H_g for the ground and H_{wall} for the wall, both derived from two-dimensional analysis and calculations including both method A and B, give results with relatively low deviation (0.1-4.3%) compared to those of three-dimensional analysis. This includes varying the shape of the floor slab, but retaining a constant value of B'. The results for analysis made for a B' of 8 m are not applicable to larger slabs however, as the deviation lies between 4.4% and 10.3%.

5 Conclusion

The main purpose of this thesis has been to specify, analyze and verify the calculation methods explained in two ISO-standards; SS-EN ISO 10211:2007 and SS-EN ISO 13370:2007.

From the experience from the workshop in March 2011 mentioned in the background, and from few interviews that have been made with engineers (specially H. Wetterlund and S. Kildishev), the instructions in these two standards can be greatly improved by more thorough descriptions, and might also need additional illustrations to explain e.g. placement of cuts and boundaries. Closer description or recommendation of the methods and their difference for the results would also be useful in the standards.

As for the study of the importance of correct parameter input, all parameters have shown to have importance for correct calculations of the Ψ_g-value. The size of the floor slab and the thickness and thermal conductivity of the ground insulation both have greatly importance to the Ψ_g-value; the soil's thermal conductivity have some importance while the amount of soil in the detail has some to little importance.

The verification shows that the shape of the floor slab has little importance for the heat transfer coefficients H_g for ground and H_{wall} for the wall together. The results for analysis made for a B' of 8 m are not applicable to larger slabs, and as for basement cases, the standard is insufficient or too inaccurate to give reliable results.

6 Discussion

The main purpose of standards of the kind used in this thesis, is to ensure that there are as little difference and errors between the calculated results as possible. Further on, the values calculated need to be calculated in the same way they are supposed to be used.

As an example, the wall's transmittance is suggested to be calculated through numerical calculation, as in the procedure used in this report, see Chapter 3.2 and Appendix A. If there is a joist construction in the wall, this is included in the calculation of L_{2D}. Therefore, one might think that it needs to be included in the analysis of $U_w \cdot h_w$ as well, so that in the end the thermal transfer ability of the joist is excluded from the Ψ-value.

If the joist is excluded from the Ψ-value however, it instead needs to be included in the wall's U-value, or added as an extra Ψ-value when all thermal transmittances are applied on for the whole building. For this reason, it might be more convenient to include the joist in the Ψ-value. This is an example of details that might need mentioning in the standard for the safety of errors. Future thesis can include analysing similar details and whether they have a significant effect compared to the whole building envelope.

Other aspects to study in future thesis are other shapes and sizes of floor slabs for the verification, also including less insulated floor slabs, see equation (3.10) in Chapter (3.2). The slab-sizes analyzed for this thesis has been relatively simple, only changing the width-length ratio of a rectangular slab. The values derived from two-dimensional analyses can also be tested on more circular slab shapes, or L- and T-shaped slabs.

One aspect of the theory behind the standards is especially important to analyse: the assumption of heat transferring only between indoor and outdoor environment vs. assuming a constant temperature at a certain depth beneath a building. The accuracy of calculating U- and Ψ-values between indoors and outdoors might be less significant if some of the heat transferred is instead lost to or gained from the subsoil. If so, there are some kind of heat transferring abilities (preferably U-values) for the ground between the subsoil and indoors and outdoors, which in the worst case might render differently calculated U-values useless.

References

Aercrete (2011), *Foam Concrete* [online] Available at: <http://www.aercrete.se/eng/foam6.html> [Accessed 20 August 2011]

Akander J. (1997), *Efficient detailling of energy flow in building components*, Royal Institute of Technology, Department of Civil and Architectural Engineering, Stockholm, Sweden.

Anglia Ruskin University (2011), *Harvard System of Referencing Guide* [online] Available at: <http://libweb.anglia.ac.uk/referencing/harvard.htm> [Accessed at 12 October 2011]

Blocon, (n.d.). *HEAT2* [pdf] Available at: <http://www.buildingphysics.com/manuals/HEAT2_5.pdf> [Accessed 20 August 2011]

Blocon, (n.d.). *HEAT2-Heat transfer in two dimensions* [online] Available at: <http://www.buildingphysics.com/index-filer/heat2.htm> [Accessed 20 August 2011]

Blocon, (n.d.). *HEAT3-Heat transfer in three dimensions* [online] Available at: <http://www.buildingphysics.com/index-filer/Page691.htm> [Accessed 20 August 2011]

Blomberg T. (1996), *Heat Conduction in Two and Three Dimensions* [pdf] Available at <http://www.buildingphysics.com/manuals/avh_TB.pdf> [Accessed at 20 August 2011]

Infomind (2011). *flixo professional* [pdf] Available at: <http://www.infomind.ch/bph/downloads/flixo/flixo4_1de.pdf> [Accessed 20 August 2011]

Infomind GmbH (2002). *Wärmebrückenkatalog* [pdf] Available at <https://www.awaso.ch/awaweb/60_energie/7.5.pdf> [Accessed 20 August 2011]

Isodrän (n.d.), *ISODRÄN-skivan* [online] Available at <http://www.isodran.se/index.php/kallarvagg> [Accessed at 20 August 2011]

Jansson M., Engineer, NCC Teknik [Interviewed at 12 March 2011]

Gustavsen A., Thue Vincent J., Blom P., Dalehaug et.al. (2008) *Prosjektrapport 25 – Kuldebroer – Beregning, kuldebroverdier og innvirkning på energibruk*, SINTEF Byggforsk, Oslo, Norway, 93 pp.

Hagentoft C-E. (2009), *Introduction to Building Physics*, Studentlitteratur, Lund, Sweden, 421 pp.

Hagentoft C-E., Author and professor in building physics, Chalmers University of Technology [Interviewed at several occasions Spring and Summer 2011]

Kildishev S., Building physician, Tyréns AB [Interviewed at several occasions Spring and Summer 2011]

Konieczny G. (2005), *Energy Declaration of Buildings and Building Details* [pdf] Available at <http://www.ibpsa.org/proceedings/BS2005/BS05_0549_554.pdf> [Accessed at 20 August 2011]

Mao G. (1997), *Thermal bridges – Efficient details for energy analysis in buildings*, Royal Institute of Technology, Department of building sciences, Stockholm, Sweden, 117 pp.

Passive House Institute, (n.d.). *Thermal Bridges*. [online] Available at: <http://passipedia.passiv.de/passipedia_en/basics/building_physics_-_basics/heat_transfer/thermal_bridges> [Accessed at 10 April 2011]

Petersson B-Å. (2004), *Tillämpad Byggnadsfysik*, Studentlitteratur, Lund, Sweden, 515 pp.

Plast- & Kemiföretagen (2010), *EPS i grund och mark*, EPS-bygg, Stockholm, Sweden, 77 pp.

Rantala S. (2005), *On Thermal Interaction between Slab-on-Ground Structures and Subsoil in Finland* [pdf] Available at <http://dspace.cc.tut.fi/dpub/bitstream/handle/123456789/117/rantala.pdf> [Accessed at 20 August 2011]

Schild K., Doctor of Engineering, TU Dortmund University [contacted via e-mail 12 August 2011]

Segerholm I., Engineer, Chalmers University of Technology [Interviewed Spring 2011]

SIS Swedish Standards Institute (2007), *SVENSK STANDARD SS-EN ISO 14683:2007 – Thermal bridges in building constructions – Linear thermal transmittances – Simplified methods and default values* (Köldbryggor i byggnadskonstruktioner – Linjär värmegenomgångskoefficient – Förenklade metoder och schablonvärden), SIS, Brussels, Belgium, 23 pp.

SIS Swedish Standards Institute (2007), *SVENSK STANDARD SS-EN ISO 13370:2007 – Thermal performance of buildings – Heat transfer via the ground – Calculation methods* (Byggnaders termiska egenskaper – Värmeöverföring via marken – Beräkningsmetoder), SIS, Brussels, Belgium, 48 pp.

SIS Swedish Standards Institute (2007), *SVENSK STANDARD SS-EN ISO 10211:2007 – Thermal bridges in building construction – Heat flows and surface temperatures – Detailed calculations* (Köldbryggor I byggnadskonstruktioner – Värmeflöden och yttemperaturer – Detaljerade beräkningar), SIS, Brussels, Belgium, 45 pp.

Staelens P. (1988), *Thermal bridges – A non-computerized calculation procedure*, Division of Building Technology, Gothenburg, Sweden, 145 pp.

The Engineering Toolbox, (n.d.). *Overall Heat Transfer Coefficient*. [online] Available at: <http://www.engineeringtoolbox.com/overall-heat-transfer-coefficient-d_434.html> [Accessed 11 May 2011]

Theoboldt I., Passive House Certifier, Passivhusbyrån, [Interviewed 8 March and 25 March 2011]

Wetterlund H., Carlsson H., Hagentoft C-E., Wallin M. (2010), Mark-kant värmeförlust, *Bygg & teknik* (2/10) pp.44-46.

