

## EFFECT OF GROUND THERMAL INERTIA ON THE ENERGY BALANCE OF COMMERCIAL LOW-RISE BUILDINGS

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### ABSTRACT

Commercial low-rise buildings are characterized by large volumes and prevalence of heat transfers with the ground and the roof. The inertia of these lightweight structures is mainly given by the slab/ground. Heat transfer from/to the ground is an important term of the energy balance. The present study aims to assess the importance of both the one-dimensional and the three-dimensional modeling level used to account for the ground in the energy balance of a low-rise building. The computed energy consumption and thermal comfort are particularly sensitive to the inertia and the ground model for the tested configuration of commercial buildings; especially for the summer period when no cooling system is used. However, during the winter period when the heating system is operating, the simple one-dimensional model gives results similar to the more complex three-dimensional one.

### INTRODUCTION

Buildings can be classified into several types such as residential, commercial and industrial (Krarti, 2010). In France, the building energy demand accounted for 71 Mtep which stands for 43.87% of total annual primary energy consumption in 2010 (Développement durable, 2012). 20.9% of this energy is consumed by the tertiary sector / commercial buildings (Rabai, 2012). The part dedicated to the tertiary sector has continuously increased up, and is 15% higher than in 2001. In contrast, other sectors succeeded to reduce the energy consumption: -1% for transportation, -6% for residential and -21% for the industrial sector.

The energy consumption of commercial buildings is mostly associated to heating and air-conditioning. The heating and cooling systems account for 57% of total building energy needs (Balaras et al., 2000; Chwieduk, 2003). In order to reduce this energy spending, thermal losses through the building envelope have to be minimized. The ground floor is known as one of important factors in the energy balance for commercial low-rise building. In a study by Labs (Labs et al., 1988), the heat loss through a non-insulated floor was found to account for 10% of the total building energy budget. Improving the floor

thermal quality by adding insulation can lead to 30%-50% energy efficiency (Deru, 2003). Thermal inertia of the building envelope is another key factor. For example, Aste et al. (2009) showed a 10% difference in the heating loads between high and low thermal inertia envelopes of a studied building. Both issues have to be handled properly to reduce building energy consumption.

Efforts have been put during the last 10 years to better predict the heat transfer between building and the ground. The complexity of the energy coupling comes from the fact that the heat transfer through the ground is three-dimensional. To correctly represent these heat exchanges, the thermal properties of the ground (density, thermal conductivity and thermal capacity) have to be determined but other parameters such as the ground homogeneity and moisture content, the density of neighboring buildings (density), and the occupation of the ground level (vegetation, urban area...) can be relevant too.

Various studies have proposed different level of modeling regarding the coupling between the building and the ground. Zhong and Braun (2007) studied heat transfer through the floor (slab on grade) of a small commercial building. A simplified model has been developed. This model takes into account the steady loss along the perimeter of the slab and one dimensional transient one under the slab. Adjali et al. (2000) conducted a numerical study to assess the ground temperature under slab developing 2D/3D models. They assumed that from a distance of 10 meters from the slab (horizontally and vertically), the heat transfer was negligible. Luo et al. (2010) studied the impact of the type of boundary conditions applied to the ground model (constant heat flux or zero temperature) according to the depth and the temperature inside a house. Landman and Delsante (1987, 1986) and Davies (1993) have analyzed the heat transfer between a floor and vertical and horizontal perimeter insulation in steady-state. Bahnfleth and Pedersen (1990) have studied the impact of the area to perimeter ratio of the slab and showed that the heat loss is an increasing function of this ratio. Mingfang and Qigao (1998) studied the heat flux stratification near the end of the floor from an analytical model of a semi-infinite homogeneous medium. Zhou et al. (2002) used finite elements to calculate the temperature distribution in the ground. They showed that up

to a certain distance (15 m horizontally and 10 m vertically), the fluctuation of ground temperature is influenced by the heat transfer through the floor. On the other hand, Adjali et al. (2000) have determined that the far field boundaries for their simulations were 10m horizontally and vertically.

In the present paper, we are interested in analyzing the impact of ground thermal inertia on energy consumption and comfort of a commercial building. In the first part, three conventionally-used models are presented to simulate the thermal behavior of the ground. The second part presents the results obtained by these different models. The impacts of ground parameters (thermal conductivity, heat capacity, dimensions...) on the energy performance of this type of building in terms of heating and cooling are also studied.

## METHODOLOGY

### Description of the commercial building

The study is carried out on a one floor commercial building with a cubic shape (Figure 1) located in a temperate climate (Poitiers, France). The base of the building is a square of 36m sides. The height of the building is 6m. It is made of steel structure with a horizontal large roof surface provided with skylights.

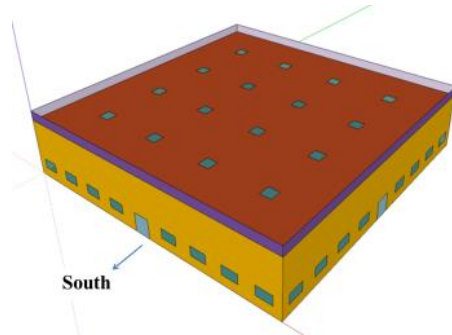


Figure 1. Geometry of the studied commercial building

The vertical walls (except the northern one) include 30m<sup>2</sup> of windows. The building is fitted with 16 skylights covering 2.4% of the total roof area (31.36 m<sup>2</sup>). The exterior walls (horizontal and vertical) have a total thickness of 30.5cm (1.3cm of gypsum, 14cm of glass wool, 15cm of rock wool and an outer steel cladding of 2mm). The thermal inertia of the building is mainly related to concrete slabs (160 mm thickness in ground floor with no thermal insulation).

