Thermal bridges numerical study in building retrofitting and ground model coupling with whole building energy software “EnergyPlus”

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Abstract
Today in France, building sector represents 44% of final energy consumption (Énergie dans les bâtiments, 2016). Nowadays, heat losses through the foundation are more and more affecting energy consumption (Dmytro 2017). Actually, different models (Martin 2012; Baba 2015) calculate thermal bridges (TB) and heat transfer via slab, foundation and soil.

The aim of this work is to highlight the importance of calculating ground thermal bridges in slab on grade houses, and propose a new model where heat and humidity conditions are taken into account. First results were obtained with THERM software to determine the impact of wall-slab junctions under several solutions (500 kWh reduction). Then, we developed a numerical model in Python and coupled it with EnergyPlus software to calculate slab temperature and moisture transfer. The model is validated against Benchmark analytical results.

Key Innovations
Thermal bridges, slab on grade house, Renovation, Energy consumption, Ground heat and moisture transfer, Co-simulation.

Practical Implications
This article works on the co-simulation between EnergyPlus and Python. The functional mock-up unit FMU can be used for this purpose. It allows two components to be simulated simultaneously and thus to exchange values at every time step. Binaries for multiple source code are included for coupling (within FMU).

Introduction
In general, heat losses in buildings occur via walls (30%), roofs (25%), windows with doors (25%), slab and thermal bridges (20%) (Dmytro 2017). Renovation presents a major solution to overcome thermal losses. The French National Housing Agency (“Chiffres de la construction 2019”) recorded 155,000 renovated house units in 2019 (almost the double of 2017). Heat loss through ground floored buildings in contact with soil plays an important role in a construction’s thermal behaviour (Zhong and Braun 2007). Thermal bridge (TB) is defined as a discontinuity between materials, junctions or structures, it is a multi-dimensional heat-flow where the gradient of heat-flow varies compared with surrounding elements (Nagy 2014). Thermal bridges of a slab on grade building are located at junctions of facades and floors, facades and roofs, facades and low floors, as well as all openings (doors, windows).

In foundations, TB is common along perimeter between external wall and slab interface (Kruis 2015). The construction elements near the perimeter, which lead to thermal bridges, need to be described and defined (geometry).

Ground (soil) is considered as a porous material. It is exposed to heat, air and moisture transfer and its thermal inertia affecting building’s internal conditions (Janssen, Carmeliet, and Hens 2004). In fact, an excess of moisture in soil can directly affect energy performance. For example, a dry porous medium can provide a good insulation due to its low thermal conductivity, but the presence of water vapor or liquid water especially in old existing buildings where soil is not or partially insulated can lead to a serious degradation of these performances and have a negative impact on ground heat transfer (heat loss) (M. Deru, Judkoff, and Neymark 2002).

Through the FMU Standard, co-simulation between EnergyPlus software and Python platform (Nouidui, Wetter, and Zuo 2014) allows an exchange of information between traditional building and other external models, without significantly extending calculation time. An FMU is a package that contains model description, models, executable programs and source code for different software co-simulation. The work presented in this article thus demonstrates the ability of this standard to operate with a dynamic thermal simulation tool, as well as Python models, in a dedicated platform, to reproduce interior conditions behaviours.

The purposes of this article are to define and calculate thermal bridges at ground level using THERM software, then to propose solutions for retrofitting based on insulation type (I or L), insulation thickness and depth. Finally to see its effect on energy consumption using EnergyPlus software. Due to the importance of moisture content in soil, a new model “HamoPy” is proposed and
validated against Annex A of EN 15026:2007 (European Standard EN 15026:2007 2007). This model will be coupled with EnergyPlus (using FMU) to replace its existing ground model which neglects this aspect. Primary results of this coupling are shown in this paper (neglecting moisture transfer).

**Methodology**

**Thermal bridges calculation**

Thermal bridges calculations (temperature-fluxes-conductance) between construction joints were calculated using THERM 7.7 software (Lawrence Berkeley National Laboratory, USA) (“THERM Software”). THERM uses a steady state two-dimensional conduction heat-transfer model (Validated against ISO 10211:2017). It calculates TB effects in building components such as windows, walls, foundations, roofs, and doors.