Wetterlund H., Author and advisor in building physics, WSP Group [Interviewed at 21 March and 1 April 2011]

Appendix A: Calculation procedure for a wall-floor junction

Appendix A works as a more comprehendible extensive instruction on how to perform the procedures explained in SS-EN ISO 10211:2007 for finding the U_g- and ψ_g-values of a wall-floor junction. It repeats the formulas needed for method A and B, as well as explains more thoroughly how to perform the numerical simulations. As mentioned in Chapter 3, the user analyses a whole detail with correct boundaries and boundary conditions and then removes the thermal coupling coefficients for the floor and ground and the transmittance of the wall to find the ψ_g-value of the corner, as explained in the equations below. Method A uses equation (3.4) while method B uses equation (3.6).

$$\psi_g = L_{2D} - U_w \cdot h_w - 0.5 \cdot B' \cdot U_g \qquad \left[\frac{W}{m \cdot K}\right] \qquad (3.4)$$

$$\psi_g = L_{2D} - U_w \cdot h_w - L_{2D,a} \qquad \left[\frac{W}{m \cdot K}\right] \qquad (3.6)$$

Where:

Ψ_g is the linear thermal transmittance of the corner [W/m]
L_{2D} is the thermal coupling coefficient for the whole analysed detail [W/m]
$L_{2D,a}$ is the thermal coupling coefficient of the floor and ground [W/K]
U_w is the thermal transmittance of the wall [W/m]
h_w is the internal height of the wall [W/m]
B' is the characteristic dimension of the floor [m]
U_g is the thermal transmittance of the floor and ground [W/m]

A.1 Thermal transmittance of a junction

The size of the detail to be simulated depends on the floor's characteristic dimension B', which is defined in equation (3.7).

$$B' = \frac{A}{0.5 \cdot P} = \frac{b \cdot c}{b + c} \qquad [m] \qquad (3.7)$$

Where:

A is the ground-floor area of the floor slab [m^2]
P is the external perimeter of the floor slab [m]
b, c are the external measures of the floor slab [m]

Once the characteristic dimension B' is known, the size of the detail is known according to Figure 3.7 and corresponding equations (3.21), (3.22) and (3.11).

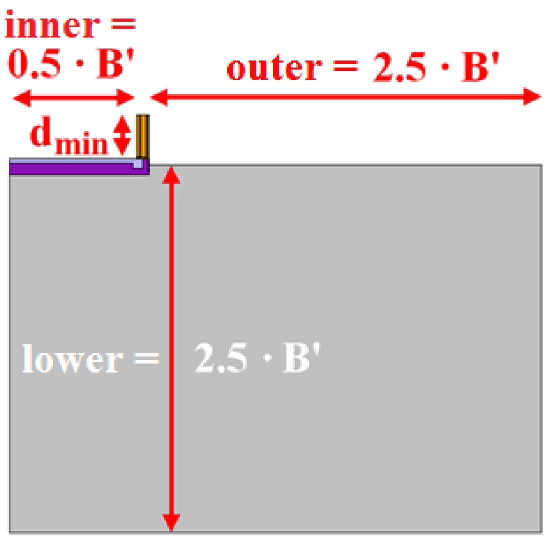

Figure 3.7 The distances to the cut-off planes for a two-dimensional analysis are shown in red arrowed lines.

$$d_{inner} = 0.5 \cdot B' \qquad [m] \qquad (3.21)$$

$$d_{lower} = d_{outer} = 2.5 \cdot B' \qquad [m] \qquad (3.22)$$

$$d_{min} = min\begin{cases} 3 \cdot t_{thick} \\ 1\ m \end{cases} \qquad [m] \qquad (3.11)$$

Where:

d_{inner} is the distance from the wall to the inner cut-off plane [m]
d_{lower} is the distance from the ground level to the lower cut-off plane (sub-soil) [m]
d_{outer} is the distance from the wall to the outer cut-off plane [m]
d_{min} is the minimum cut-off distance [m]
t_{thick} is the thickness of the wall [m]

Below is a list of materials and their recommended values of thermal conductivity if unknown for the user. If the user is uncertain of what ground material (type of soil) should be used, he/she should assume a λ-value of 2 W/m·K, used for sand and gravel.

Table 4.0.1 Material list with recommended values for thermal conductivity.

Materials		
Cellular plastic	0.036	W/m·K
Mineral Wool	0.04	W/m·K
Gypsum Board	0.22	W/m·K
Isodrän	0.042	W/m·K
Concrete	1.7	W/m·K
LW Concrete 1600	0.8	W/m·K
Brick 6/19-hole	0.6	W/m·K
Leca block	0.205	W/m·K
Aercrete 1200 (Beam)	0.27	W/m·K
Aercrete 1800 (Carpet)	0.7	W/m·K
Aercrete 400 (Floor)	0.08	W/m·K
Plaster	1	W/m·K
Wood	0.14	W/m·K
Wood+MW 600/45	0.0475	W/m·K
Aluminium	226	W/m·K
Soil materials		
Clay, silt	1.5	W/m·K
Sand, gravel	2	W/m·K
Homogenous rock	3.5	W/m·K

Once a detail is constructed, all boundaries need their boundary conditions defined. The inside of the wall and floor are assumed having indoor temperature, while the outside of the wall and the ground are assumed having outdoor temperature. All other boundaries (including the upper cut of the wall) are assumed adiabatic, which means that no energy transfers through those boundaries in the analysis. Adiabatic boundary condition can be set in the software used; In HEAT2 and HEAT3 the boundary conditions are set in a specific boundary condition's list under Input.

Since there are only two different temperature zones used in the analysis (outdoors and indoors), the total heat flow through the detail equals the heat exchange between those two temperature zones. If a temperature difference of 1K is assumed between indoors and outdoors, the thermal coupling coefficients and the heat exchange will have the same magnitude. If the analysis is done any other temperature difference, the result of the analysis [W/m] needs to be divided by the same temperature difference ΔT.

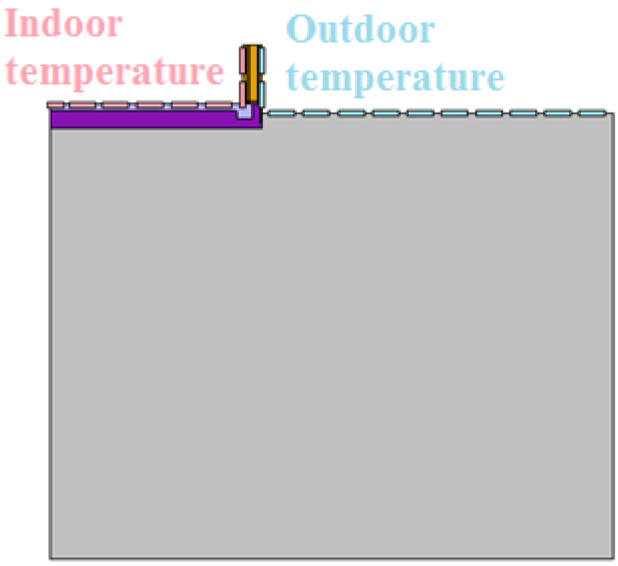

Figure A.0.1 An example of boundary conditions in a detail.

Figure A.0.1 illustrates, with dashed lines, where to assume indoor and outdoor temperatures. Anywhere else, including top edge of the wall, adiabatic boundary conditions are assumed. Know that some of the soil in this figure has been cut out for this particular illustration, to show the junction more thoroughly.

A.2 Thermal transmittance of a wall

Calculating the thermal transmittance of the wall $h_w \cdot U_w$ can either be done by hand or by using heat calculating software. In reality though, walls often include smaller structural details such as joists, making the wall section irregular. The more irregular the wall section is, the more incorrect it is to assume a one-dimensional heat flow. For this reason, using the built up detail of the wall included in the L_{2D} analysis might be more accurate than calculating one by hand.

Beside the possible two-dimensional flow within the wall, there may also be vertical heat transfer between the wall bottom and the floor corner. For an easier separation of the flow through the wall and the flow through the rest of the junction, the lower and upper parts of the analyzed wall are instead assumed adiabatic, i.e., no heat exchange occurs through those boundaries.

If using method A, simply remove all the floor and ground material below the wall, set the top and bottom of the wall as adiabatic (Wetterlund, 2010) and the ΔT between inner and outer sides of the wall to 1K.

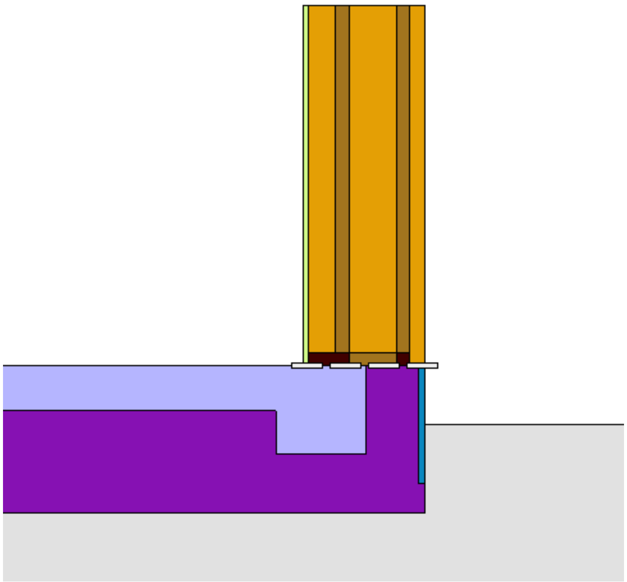

Figure A.0.2 Dashed line shows where to cut the wall.

In Figure A.0.2 the dashed line shows where to separate the wall from the ground detail. Everything below and around (not above) that line is then removed for the wall analysis.

This specific wall is a standard timber stud wall made up of timber studs (darker brown) with mineral wool insulation in between (lighter) and wooden joists in the bottom (very dark brown). There is also a layer of plaster covering the inside. The wall has a ventilated facade (facade with air gap behind for self-ventilation of moisture). The air behind the facade is in this detail assumed to have temperature as outside. For that reason the facade is excluded in this detail.

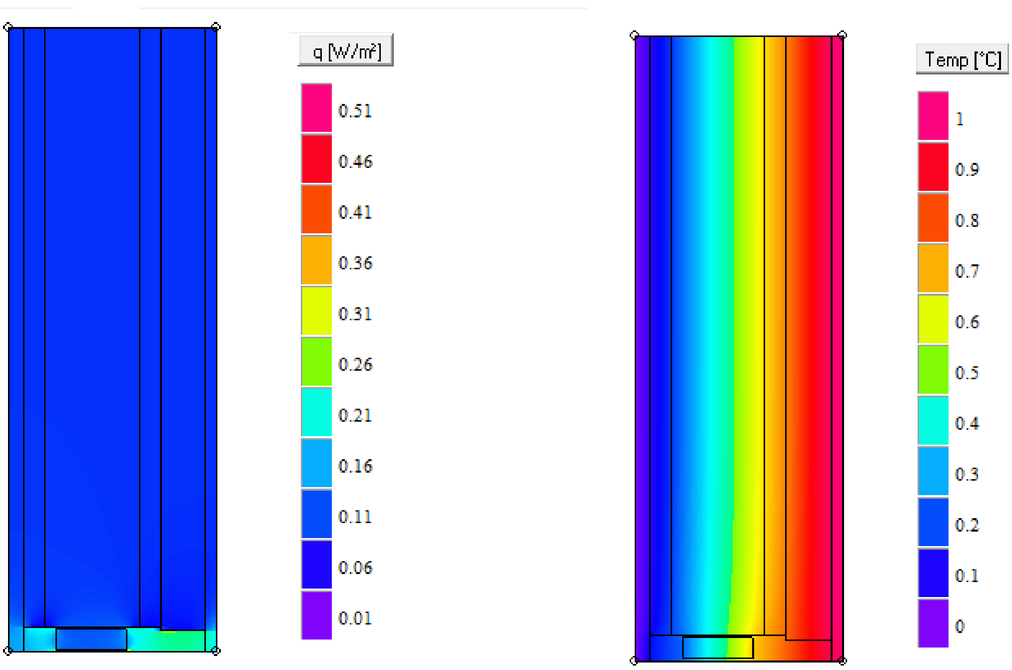

Figure A.0.3 Heat flow and temperature distribution in an analysed wall.

In Figure A.0.3 the total transmittance $h_w \cdot U_w$ for the analysed wall has been simulated as an example. Top and bottom of the wall has been assumed adiabatic. In this heat flow figure it is visible through bright colours that the wooden joist in the bottom of the wall conducts extra heat through the wall, making it a thermal bridge. The intensity of heat flow (heat flux) can be compared with the colour scale to the right. This analysis shows that the heat flow is 2-5 times more intense through the wooden joist in the bottom part of the wall. Figure A.0.3 also shows the temperature distribution in the same wall.

A.3 Thermal transmittance of ground

The heat flow pattern through the ground (including floor) is more complex than that of a wall. The most intense heat exchange often occurs directly under the wall at the corner, but depending on the size and geometry of the corner construction, the magnitude and pattern of the heat flow varies. In SS-EN ISO 10211:2007 there are two different ways to calculate the heat loss through ground; method B and method A.

In both methods it is important that this ground transmittance represents only the heat that transfers from the floor surface, through the floor down to the ground and under (not through) the wall up to the surface.

A.3.2 Method A

This method evaluates the approximate distance the heat will transfer underneath the wall by evaluating the resistance of the heat transfer from indoors to outdoors. This resistance is expressed via a parameter, the equivalent thickness d_t, see equation (3.2).

$$d_t = w + \lambda\left(R_{si} + R_{floor} + R_{se}\right) \tag{3.2}$$

Where:

d_t is the equivalent thickness [m]
w is the total thickness of the wall [m]
λ is the heat conductivity of the ground material [W/m·K]
R_{floor} is the total thermal resistance of the floor construction [m^2K/W]
R_{si}, R_{se} are the thermal ground surface resistances of indoors and outdoors [m^2K/W]

The equivalent thickness is useful not only for calculating the thermal transmittance of the ground, but to inform whether the floor is well insulated or not. What is worth noticing in this formula is that as long as the floor is somewhat insulated, R_{floor} will by far have the largest influence on d_t, see Example A.1.

Example A.1:
A floor with 150 mm concrete (λ=1.7 W/m·K) and 50 mm EPS insulation (λ=0.036 W/m·K) lies on sand and gravel. The outer wall standing on the floor corner has a total thickness of 350 mm. If translating the thermal resistance of the floor, inner surface, outer surface and soil under the wall to equivalent thicknesses, they would be 2.8 m, 0.34 m, 0.08 m and 0.35 m respectively, see Equations (A.1) to (A.4).

R_{floor}	$d_t = \lambda \cdot R_{floor} = 2\left(\frac{0.150}{1.7} + \frac{0.05}{0.036}\right) = 2.8\,m$	(A.1)
R_{si}	$d_t = \lambda \cdot R_{si} = 2 \cdot 0.17 = 0.34\,m$	(A.2)
R_{se}	$d_t = \lambda \cdot R_{se} = 2 \cdot 0.04 = 0.08\,m$	(A.3)
w	$d_t = w = 0.350\,m$	(A.4)

In other words, the floor insulation has the largest impact on d_t*, even for less insulated floors.*

Once the equivalent thickness is known it can be used to calculate the thermal transmittance of the ground and floor. To be able to do this it must first be known whether the floor is well insulated or not. In SS-EN ISO 13370:2007 there are definitions (Equations 4 and 5 in the standard) for well insulated respectively less well insulated floors, see equations (3.9) and (3.10):

Well-insulated floors: $d_t \geq B'$ (3.9)

Less or non-insulated floors: $d_t < B'$ (3.10)

The calculation of the ground's U-value has two different definitions, depending on which category the floor insulation grade belongs to, see equations (3.11) and (3.12).

Well-insulated floors:

$$U_g = \frac{\lambda}{0.457 \cdot B' + d_t} \quad (3.11)$$

Less or non-insulated floors:

$$U_g = \frac{2\lambda}{\pi \cdot B' + d_t} \cdot \ln\left(\frac{\pi \cdot B'}{d_t} + 1\right) \quad (3.12)$$

Where:

λ is the thermal conductivity of the ground material [W/m·K]

B' is the characteristic dimension of the floor [m]

d_t is the equivalent thickness of the ground [m]

The detail exemplified throughout this chapter (Example A.1) has a floor construction made up of 150 mm concrete (λ=1.7 W/m·K), 50 mm insulation (λ=0.036 W/m·K) and lying on sand (λ=2.0 W/m·K). The total wall thickness is 350 mm. This gives the ground an equivalent thickness d_t of 20.45 m, see equation (A.5).

$$d_t = 0.350 + 2.0 \cdot \left(0.17 + \frac{0.15}{1.7} + \frac{0.05}{0.036} + 0.04\right) = 3.72\,m \quad (A.5)$$

The slab from the same detail has a characteristic dimension B' of 7.78 m. Since $d_t > B'$ (well insulated floor), U_g is equal to 0.275 W/m^{2}K.

$$U_g = \frac{2.0}{0.457 \cdot 7.78 + 3.72} = 0.275\, W/m^2K \tag{3.3}$$

A.3.1 Method B

Just as for the wall analysis, this analysis can be done by starting from the L_{2D} analysis and then altering and removing different parts. In short, the uniform floor (closer to the middle of the slab and excluding the normally thicker corner floor beam) is extended to the inner wall edge, the ground under the floor is raised to the same height as outdoor ground and the wall is replaced with adiabatic boundary conditions. The top of the floor is then assumed having indoor climate, while the ground outside the adiabatic boundary has outdoor climate. This whole procedure can be shown in three steps, illustrated through Figure A.0.4 to Figure A.0.7.

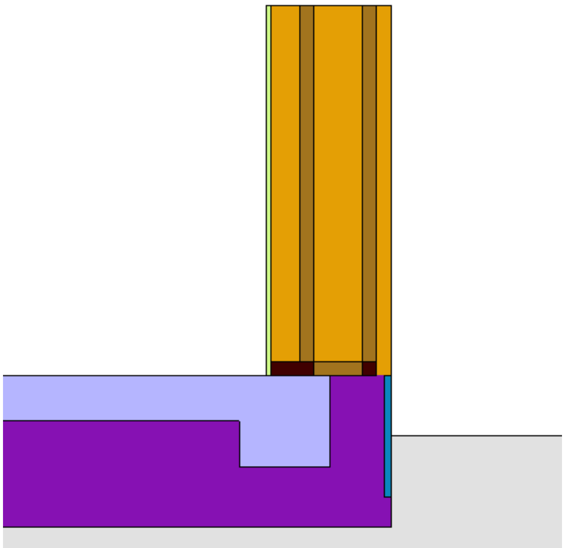

Figure A.0.4 Original detail of the corner.