Information about the thermal transmittance coefficient (U [W/m².K]), averaged for the whole element, can be used for further quantitative assessment of a joint, namely calculation of the linear thermal transmittance coefficient ψ [W/m.K]. ψ is calculated, based on (ISO 10211 2017), by using this equation (1):

\[ \psi = \frac{L_{2D} - h_{c}U_{w} - 0.5bU_{s}}{h_{c}U_{f}} \]  

where \( L_{2D} \) is the thermal coupling coefficient obtained from the 2D analysis of the modelled element as a multiplication of the averaged thermal transmittance U and the joint’s length [W/(m.K)]; \( b \) is the width of the floor [m], \( h_{c} \) is the minimum distance from junction to the cut-off plane [m], \( U_{s} \) and \( U_{f} \) are the thermal transmittance coefficients of the floor and wall [W/(m².K)]. The values of the \( U_{g} \) and \( U_{w} \) coefficients were calculated in THERM according to ISO 6946 (ISO 6946 2017) and ISO 13370 (ISO 13370 2017) standards.

**TB calculation with EnergyPlus**

EnergyPlus is a free, open-source whole building energy simulation program used by engineers, architects, and researchers to model energy consumption for heating, cooling, ventilation, lighting, process loads and water use in buildings. It was developed by the DOE (Department of Energy, USA).

The results from THERM (ψ) will be used to define thermal bridges in EnergyPlus. A new thermal conducance for the wall (where the TB exist) will be calculated based on this equation (2) (ISO 10211 2017):

\[ U_{w,new} = \psi.L + U_{w}A_{w} \]  

where \( A_{w} \) is the area of the wall [m²], \( U_{w} \) is the old thermal conductance of the wall [W/m².K] (without TB), \( U_{w,new} \) is the new one [W/m².K] and \( L \) is the joint’s length between the wall and floor [m]. So the next step is to enter the U to EnergyPlus and calculate the energy consumption.

**Heat and moisture transfer model**

(Janssen, Blocken, and Carmeliet 2007) presented a model to describe heat and moisture transfer under atmospheric conditions. It can be expressed by these equations (3):

\[ \frac{\partial w}{\partial t} + \nabla T (g_{m,t} + g_{m,v}) \]

where \( w \) is water content [kg/m³], \( p \) is capillarity pressure [Pa], \( t \) is time [s], \( g_{m,t} \) and \( g_{m,v} \) are presented by (4) and (5):

\[ g_{m,t} = -K \nabla T \]  

\[ g_{m,v} = \frac{\nabla_{p} y}{\nabla_{p} T} \nabla_{c} \]  

where \( K \) is liquid permeability for \( p \), gradients [-], \( p \) is vapor pressure [Pa], \( \nabla_{c} \) is vapor permeability for \( p \), gradients [-], \( \rho_{v} \) is liquid density [kg/m³], \( R \) is precipitation on surface [kg/m².s], \( T \) is temperature [K], \( L \) is heat of vaporization [J/kg] and \( \psi \) is normalized thermal derivative [K⁻¹]. Moreover, the energy balance is represented by (6):

\[ \frac{c_{p} \rho_{v} + c_{w} \rho_{l}}{\nabla_{T}} + \left( c_{T} \frac{\partial w}{\partial t} \frac{\partial p}{\partial T} \right) = -\nabla (g_{h,c} + g_{h,a}) \]  

where \( c_{v} \) is solid specific heat [J/kg K], \( c_{l} \) is liquid specific heat [J/kg K], \( \rho_{o} \) is solid density [kg/m³], \( g_{h,c} \) and \( g_{h,a} \) are presented by (7) and (8):

\[ g_{h,c} = -\lambda \nabla T \]  

\[ g_{h,a} = c(T) g_{h,c} + (c_{l}T + L_{o}) g_{v} \]  

where \( c_{v} \) is vapor specific heat [J/kg K]. In this model, the potential of moisture transfer is capillarity pressure. In addition, moisture transfer is under two phases: liquid “\( g_{cm} \)” and vapor “\( g_{cm} \)”.

**EnergyPlus and Python coupling (FMU)**

To consider ground heat and moisture effect in EnergyPlus simulation a new model should be coupled. Co-simulation between several tools makes it possible to extend their own functionalities. Coupling EnergyPlus, or other simulation software, with external programs has been done in past, either by creating specific interfaces to external programs in the source code of EnergyPlus, or by using middleware, such as the Buildings Controls Virtual Test Bed in (Wetter 2011) and in (Langevin, Wen, and Gurian 2015). In 2013, (Nouldui, Wetter, and Zuo 2014) propose to link EnergyPlus directly with an external program, using the Functional Mock-up Interface (FMI).

The FMI standard can therefore be used to co-simulate EnergyPlus with the Python platform. In this context, co-simulation allows the two components to be simulated simultaneously and thus to exchange values dynamically and without middleware. To perform a co-simulation one of the two software must be the "master". The second one must be exported to a special folder called Functional Mock-up Unit (FMU). The FMU is a folder composed of a Python description file, a model containing information relating inputs and outputs of the co-simulated software, and an FMU file (.fmu) describing the idf file used with weather file .epw and the FMI (Version 1.0).
To couple slab and soil temperatures, the EnergyPlus slab model should be replaced by the new Python code. This step can be done by using the “OtherSideCoefficient” object in E+ (Figure 2):

Using this object, we can apply exterior surface temperature for walls, roofs and slabs in EnergyPlus. As shown in Figure 2, slab convective coefficient for exterior surface should be 0. Therefore, the slab R-value in E+ is set to be infinite (E+ slab thickness is set close to 0) and all phenomena’s and heat flows can be seen in Python model. Slab surface temperature is send to E+ at every time step.

Case Studies

Figure 1 shows the exchange process and the files required for the co-simulation between EnergyPlus and Python. As part of our external model (Python model: HamoPy.py), a configuration file is systematically used: FmuToPython.py, includes information on inputs to our Python model (HamoPy): Zone Temperature and Interior Air Relative Humidity. Outputs (of Python model= Input to EnergyPlus): Interior Slab Temperature, and Ground Vapor flux. As mentioned before the FMU file (.fmu) will include information on our idf file, weather file and FMI. Finally, once these three files are integrated into the simulation environment, the main EnergyPlus .idf file must be adapted to co-simulation. For this, the modeller must activate external interface, define the FMU linked to EnergyPlus, and indicate the input and output variables (for more details: refer to the application guide for external interfaces of EnergyPlus (“EnergyPlus”)). When Python starts the simulation, it reads the main file and determines if it is linked to an FMU. If this is the case, Python initializes the FMU. Once this pre-process has been completed, the co-simulation can begin and has three phases. First, the FMU retrieves the environmental variables of Python in the form of a table of values, then the FMU algorithm runs. Finally, at each time step results are returned to the EnergyPlus software.

![Figure 1: Files used to carry out co-simulation with Python platform and E+ using FMU (inspired from (Middleton)).](image)

Figure 3: Case study based on (ISO 10211 2017).

THERM (TB calculation) and EnergyPlus (Thermal zone calculation) simulation (Figure 3): The studied zone dimensions is: 6mx6mx3m. It has one glazed door (2mx0.8m) and window (2mx1m). Concerning external conditions, they are represented by the climate of Hamburg. The internal one are represented by constant temperature of 20°C. This zone is considered as a living room (2 person seated). The air change rate per hour is 0.5 ACH. Finally, the simulation run period is one year. Wall composition (material properties are found in WUFI’s library) is: 20 cm of concrete (2.3 W/m.K). Slab composition is: 20 cm of concrete (2.3 W/m.K) and 10 cm of gravel (2 W/m.K) and soil (2 W/m.K). Two case studies are shown in this paper: Different ground insulation types (shape of I and L) polyurethane (0.04 W/m.K) will be discussed in next paragraph. EnergyPlus and Python: Zone dimensions are similar to previous example. Walls, roof and slab are made of concrete (λ=2 W/m.K, cρ=25 cm, cρ=20cm), and soil is made of Clay (λ=0.288 W/m.K, cρ=20 m). The calculation is done under San Francisco climate from 1 until 10 January (No heating). All hydrothermal properties of this materials can be found also in WUFI’s library (“WUFI Software”).

Results

In this paragraph, TB calculations were done for different cases: no insulation and exterior insulation with different depth, thickness and height (above the ground). The two types of insulation (Figure 4) are I and L (new type). In next calculations, d, e, 1 and H will represent insulation...
depth, thickness, width and height above ground [m] respectively. Distance from ground’s level to wall-slab junction is H=0.3m.

**Figure 4: Different type of exterior insulation.**
For no exterior insulation and based on equations 1 and 2, the linear thermal transmittance coefficient Ψ is found to be Ψ=0.618 W/m.K.

**Figure 5: Annual energy consumption with and without TB.**
Figure 5 shows a histogram of annual energy consumption (calculated by E+) with and without TB. A difference of 2.6% exists between considering thermal bridges and not for a single zone.