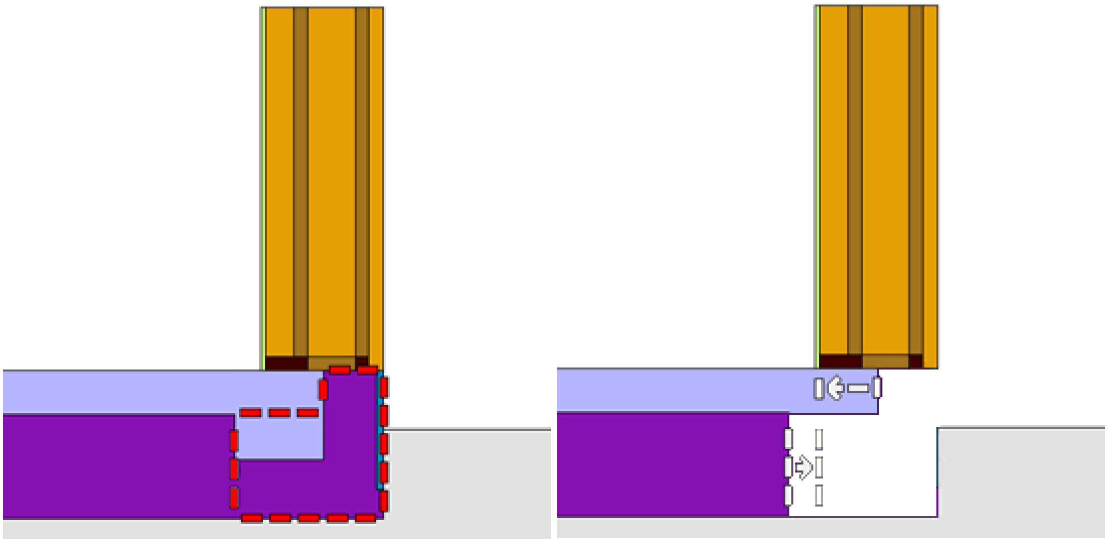

Figure A.0.5 Step 1.

Step 1: Cut out everything underneath the wall that stands out from the homogenous construction of the floor. The only part left of the floor later should be the layers of the inner floor, which may now be horizontally adjusted so that they end at the inner edge of the wall (see next figure to see where the floor should end).

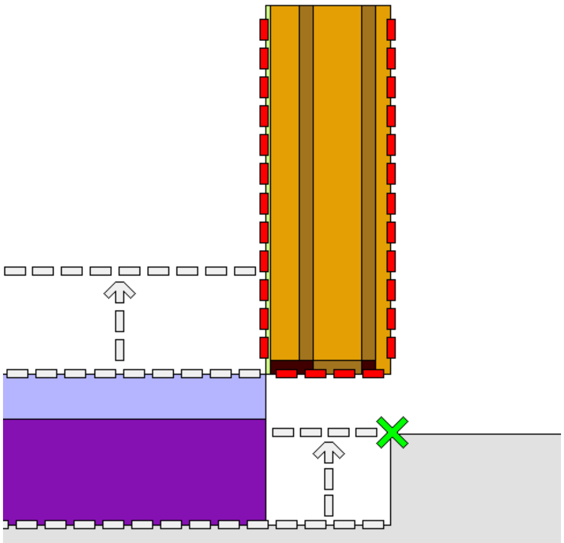

Figure A.0.6 Step 2.

Step 2: Once the floor is at the correct horizontal position, lift the ground underneath the building (together with the floor) to the same level as the ground outside the building. After this is done, mark the point of the ground underneath the outer corner of the wall (where the wall's corner would be if the wall would stand on the ground), marked with an X in Figure A.0.6 and Figure A.0.7. This point will later separate outdoor boundary condition from adiabatic boundary condition (the tool for doing so in HEAT 2 is called "open boundary line segment"). When this point is known, remove the wall.

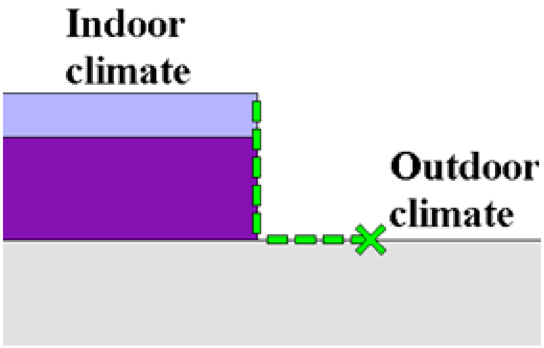

Figure A.0.7 Step 3a.

Step 3a: Between the marked point and the upper corner of the floor, the boundary condition should be assumed adiabatic. This can now be considered as an invisible wall without any heat exchange. The top of the floor now represents the indoor climate, while all ground outside the “invisible wall” is outdoor climate. Just as for the L_{2D} analysis, the outer sides and bottom of the analysis are considered adiabatic.

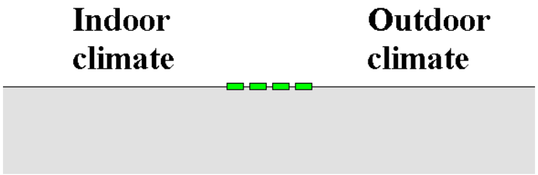

Figure A.0.8 Step 3b.

Step 3b: An alternative to moving and altering the floor in this analysis, is to replace the floor with a surface resistance equivalent to the floor’s resistance. The floor’s resistance can be calculated by hand if the thickness and thermal conductivity of the layers are known. For this analysis, $L_{2D,a}$ of 3b differs 0.1% from that of 3a.

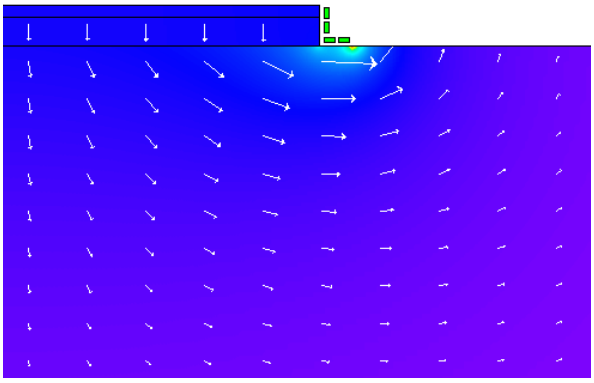

Figure A.0.9 The ground's thermal transmittance.

The result of the $L_{2D,a}$ analysis is seen in Figure A.0.9 and shows the heat loss through the ground to the outside, excluding any heat exchange through the corner or wall construction. The adiabatic boundary is marked with green dashed lines. It is apparent by the colour change representing an increase of heat flow that much of the heat transfers the shortest way, going along the borders of and under the wall.

Appendix B: Calculations made in Microsoft Excel

All calculations done in this work that have not been simulated in HEAT, have been calculated in Microsoft Excel. The main data for each detail, as well as the parameters that have been varied and tested and their results are documented and sorted in different lists. Other than the main data for each detail, each parameter study varied and the results are sorted through different colours with corresponding titles. Each parameter study is listed below together with the details that have been included in each study.

B.1 Detail characteristics and Ψ-value calculation

These boxes six boxes, coloured in light grey and used for all details, include the necessary input data for calculating the Ψ-value for the standard case of each detail. These data include the dimensions and B' of the slab, height of the wall and thicknesses and thermal conductivities of the material layers in the floor and wall construction. They also show the simulation results for L_{2D}, $L_{2D,a}$, $L_{2D,wall}$, U_g and Ψ (internal and external). These results are shown for all four details.

B.2 Three-dimensional heat flow

These four orange boxes (one for each slab shape) are used for Detail 1 and 3 and show the simulation and calculation results used for the 3D-analyses in the verification in Chapter 4.8. Included are the dimensions of the 3D-analysis slab, the results of each HEAT3 simulation and the calculation of the steady state heat transfer ability H_g of each detail. H_g is calculated by first calculating the heat transfer ability of the walls (H_{wall}), ground (H_{floor}) and corner junction (H_{psi}) and then adding them together. These three abilities are calculated by multiplying the dimensions of each element with the U- and Ψ-values calculated in the standard 2D-calculation. Lastly, a comparison with H_g and L_{3D}(HEAT3 results) is made and shown as Diff [%] for method A and B.

B.3 Soil material

This green box shows the varied λ-value and the calculated values used in method A. The recorded simulation results for L_{2D} and $L_{2D,a}$ are listed as well. Lastly, the Ψ-value is calculated for method A and B and then compared to the standard calculated Ψ-value, where the difference is shown in Diff [%] for both methods. This study is done for all four details.

B.4 Insulation conductivity and insulation thickness

Similar to the soil material box, but shown in purple and blue respectively, these boxes list the calculated and simulated results needed for the calculation of the Ψ-value. Included are also the relative conductivity and thickness respectively, calculated R_{floor} and simulated $L_{2D,wall}$. Calculations and simulations are done for all four details.

B.5 Varying B' and amount of soil

These two boxes (dark red and light brown respectively) are similar to previous boxes, but instead showing the values of B' that the boundary distances have been adjusted according to. The boundary distances have been varied for Detail 1, 2 and 3.

B.6 Number of cells and simulation time

L_{2D}, $L_{2D,a}$ and $L_{2D,wall}$ have all been simulated with different degrees of discretization, with and without expansion point. The results have been recorded in a pink result box and have then been compared to results for analyses with half the amount of cells, to see the difference in percent each time the number of cells is doubled. The difference is referred to as change [%]. The simulation time for L_{2D} (Detail 1 and 3) and $L_{2D,a}$ (Detail 2) with and without expansion point that has been recorded is shown in a dark green box. If no time is shown, the simulation time has either been too short of longer than 20 minutes, which has then not been recorded.