**Case 1: Insulation type 1**

**Figure 6: Linear Thermal Transmittance Psi as a function of exterior insulation thickness (0.02 m, 0.07m , 0.12m) and height (H in Figure 4); the depth (d in Figure 4) is constant d=2m.**
Figure 6 represents Psi variation for different exterior insulation thicknesses (0.02 m, 0.07m, 0.1m) and heights (H in Figure 4); the depth (d in Figure 4) is constant d=2m.

Concerning Figure 7, same as (a) but “d” is equal to 0.6m. It was shown from Figure 4 and 5: if H>0.3m linear thermal transmittance will decrease with thickness and depth to achieve 85% TB reduction (with respect to no insulation case) for depth=2m, thickness=12cm, and height= 0.8m. Otherwise if H<0.3, Ψ will increase when d and e increase. This result is due to the fact that insulation blocks heat flux to pass from interior to exterior through junction (figure 8).

**Figure 7: Linear Thermal Transmittance Psi as a function of exterior insulation thickness (0.02 m, 0.07m , 0.12m) and height (H in Figure 4); the depth (d in Figure 4) is constant d=0.6m.**

**Figure 8: Heat fluxes paths with and without insulation.**
Figure 8 shows how the flux is redirected (no insulation and insulation case). Heat fluxes will have a long trajectory to exterior. Larger dark patches occur at the top (insulation case). Heat fluxes will take the closer path (closer weak point) where no insulation exist to block heat loss.
Case 2: Insulation type L

![Figure 9: Linear Thermal Transmittance Psi as a function of exterior insulation thickness (0.02 m, 0.07 m, 0.12 m) and length (1 in Figure 4); the height (H in Figure 4) is constant H=0.363m.](image)

For the new type “L”, H is set to be 0.363m and the variation of psi with insulation thickness and length “l” is shown in Figure 9. The linear thermal transmittance will decrease when insulation thickness are increased.

![Figure 10: Heat fluxes paths with L insulation.](image)

Compared to case 1 (I type with e=12cm, H=0.363m and d=1m): 60% reduction, the “L” type with horizontal width of 1m (same thickness and height) can reduce TB to 54% with respect to no insulation case.

**EnergyPlus and THERM**

Compared to no insulation case, annual heating energy consumption is decreased when height and thickness are increased (Figure 11). It will achieve a 2.2% reduction during the year with an insulation: depth=2m, H=0.8m and e=12 cm (Where thermal bridge is reduced to 85%).

**Case 1**

![Figure 11: Ideal heating annual energy consumption (With TB) for different insulation height (depth is constant, d=2m) compared with no insulation case.](image)

**Case 2**

Similar behaviour had been found for the “L” case where energy consumption decreases when increasing insulation width and thickness (Figure 12).

![Figure 12: Ideal heating annual energy consumption for different insulation widths (Height is constant, H=2m) compared with no insulation case (TB is taken into account).](image)

A 1.5 % reduction of the annual heating power could be reached (H=0.363, l=1.5m, e=12cm).

**Ground heat and moisture transfer model (HamoPy) validation**

It is important to consider moisture transfer at ground’s level. Any increase in water content will lead to an important degradation of these performances and have a negative impact on ground heat transfer (heat loss) (M. Deru, Judkoff, and Neymark 2003).

To ensure that this model can be used in soil heat and moisture transfer, it should be validated against analytical solutions or experimental results. In literature, we have the British norm “EN 15026:2007: Hygrothermal performance of building components and building elements — Assessment of moisture transfer by numerical simulation” (European Standard EN 15026:2007 2007). It describes the practical application of hygrothermal simulation software used to calculate one-dimensional transient heat and moisture transfer in building envelope subjected on both sides to fluctuating climatic conditions. Annex A of EN 15026:2007 defines the moisture uptake in a semi-infinite region. It deals with thick homogeneous material (20 m) in equilibrium with a constant surrounding climate. Material is perfectly airtight.

The purpose here is to predict the temperature and moisture profiles at time t=7, 30 and 365 days within the wall. Material’s properties can be found in (European Standard EN 15026:2007 2007). Initial material conditions is set to be T0=20°C and RH0=50%. Dirichlet boundary conditions are set at the top edge (T=30°C, RH=95%) and adiabatic one for the bottom. Using the HamoPy model, calculation is done. Results are compared to analytical solution and are shown in Figures 13 and 14 for water content and temperature distribution at 7, 30 and 365 days. It should be noted that the mesh between x=0 and x=0.5 m is set to be 400 elements, between 0.5 and 5 m the mesh is 200 elements and 100 from 5 to 20 m. For the first 50 cm of the domain, the mesh is set to be finer.
in order to resolve the quickly decreasing moisture profile in this region.

![Figure 13: Moisture distribution at 7 days, 30 days and 365 days](image1)

Figure 13 and 14 represent moisture content and temperature distribution at days: 7, 30 and 365.

![Figure 14: Temperature distribution at 7 days, 30 days and 365 days](image2)

Hamopy results are close to the analytical solution of EN 15026 and they are within the permissible error range (±2.5%).

**EnergyPlus coupled with HamoPy**

Figure 15 shows a comparison between the coupled model (HamoPy: only thermal calculation) with EnergyPlus and a validated transient 2D heat transfer model (in E+): KIVA (Kruis 2015).

![Figure 15: Interior slab surface temperature as a function of time (h)](image3)

Interior slab surface temperatures are compared (Figure 15), the error will vary between 0 and 0.4 °C which is acceptable with respect to the validated model. These results are in a good agreement with Kiva (validated model). Concerning zone temperature for the two cases, Figure 16 represents two merged curves which is in accordance with previous results (Figure 15).

**Discussion**

The method used in our calculation is described in equation (1) and (2). The linear transmittance coefficient is found based on a 2D (steady state) conduction heat transfer model (THERM). This coefficient is then used in EnergyPlus to calculate effects of thermal bridges on energy consumption. Our case study is a single zone (6mx6mx2.7m). It was found that taking into account ground thermal bridges will increase annual heating energy consumption by 2.6% from 20721 kWh to 20196 kWh (Figure 5). It is important to include the effect of TB and new solutions should be proposed to reduce consumption.

![Figure 16: Zone temperature as a function of time (h).](image4)

In our study two types of exterior insulation (polyurethane $\lambda=0.038$ W/m.K) are applied. Results show that exterior insulation increases slab interior surface temperature and reduce condensation risk. Figure 17 shows how this temperature is increased between no insulated (9.2°C) and insulated case (14.4°C) (depth=2m, thickness=12cm, and height= 0.363m). The two insulation types (I and L) can have similar efficiencies (for specified condition) but the type L (case 2 in Figure 4) looks to be more reliable concerning applicability of insulation for different types of soil. And finally its low installation cost with respect to I case (excavate the soil).

When calculating thermal bridges it is important to use reliable thermal properties such as thermal conductivity. In any porous material (like soil), it will vary proportionally in function of water content to achieve high values (factor of 10) (M. P. Deru and Kirkpatrick 2002). Therefore it is important to include heat moisture transfer in our study. HamoPy is a 1D heat and moisture

![Figure 17: Temperature distribution at the ground surface: insulated and no insulated case.](image5)
transfer model. It is able to predict heat and moisture transfer in semi-infinite regions (ground).

**Conclusion**

The purpose of this article is to show the importance of ground thermal bridges during calculating heating consumption and slab surface temperature (using THERM). Also to highlight the importance of co-simulation between EnergyPlus and Python using FMU. Moreover to consider TB effect and ground heat transfer in EnergyPlus via FMU coupling.

It is important to consider TB and propose new solutions to reduce energy consumption. Results show that: the more insulation is deeper, lengthen and higher above ground the more energy reduction is found. The two solutions (insulation types) have high efficiencies (at specified thickness, depth and width). The type L is more preferable because it can have similar efficiency as I without need to excavate soil (less cost and more practical).

FMU looks to be a good standard to link EnergyPlus with Python. Co-simulation is successfully done (FMU) (Figure 15, 16) via zone and slab surface temperature. Results was validated against Kiva model (via interior slab surface and zone temperature).

Due to huge importance of soil moisture transfer, HamoPy can be used in ground heat and moisture transfer.

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**Nomenclature**

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<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tr>
<td>b</td>
<td>Half width of the zone</td>
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<tr>
<td>c_l</td>
<td>Liquid specific heat</td>
<td>J/kg K</td>
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<td>c_o</td>
<td>Solid specific heat</td>
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<td>c_v</td>
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<td>FMI</td>
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and Building Elements — Assessment of Moisture Transfer by Numerical Simulation.”