Slab size	[m]
Slab length	16
B':	8,00
Lower limit	20,0
Outer limit	20,0
Inner limit	4,0

Floor constr.	[m]	[W/mK]	[m^2K/W]
Floor:	Thickness	Lambda	Resistance
Inner			0,170
Concrete	0,100	1,700	0,059
Cell. Plastic	0,400	0,036	11,111
Total excl. R_{si}			11,170

Wall constr.	[m]	[W/mK]	[m^2K/W]
Wall 1:	Thickness	Lambda	Resistance
Outer			0,100
IFS	0,030	0,036	0,833
MW_1	0,045	0,048	0,947
MW_2	0,200	0,040	5,000
MW_3	0,045	0,048	0,947
MW_4	0,095	0,040	2,375
Gypsum	0,026	0,220	0,118
Inner			0,040
Total excl. R_{si}			10,221
Total	0,441	0,097	10,361

Wall heat transfer		
h_{wall}	1,323	[m]
h_f	0,100	[m]
$L_{2D,wall}$	0,132	[W/m]
U_w	0,100	[W/m^2]
h_w*U_w	0,128	[W/m]
$(h_w+h_f)*U_w$	0,142	[W/m]

Floor heat transfer		
w	0,441	[m]
d_t	23,201	[m]
$U_g(d_t>B')$	0,074	[W/m^2K]
$U_g(d_t<B')$	0,061	[W/m^2K]
$0,5*B'*U_g$	0,298	[W/m·K]
$0,5*(B'+w)*U_g$	0,314	[W/m·K]
$L_{2D,a}$	0,302	[W/m·K]
$U_g(B)$	0,076	[W/m·K]

Psi-calculation 2D		
L_{2D}	0,517	[W/m]
ψ(A)int	0,087	[W/m]
ψ(A)ext	0,060	[W/m]
ψ(B)	0,082	[W/m]
Diff.A-B	5,5	[%]

Appendix B: Detail 1

3D 16X16		
h_{wall}	1,32	[m]
l_{wall1}	8,0	[m]
l_{wall2}	8,0	[m]
H_{wall}	2,118	[W/K]
H_{psi} (A)	1,391	[W/K]
H_{psi} (B)	1,318	[W/K]
H_{floor}(A)	4,766	[W/K]
H_{floor}(B)	4,838	[W/K]
H_g(A)	8,275	[W/K]
H_g(B)	8,275	[W/K]
L_{3D}	8,250	[W/K]
Diff(A)	-0,3	[%]
Diff(B)	-0,3	[%]

3D 12X24		
h_{wall}	1,32	[m]
l_{wall1}	6,0	[m]
l_{wall2}	12,0	[m]
H_{wall}	2,298	[W/K]
H_{psi} (A)	1,565	[W/K]
H_{psi} (B)	1,483	[W/K]
H_{floor}(A)	5,362	[W/K]
H_{floor}(B)	5,443	[W/K]
H_g(A)	9,143	[W/K]
H_g(B)	9,225	[W/K]
L_{3D}	9,339	[W/K]
Diff(A)	2,1	[%]
Diff(B)	1,2	[%]

3D 10X40		
h_{wall}	1,32	[m]
l_{wall1}	5,0	[m]
l_{wall2}	20,0	[m]
H_{wall}	3,192	[W/K]
H_{psi} (A)	2,173	[W/K]
H_{psi} (B)	2,060	[W/K]
H_{floor}(A)	7,447	[W/K]
H_{floor}(B)	7,560	[W/K]
H_g(A)	12,699	[W/K]
H_g(B)	12,812	[W/K]
L_{3D}	12,820	[W/K]
Diff(A)	1,0	[%]
Diff(B)	0,1	[%]

3D 24X24		
h_{wall}	1,32	[m]
l_{wall1}	12,0	[m]
l_{wall2}	12,0	[m]
H_{wall}	3,178	[W/K]
H_{psi} (A)	2,086	[W/K]
H_{psi} (B)	1,978	[W/K]
H_{floor}(A)	10,724	[W/K]
H_{floor}(B)	10,886	[W/K]
H_g(A)	15,879	[W/K]
H_g(B)	16,042	[W/K]
L_{3D}	15,180	[W/K]
Diff(A)	-4,4	[%]
Diff(B)	-5,4	[%]

Appendix B: Detail 1

Soil material									
λ_{ground} [W/m·K]	1,0	1,5	2,0	2,5	3,0	3,5	4,0	4,5	5,0
L_{2D} [W/m·K]	0,471	0,500	0,517	0,528	0,536	0,542	0,547	0,550	0,553
$L_{2D,a}$ [W/m·K]	0,266	0,289	0,302	0,311	0,317	0,322	0,325	0,328	0,330
d_t [m]	11,82	17,51	23,20	28,89	34,58	40,27	45,96	51,65	57,34
$U_g(d_t>B')$ [W/m^2·K]	0,065	0,071	0,074	0,077	0,078	0,080	0,081	0,081	0,082
0,5*B'*U_g [W/m·K]	0,258	0,283	0,298	0,307	0,314	0,319	0,322	0,325	0,328
Psi(A) [W/m·K]	0,080	0,084	0,087	0,089	0,090	0,091	0,092	0,092	0,093
Psi (A) change [%]	-8,3	-3,1	0,0	2,1	3,5	4,7	5,5	6,2	6,9
Psi(B) [W/m·K]	0,072	0,079	0,082	0,085	0,087	0,088	0,089	0,090	0,091
Psi (B) change [%]	-12,4	-4,7	0,0	3,2	5,2	6,9	8,3	9,3	10,3

Insulation conductivity						
λ_{ins} [W/m·K]	0,0300	0,0325	0,0350	0,0375	0,0400	0,0425
Relative λ_{ins} [%]	83,3	90,3	97,2	104,2	111,1	118,1
L_{2D} [W/m·K]	0,464	0,486	0,509	0,531	0,551	0,572
$L_{2D,a}$ [W/m·K]	0,259	0,277	0,295	0,313	0,330	0,347
L_{2Dwall} [W/m·K]	0,132	0,132	0,132	0,132	0,132	0,132
R_{floor} [m^{2}K/W]	13,392	12,367	11,487	10,725	10,059	9,471
d_t [m]	27,65	25,59	23,84	22,31	20,98	19,80
$U_g(d_t>B')$ [W/m^{2}K]	0,064	0,068	0,073	0,077	0,081	0,085
0,5*B'*U_g [W/m·K]	0,256	0,274	0,291	0,308	0,325	0,341
Psi (A) [W/m·K]	0,076	0,080	0,085	0,090	0,094	0,098
Psi (A) change [%]	-12,8	-7,4	-2,1	3,7	8,0	12,8
Psi (B) [W/m·K]	0,073	0,077	0,081	0,085	0,088	0,092
Psi (B) change [%]	-12,0	-6,9	-1,9	3,5	7,3	11,7

Appendix B: Detail 1

Insulation thickness							
Thickness [m]	0,480	0,443	0,411	0,384	0,360	0,339	0,320
Relative thickness [%]	120,0	110,8	102,9	96,0	90,0	84,7	80,0
L_{2D} [W/m·K]	0,479	0,495	0,511	0,526	0,542	0,557	0,571
$L_{2D,a}$ [W/m·K]	0,259	0,277	0,295	0,313	0,330	0,347	0,364
L_{2Dwall} [W/m·K]	0,132	0,132	0,132	0,132	0,132	0,132	0,132
R_{floor} [m²K/W]	13,392	12,367	11,487	10,725	10,059	9,471	8,948
d_t [m]	27,65	25,59	23,84	22,31	20,98	19,80	18,76
$U_g(d_t>B')$ [W/m²K]	0,064	0,068	0,073	0,077	0,081	0,085	0,089
0,5*B'*U_g [W/m·K]	0,256	0,274	0,291	0,308	0,325	0,341	0,357
ψ (A) [W/m·K]	0,091	0,089	0,088	0,086	0,085	0,083	0,082
ψ (A) change [%]	4,1	2,4	0,7	-1,1	-2,7	-4,3	-5,8
ψ (B) [W/m·K]	0,087	0,085	0,083	0,081	0,079	0,077	0,075
ψ (B) change [%]	5,8	3,4	1,0	-1,6	-4,0	-6,4	-8,7

Varying amount of soil			
B' excl. Int. Length [m]	4	8	12
L_{2D} [W/m·K]	0,515	0,517	0,518
$L_{2D,a}$ [W/m·K]	0,301	0,302	0,303
d_t [m]	23,20	23,20	23,20
$U_g(d_t>B')$ [W/m²·K]	0,080	0,074	0,070
0,5*B'*U_g [W/m·K]	0,160	0,298	0,418
ψ(B) [W/m·K]	0,081	0,082	0,083
ψ (B) change [%]	-1,2	0,0	0,1

Varying B'					
B' [m]	4	6	8	10	12
L_{2D} [W/m·K]	0,381	0,451	0,517	0,579	0,637
$L_{2D,a}$ [W/m·K]	0,161	0,234	0,302	0,367	0,428
d_t [m]	23,20	23,20	23,20	23,20	23,20
$U_g(d_t>B')$ [W/m²·K]	0,080	0,077	0,074	0,072	0,070
0,5*B'*U_g [W/m·K]	0,160	0,231	0,298	0,360	0,418
ψ(A) [W/m·K]	0,088	0,088	0,087	0,086	0,086
ψ (A) change [%]	1,6	0,8	0,0	-1,1	-0,6
ψ(B) [W/m·K]	0,087	0,085	0,082	0,079	0,077
ψ (B) change [%]	5,2	2,8	0,0	-4,2	-6,6

Appendix B: Detail 1

Number of cells											
# of cells:		25	50	75	100	150	200	300	400	600	700
without exp.	L_{2D} [W/m·K]:	0,502	0,506	0,507	0,508	0,509	0,512	0,513	0,515	0,516	0,516
change [%]			0,7		0,3	0,3	0,8	0,8	0,5	0,5	0,2
with exp.	L_{2D} [W/m·K]:	0,509	0,512	0,513	0,513	0,514	0,516	0,517	0,517	0,517	0,518
change [%]			0,7		0,2	0,2	0,6	0,6	0,3	0,1	0,0
without exp.	$L_{2D,a}$ [W/m·K]:	0,299	0,301	0,301	0,302	0,302	0,302	0,302	0,302	0,302	0,302
change [%]			0,7		0,3	0,2	0,1	0,1	0,0	0,0	0,0
with exp.	$L_{2D,a}$ [W/m·K]:	0,302	0,302	0,302	0,302	0,302	0,302	0,303	0,303	0,303	0,303
change [%]			0,2		0,0	0,0	0,0	0,0	0,0	0,0	0,0
without exp.	$L_{2D,wall}$ [W/m·K]:	0,132	0,132	0,132	0,132	0,132	0,132	0,132	0,132	0,132	0,132
with ref.		0,132	0,132	0,132	0,132	0,132	0,132	0,132	0,132	0,132	0,132
without exp.	ψ-value [W/m·K]	0,071	0,073	0,073	0,073	0,074	0,077	0,078	0,080	0,081	0,081
change [%]			1,8		0,8	1,2	5,5	5,3	3,5	3,5	1,3
with exp.		0,075	0,078	0,079	0,078	0,079	0,081	0,082	0,082	0,083	0,083
change [%]			3,6		1,2	0,9	3,6	3,5	1,5	0,5	0,2

Simulation time for L_{2D} [s]										
# of cells:	25	50	75	100	150	200	300	400	600	700
Without exp. Point				0	0	0	5	14	40	47
With exp. Point				0	2	3	5	26	360	

Appendix B: Detail 1

Slab size	[m]
Slab length	16
B':	8,00
Lower limit	20,0
Outer limit	20,0
Inner limit	4,0

Floor constr.	[m]	[W/mK]	[m^2K/W]
Floor:	Thickness	Lambda	Resistance
Inner			0,170
Concrete	0,100	1,700	0,059
Cell. Plastic	0,200	0,036	5,556
Total excl. R_{si}			5,614

Wall constr.	[m]	[W/mK]	[m^2K/W]
Wall 1:	Thickness	Lambda	Resistance
Outer			0,040
Brick	0,100	0,600	0,167
MW	0,100	0,040	2,500
Brick	0,100	0,600	0,167
Plaster	0,010	1,000	0,010
Inner			0,130
Total excl. R_{si}			2,843
Total	0,310	0,332	3,013

Wall heat transfer		
h_{wall}	1,000	[m]
h_f	0,160	[m]
$L_{2D,wall}$	0,320	[W/m]
U_w	0,320	[W/m^2]
h_w*U_w	0,332	[W/m]
$(h_w+h_f)*U_w$	0,371	[W/m]

Floor heat transfer		
w	0,310	[m]
d_t	11,959	[m]
$U_g(d_t>B')$	0,128	[W/m^2K]
$U_g(d_t<B')$	0,122	[W/m^2K]
$0,5*B'*U_g$	0,512	[W/m·K]
$0,5*(B'+w)*U_g$	0,532	[W/m·K]
$L_{2D,a}$	0,526	[W/m·K]
$U_g(B)$	0,132	[W/m·K]

Psi-calculation 2D		
L_{2D}	1,066	[W/m]
ψ(A)int	0,234	[W/m]
ψ(A)ext	0,163	[W/m]
ψ(B)	0,220	[W/m]
Diff.A-B	6,4	[%]

Appendix B: Detail 2

Soil material									
λ_{ground} [W/m·K]	1	1,5	2	2,5	3	3,5	4	4,5	5
L_{2D} [W/m·K]	0,936	1,014	1,066	1,105	1,134	1,158	1,177	1,193	1,206
$L_{2D,a}$ [W/m·K]	0,429	0,489	0,526	0,552	0,570	0,584	0,595	0,604	0,611
d_t [m]	6,13	9,05	11,96	14,87	17,78	20,70	23,61	26,52	29,43
$U_g(d_t>B')$ [W/m^2·K]	0,104	0,118	0,128	0,135	0,140	0,144	0,147	0,149	0,151
0,5*B'*U_g [W/m·K]	0,417	0,472	0,512	0,540	0,560	0,575	0,587	0,597	0,604
Psi(A) [W/m·K]	0,199	0,221	0,234	0,245	0,255	0,263	0,270	0,276	0,281
Psi (A) change [%]	-15,0	-5,5	0,0	4,8	8,9	12,4	15,4	18,0	20,3
Psi(B) [W/m·K]	0,186	0,204	0,220	0,233	0,244	0,254	0,262	0,268	0,275
Psi (B) change [%]	-15,2	-7,1	0,0	6,1	11,1	15,3	19,0	22,1	24,9

Insulation conductivity						
λ_{ins} [W/m·K]	0,0300	0,0325	0,0350	0,0375	0,0400	0,0425
Relative λ_{ins} [%]	83,3	90,3	97,2	104,2	111,1	118,1
L_{2D} [W/m·K]	1,006	1,032	1,057	1,081	1,104	1,126
$L_{2D,a}$ [W/m·K]	0,459	0,488	0,516	0,542	0,568	0,593
L_{2Dwall} [W/m·K]	0,320	0,320	0,320	0,320	0,320	0,320
R_{floor} [m^{2}K/W]	6,725	6,213	5,773	5,392	5,059	4,765
d_t [m]	14,18	13,16	12,28	11,51	10,85	10,26
$U_g(d_t>B')$ [W/m^{2}K]	0,112	0,119	0,126	0,132	0,138	0,144
0,5*B'*U_g [W/m·K]	0,449	0,476	0,502	0,527	0,552	0,575
Psi (A) [W/m·K]	0,237	0,236	0,234	0,233	0,232	0,231
Psi (A) change [%]	1,4	0,8	0,2	-0,3	-0,7	-1,1
Psi (B) [W/m·K]	0,227	0,224	0,221	0,218	0,216	0,213
Psi (B) change [%]	3,1	1,8	0,5	-0,7	-1,9	-2,9

Appendix B: Detail 2

Insulation thickness							
Thickness [m]	0,240	0,222	0,206	0,192	0,180	0,169	0,160
Relative thickness [%]	120,0	110,8	102,9	96,0	90,0	84,7	80,0
L_{2D} [W/m·K]	1,012	1,035	1,058	1,079	1,099	1,119	1,138
$L_{2D,a}$ [W/m·K]	0,459	0,488	0,516	0,542	0,568	0,593	0,617
L_{2Dwall} [W/m·K]	0,320	0,320	0,320	0,320	0,320	0,320	0,320
R_{floor} [m^2K/W]	6,725	6,213	5,773	5,392	5,059	4,765	4,503
d_t [m]	14,18	13,16	12,28	11,51	10,85	10,26	9,74
$U_g(d_t$>B') [W/m^2K]	0,112	0,119	0,126	0,132	0,138	0,144	0,149
0,5*B'*U_g [W/m·K]	0,449	0,476	0,502	0,527	0,552	0,575	0,597
ψ (A) [W/m·K]	0,244	0,239	0,235	0,231	0,228	0,224	0,221
ψ (A) change [%]	4,2	2,4	0,6	-1,1	-2,7	-4,2	-5,7
ψ (B) [W/m·K]	0,233	0,228	0,222	0,216	0,211	0,206	0,201
ψ (B) change [%]	6,1	3,5	1,0	-1,5	-4,0	-6,3	-8,6

Varying amount of soil			
B' excl. Int. Length [m]	4	8	12
L_{2D} [W/m·K]	1,057	1,066	1,068
$L_{2D,a}$ [W/m·K]	0,522	0,527	0,527
d_t [m]	11,96	11,96	11,96
$U_g(d_t$>B') [W/m^2·K]	0,145	0,128	0,115
0,5*B'*U_g [W/m·K]	0,290	0,512	0,688
ψ(B) [W/m·K]	0,215	0,220	0,220
ψ (B) change [%]	-2,0	0,0	0,1

Varying B'					
B' [m]	4	6	8	10	12
L_{2D} [W/m·K]	0,859	0,967	1,066	1,156	1,239
$L_{2D,a}$ [W/m·K]	0,295	0,417	0,527	0,625	0,718
d_t [m]	11,96	11,96	11,96	11,96	11,96
$U_g(d_t$>B') [W/m^2·K]	0,145	0,136	0,128	0,121	0,115
0,5*B'*U_g [W/m·K]	0,290	0,408	0,512	0,605	0,688
ψ(A) [W/m·K]	0,249	0,239	0,234	0,231	0,231
ψ (A) change [%]	6,3	2,2	0,0	-1,1	-1,2
ψ(B) [W/m·K]	0,244	0,230	0,220	0,211	0,202
ψ (B) change [%]	11,0	4,8	0,0	-4,0	-8,3

Appendix B: Detail 2

Number of cells											
# of cells:		25	50	75	100	150	200	300	400	600	700
without exp.	L_{2D} [W/m·K]:	1,005	1,025	1,033	1,038	1,043	1,045	1,049	1,058	1,060	1,062
change [%]			2,0		1,3	0,9	0,7	0,6	1,3	1,1	0,4
with exp.	L_{2D} [W/m·K]:	1,043	1,050	1,053	1,053	1,055	1,063	1,066	1,067	1,067	1,067
change [%]			0,6		0,3	0,2	0,9	1,0	0,4	0,1	0,0
without exp.	$L_{2D,a}$ [W/m·K]:	0,515	0,521	0,524	0,524	0,525	0,526	0,526	0,526	0,526	0,526
change [%]			1,2		0,7	0,3	0,3	0,1	0,1	0,2	0,0
with exp.	$L_{2D,a}$ [W/m·K]:	0,522	0,526	0,526	0,526	0,526	0,526	0,526	0,526	0,526	0,526
change [%]			0,6		0,1	0,1	0,1	0,0	0,0	0,0	0,0
without exp.	$L_{2D,wall}$ [W/m·K]:	0,320	0,320	0,320	0,320	0,320	0,320	0,320	0,320	0,320	0,320
with ref.		0,320	0,320	0,320	0,320	0,320	0,320	0,320	0,320	0,320	0,320
without exp.	ψ-value [W/m·K]	0,171	0,184	0,190	0,194	0,197	0,199	0,203	0,212	0,213	0,216
change [%]			7,9		5,2	4,0	2,8	2,9	6,5	5,1	1,9
with exp.		0,201	0,204	0,207	0,207	0,209	0,216	0,220	0,220	0,221	0,221
change [%]			1,4		1,6	1,1	4,5	5,2	1,8	0,4	0,2

Simulation time for $L_{2D,a}$ [s]										
# of cells:	25	50	75	100	150	200	300	400	600	700
Without exp. Point	0	0	0	0	1,45	2	7	8,5	30	33
With exp. Point	0	0	0	0	1,45	2,5	6,3	26	200	700

Appendix B: Detail 2

Slab size	[m]
Slab length	16
B':	8,00
Lower limit	20,0
Outer limit	20,0
Inner limit	4,0

Floor constr.	[m]	[W/mK]	[m^2K/W]
Floor:	Thickness	Lambda	Resistance
Inner			0,170
Aer. carpet	0,065	0,700	0,093
Aer. Floor	0,400	0,080	5,000
Total excl. R_{si}			5,093

Wall constr.	[m]	[W/mK]	[m^2K/W]
Wall 1:	Thickness	Lambda	Resistance
Outer			0,040
MW_1	0,070	0,048	1,474
MW_2	0,145	0,040	3,625
MW_3	0,090	0,048	1,895
MW_4	0,045	0,040	1,125
Gypsum	0,026	0,220	0,118
Inner			0,130
Total excl. R_{si}			8,237
Total	0,376	0,119	8,407

Wall heat transfer		
hwall	1,128	[m]
hf	0,145	[m]
L2D,wall	0,138	[W/m]
Uw	0,122	[W/m^2]
hw*Uw	0,134	[W/m]
(hw+hf)*Uw	0,156	[W/m]

Floor heat transfer		
w	0,376	[m]
dt	10,982	[m]
Ug(dt>B')	0,137	[W/m^2K]
Ug(dt<B')	0,132	[W/m^2K]
0,5*B'*Ug	0,547	[W/m·K]
0,5*(B'+w)*Ug	0,572	[W/m·K]
L2D,a	0,563	[W/m·K]
Ug(B)	0,141	[W/m·K]

Psi-calculation 2D		
L_{2D}	0,736	[W/m]
ψ(A)int	0,052	[W/m]
ψ(A)ext	0,008	[W/m]
ψ(B)	0,035	[W/m]
Diff.A-B	47,3	[%]

Appendix B: Detail 3

3D 16X16		
h_{wall}	1,13	[m]
l_{wall1}	8,0	[m]
l_{wall2}	8,0	[m]
H_{wall}	2,210	[W/K]
H_{psi} (A)	0,825	[W/K]
H_{psi} (B)	0,560	[W/K]
H_{floor}(A)	8,745	[W/K]
H_{floor}(B)	9,010	[W/K]
H_g(A)	11,514	[W/K]
H_g(B)	11,779	[W/K]
L_{3D}	11,680	[W/K]
Diff(A)	1,4	[%]
Diff(B)	-0,8	[%]

3D 12X24		
h_{wall}	1,13	[m]
l_{wall1}	6,0	[m]
l_{wall2}	12,0	[m]
H_{wall}	2,415	[W/K]
H_{psi} (A)	0,928	[W/K]
H_{psi} (B)	0,630	[W/K]
H_{floor}(A)	9,838	[W/K]
H_{floor}(B)	10,136	[W/K]
H_g(A)	12,883	[W/K]
H_g(B)	13,181	[W/K]
L_{3D}	13,440	[W/K]
Diff(A)	4,3	[%]
Diff(B)	2,0	[%]

3D 10X40		
h_{wall}	1,13	[m]
l_{wall1}	5,0	[m]
l_{wall2}	20,0	[m]
H_{wall}	3,355	[W/K]
H_{psi} (A)	1,289	[W/K]
H_{psi} (B)	0,875	[W/K]
H_{floor}(A)	13,663	[W/K]
H_{floor}(B)	14,078	[W/K]
H_g(A)	17,893	[W/K]
H_g(B)	18,307	[W/K]
L_{3D}	18,268	[W/K]
Diff(A)	2,1	[%]
Diff(B)	-0,2	[%]

3D 24X24		
h_{wall}	1,13	[m]
l_{wall1}	12,0	[m]
l_{wall2}	12,0	[m]
H_{wall}	3,314	[W/K]
H_{psi} (A)	1,238	[W/K]
H_{psi} (B)	0,840	[W/K]
H_{floor}(A)	19,675	[W/K]
H_{floor}(B)	20,272	[W/K]
H_g(A)	23,830	[W/K]
H_g(B)	24,426	[W/K]
L_{3D}	21,900	[W/K]
Diff(A)	-8,1	[%]
Diff(B)	-10,3	[%]

Appendix B: Detail 3

Soil material									
λ_{ground} [W/m·K]	1	1,5	2	2,5	3	3,5	4	4,5	5
L_{2D} [W/m·K]	0,621	0,691	0,736	0,768	0,793	0,811	0,826	0,838	0,848
$L_{2D,a}$ [W/m·K]	0,452	0,520	0,563	0,593	0,614	0,631	0,644	0,655	0,663
d_t [m]	5,679	8,330	10,982	13,633	16,285	18,936	21,587	24,239	26,890
$U_g(d_t>B')$ [W/m²·K]	0,110	0,125	0,137	0,145	0,150	0,155	0,158	0,161	0,164
0,5*B'*U_g [W/m·K]	0,439	0,501	0,547	0,578	0,602	0,620	0,634	0,645	0,655
Psi(A) [W/m·K]	0,044	0,052	0,052	0,052	0,053	0,053	0,054	0,055	0,055
Psi (A) change [%]	-15,2	0,9	0,0	0,7	2,0	3,4	4,9	6,3	7,5
Psi(B) [W/m·K]	0,031	0,033	0,035	0,038	0,040	0,042	0,044	0,046	0,047
Psi (B) change [%]	-11,7	-6,6	0,0	8,0	14,9	20,9	26,0	30,3	34,0

Insulation conductivity							
λ_{ins} [W/m·K]	0,065	0,070	0,075	0,080	0,085	0,090	0,095
Relative λ_{ins} [%]	81,3	87,5	93,8	100,0	106,3	112,5	118,8
L_{2D} [W/m·K]	0,665	0,690	0,714	0,736	0,758	0,779	0,800
$L_{2D,a}$ [W/m·K]	0,484	0,511	0,538	0,563	0,587	0,611	0,634
L_{2Dwall} [W/m·K]	0,138	0,138	0,138	0,138	0,138	0,138	0,138
R_{floor} [m²K/W]	6,247	5,807	5,426	5,093	4,799	4,537	4,303
d_t [m]	13,289	12,410	11,648	10,982	10,393	9,871	9,403
$U_g(d_t>B')$ [W/m²K]	0,118	0,124	0,131	0,137	0,142	0,148	0,153
0,5*B'*U_g [W/m·K]	0,472	0,498	0,523	0,547	0,569	0,591	0,613
Psi (A) [W/m·K]	0,054	0,054	0,053	0,052	0,051	0,050	0,049
Psi (A) change [%]	5,5	3,9	2,1	0,2	-1,5	-3,3	-4,8
Psi (B) [W/m·K]	0,042	0,040	0,038	0,035	0,033	0,030	0,028
Psi (B) change [%]	21,1	14,9	8,0	0,9	-6,0	-13,1	-20,0

Appendix B: Detail 3

Insulation thickness								
Thickness [m]	0,492	0,457	0,427	0,400	0,376	0,356	0,337	0,320
Relative thickness [%]	123,1	114,3	106,7	100,0	94,1	88,9	84,2	80,0
L_{2D} [W/m·K]	0,665	0,690	0,714	0,736	0,758	0,779	0,800	0,819
$L_{2D,a}$ [W/m·K]	0,484	0,511	0,538	0,563	0,587	0,611	0,634	0,656
L_{2Dwall} [W/m·K]	0,138	0,138	0,138	0,138	0,138	0,138	0,138	0,138
R_{floor} [m^2K/W]	6,247	5,807	5,426	5,093	4,799	4,537	4,303	4,093
d_t [m]	13,29	12,41	11,65	10,98	10,39	9,87	9,40	8,98
$U_g(d_t>B')$ [W/m^2K]	0,118	0,124	0,131	0,137	0,142	0,148	0,153	0,158
$0,5*B'*U_g$ [W/m·K]	0,472	0,498	0,523	0,547	0,569	0,591	0,613	0,633
ψ (A) [W/m·K]	0,054	0,054	0,053	0,052	0,051	0,050	0,049	0,048
ψ (A) change [%]	5,5	3,9	2,1	0,2	-1,5	-3,3	-4,8	-6,6
ψ (B) [W/m·K]	0,042	0,040	0,038	0,035	0,033	0,030	0,028	0,026
ψ (B) change [%]	21,1	14,9	8,0	0,9	-6,0	-13,1	-20,0	-27,1

Varying amount of soil			
B' excl. Int. Length [m]	4	8	12
L_{2D} [W/m·K]	0,728	0,736	0,738
$L_{2D,a}$ [W/m·K]	0,558	0,563	0,564
d_t [m]	10,98	10,98	10,98
$U_g(d_t>B')$ [$W/m^2 \cdot K$]	0,156	0,137	0,121
$0,5*B'*U_g$ [W/m·K]	0,312	0,547	0,729
ψ(B) [W/m·K]	0,032	0,035	0,036
ψ (B) change [%]	-8,0	0,3	1,4

Varying B'					
B' [m]	4	6	8	10	12
L_{2D} [W/m·K]	0,509	0,630	0,736	0,836	0,924
$L_{2D,a}$ [W/m·K]	0,319	0,449	0,563	0,667	0,760
d_t [m]	10,98	10,98	10,98	10,98	10,98
$U_g(d_t>B')$ [$W/m^2 \cdot K$]	0,156	0,146	0,137	0,129	0,121
$0,5*B'*U_g$ [W/m·K]	0,312	0,437	0,547	0,643	0,729
ψ(A) [W/m·K]	0,058	0,054	0,052	0,055	0,057
ψ (A) change [%]	12,9	5,5	0,0	7,0	10,4
ψ(B) [W/m·K]	0,052	0,043	0,035	0,031	0,026
ψ (B) change [%]	48,6	22,0	0,3	-11,7	-26,9

Appendix B: Detail 3

Number of cells											
# of cells:		25	50	75	100	150	200	300	400	600	700
without ref.	L_{2D} [W/m·K]:	0,720	0,725	0,727	0,727	0,730	0,730	0,731	0,732	0,733	0,734
change [%]			0,7		0,4	0,4	0,4	0,2	0,2	0,3	0,2
with ref.	L_{2D} [W/m·K]:	0,724	0,727	0,731	0,731	0,732	0,734	0,736	0,736	0,736	0,736
change [%]			0,3		0,6	0,2	0,4	0,5	0,3	0,1	0,0
without ref.	$L_{2D,a}$ [W/m·K]:	0,548	0,557	0,559	0,561	0,562	0,562	0,563	0,563	0,563	0,563
change [%]			1,5		0,7	0,4	0,3	0,2	0,1	0,0	0,0
with ref.	$L_{2D,a}$ [W/m·K]:	0,560	0,562	0,563	0,563	0,563	0,563	0,563	0,563	0,563	0,563
change [%]			0,4		0,1	0,0	0,1	0,0	0,0	0,0	0,0
without ref.	$L_{2D,wall}$ [W/m·K]:	0,138	0,138	0,138	0,138	0,138	0,138	0,138	0,138	0,138	0,138
with ref.		0,138	0,138	0,138	0,138	0,138	0,138	0,138	0,138	0,138	0,138
without ref.	ψ-value [W/m·K]	0,033	0,030	0,029	0,028	0,030	0,030	0,031	0,031	0,033	0,033
change [%]			-11,1		-4,4	2,7	6,0	3,0	3,7	5,8	4,5
with ref.		0,027	0,027	0,031	0,030	0,031	0,033	0,035	0,035	0,035	0,035
change [%]			0,0		13,5	3,0	8,6	10,5	6,7	1,2	-0,3

Simulation time for L_{2D} [s]										
# of cells:	25	50	75	100	150	200	300	400	600	700
Without exp. Point	0	0	0	0	1,5	2,5	4	12	30	
With exp. Point	0	0	0	0	1,5	3	6,5	25	320	

Appendix B: Detail 3

Slab size	[m]
Slab length	16
B':	8,00
Lower limit	20,0
Outer limit	20,0
Inner limit	4,0

Wall heat transfer		
h_{wall}	1,425	[m]
h_f	0,200	[m]
$L_{2D,wall}$	0,201	[W/m]
U_w	0,141	[W/m^2]
h_w*U_w	0,086	[W/m]
(h_w+h_f)*U_w	0,229	[W/m]

Floor constr.	[m]	[W/mK]	[m^{2}K/W]
Floor:	Thickness	Lambda	Resistance
Inner			0,170
Concrete	0,150	1,700	0,088
Cell. Plastic	0,350	0,036	9,722
Total excl. R_{si}			9,810

Floor heat transfer		
w	0,475	[m]
d_t	20,516	[m]
U_g(d_t>B')	0,083	[W/m^{2}K]
U_g(d_t<B')	0,070	[W/m^{2}K]
0,5*B'*U_g	0,331	[W/m·K]
0,5*(B'+w)*U_g	0,351	[W/m·K]
$L_{2D,a}$	0,337	[W/m·K]
U_g(B)	0,084	[W/m·K]

Wall constr.	[m]	[W/mK]	[m^{2}K/W]
Wall 1:	Thickness	Lambda	Resistance
Outer			0,040
Isodrän	0,070	0,042	1,667
Cell. Plastic	0,200	0,036	5,556
Leca	0,190	0,205	0,927
Plaster	0,015	1,000	0,015
Inner			0,130
Total excl. R_{si}			8,164
Total	0,475	0,061	16,498

Psi-calculation 2D		
L_{2D}	0,623	[W/m]
ψ(A)int	0,091	[W/m]
ψ(A)ext	0,043	[W/m]
ψ(B)	0,085	[W/m]
Diff.A-B	6,9	[%]

Appendix B: Detail 4

Soil material									
λ_{ground} [W/m·K]	1	1,5	2	2,5	3	3,5	4	4,5	5
L_{2D} [W/m·K]	0,570	0,603	0,623	0,636	0,645	0,652	0,657	0,661	0,665
$L_{2D,a}$ [W/m·K]	0,292	0,320	0,337	0,348	0,355	0,361	0,365	0,369	0,372
d_t [m]	10,50	15,51	20,52	25,53	30,54	35,55	40,56	45,57	50,58
$U_g(d_t>B')$ [W/m^2·K]	0,071	0,078	0,083	0,086	0,088	0,089	0,090	0,091	0,092
0,5*B'*U_g [W/m·K]	0,283	0,313	0,331	0,343	0,351	0,357	0,362	0,366	0,369
Psi(A) [W/m·K]	0,086	0,089	0,091	0,092	0,093	0,094	0,094	0,095	0,095
Psi (A) change [%]	-5,4	-2,1	0,0	1,4	2,4	3,2	3,8	4,3	4,7
Psi(B) [W/m·K]	0,077	0,082	0,085	0,087	0,089	0,090	0,091	0,092	0,092
Psi (B) change [%]	-9,9	-3,8	0,1	2,7	4,6	6,0	7,2	7,9	8,7

Insulation conductivity						
λ_{ins} [W/m·K]	0,0300	0,0325	0,0350	0,0375	0,0400	0,0425
Relative λ_{ins} [%]	83,3	90,3	97,2	104,2	111,1	118,1
L_{2D} [W/m·K]	0,545	0,578	0,610	0,641	0,672	0,701
$L_{2D,a}$ [W/m·K]	0,289	0,310	0,329	0,348	0,367	0,385
L_{2Dwall} [W/m·K]	0,181	0,190	0,199	0,207	0,216	0,224
R_{floor} [m^{2}K/W]	11,755	10,857	10,088	9,422	8,838	8,324
d_t [m]	24,40	22,61	21,07	19,74	18,57	17,54
$U_g(d_t>B')$ [W/m^{2}K]	0,071	0,076	0,081	0,085	0,090	0,094
0,5*B'*U_g [W/m·K]	0,285	0,305	0,324	0,342	0,360	0,377
Psi (A) [W/m·K]	0,079	0,083	0,088	0,092	0,096	0,100
Psi (A) change [%]	-13,3	-8,1	-3,3	1,5	5,9	10,2
Psi (B) [W/m·K]	0,075	0,079	0,082	0,086	0,089	0,092
Psi (B) change [%]	-12,2	-7,5	-3,1	1,2	4,9	8,8

Appendix B: Detail 4

Insulation thickness							
Thickness [m]	0,420	0,388	0,360	0,336	0,315	0,296	0,280
Relative thickness [%]	120,0	110,8	102,9	96,0	90,0	84,7	80,0
L_{2D} [W/m·K]	0,579	0,597	0,616	0,634	0,651	0,668	0,684
$L_{2D,a}$ [W/m·K]	0,289	0,310	0,329	0,348	0,367	0,385	0,403
L_{2Dwall} [W/m·K]	0,181	0,190	0,199	0,207	0,216	0,224	0,231
R_{floor} [m^2K/W]	11,755	10,857	10,088	9,422	8,838	8,324	7,866
d_t [m]	24,405	22,610	21,071	19,738	18,571	17,542	16,627
$U_g(d_t>B')$ [W/m^2K]	0,071	0,076	0,081	0,085	0,090	0,094	0,099
$0,5*B'*U_g$ [W/m·K]	0,285	0,305	0,324	0,342	0,360	0,377	0,394
ψ (A) [W/m·K]	0,113	0,103	0,093	0,084	0,075	0,067	0,059
ψ (A) change [%]	24,1	13,3	2,9	-7,2	-16,9	-26,4	-35,3
ψ (B) [W/m·K]	0,108	0,098	0,088	0,078	0,068	0,059	0,050
ψ (B) change [%]	27,7	15,3	3,5	-8,1	-19,4	-30,3	-40,8

Appendix B: Detail 4