The building is heated during winter season and the performance is increased by a HRV system (Heat Recovery Ventilation). For the summer conditions, the building has no air-conditioning system. In winter the air temperature is set at 19°C in occupancy period and allowed to drop down to 16°C in the remaining period. Lights are switched on when the work plane illumination is below 750 lux. The occupancy time is defined from 8AM to 10PM except on Sunday.

### Ground heat transfer models coupled to the building

In this article, three modeling level, from the most simple to the most detailed, are studied: adiabatic, one-dimensional (1D) and three-dimensional (3D) models. Those models account for heat transfer only i.e. no moisture transfer is considered here.

#### Adiabatic model:

In this model (Figure 2), it was assumed that below the concrete slab, heat transfers are null. The cold bridges between the slab and outside are calculated with the French thermal regulation (RT2005).

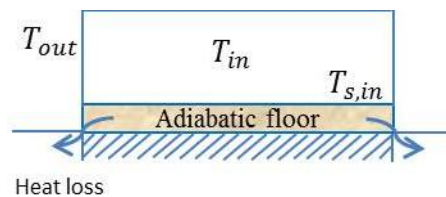


Figure 2. Adiabatic model

#### One-dimensional model (1D):

For this model (Figure 3), we consider that, below the slab, two layers of the same materials are present. The first layer (0.30m) participates to the thermal inertia (and is modeled as a massive layer) while the second layer (9.70m) has no inertia (massless). This simplification for the second ground layer and the first layer thickness are validated from the preliminary simulations (see next section). At 10m, the temperature of the ground can be considered independent of the building behavior (Adjali et al., 2000). The temperature required in the model at this depth is calculated by the model of Kusuda (Eckert and Drake Jr, 1987; Kusuda and Bean, 1984).

$$T_{(z,t)} = T_m - T_a e^{-z \left( \frac{\pi}{365 \cdot \alpha} \right)^{0.5}} \times \cos \left( \frac{2\pi}{365} \left[ t - t_p - \frac{z}{2} \left( \frac{365}{\pi \cdot \alpha} \right)^{0.5} \right] \right) \quad (1)$$

The cold bridges are calculated as for the adiabatic model.

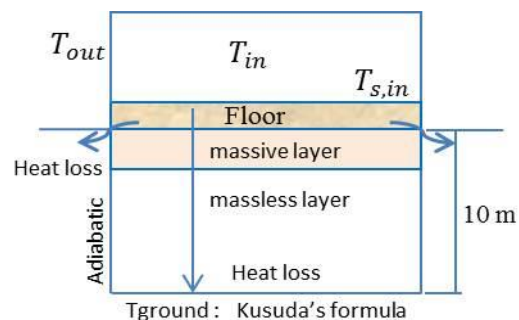
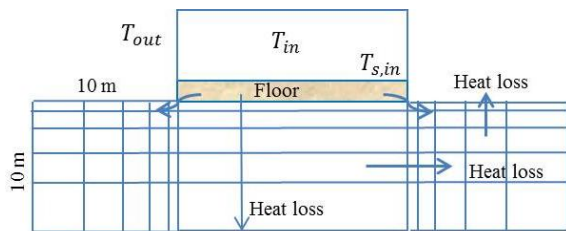


Figure 3. 1D model

*Three-dimensional model (3D):*

This model takes into account the heat transfer in the ground along the three directions (Figure 4). The heat transfer is assumed to be conductive only. This model relies on a three-dimensional finite difference representation of the ground. The details of the model are presented in Zhou et al. (2002) and McDowell et al. (2009). A distance from the slab of 10m in each direction (x, y and z) has been considered (Zhong and Braun, 2007). Adiabatic conditions are imposed to the vertical boundaries while the horizontal plane at 10m depth has a fixed temperature calculated from eq.(1). The thermal properties of the ground are supposed homogeneous. To initialize the ground temperature, the simulation is run over a two years' period to obtain a correct profile of the ground temperature for a single year. In this model, it is not necessary to evaluate the cold bridges. They are automatically integrated by the model.



Tground : 3D finite difference calculation  
 Figure 4. 3D model

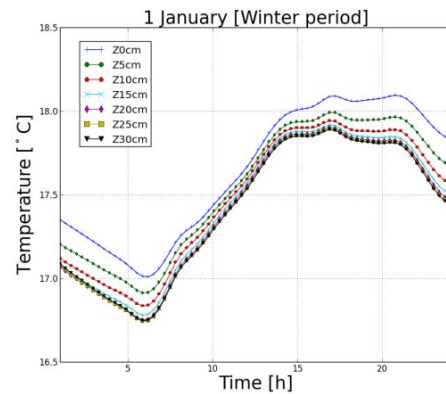
**Simulation**

The simulations have been performed using TRN-SYS 17. Coupling with CONTAM has been used to calculate the infiltration and natural ventilation. Time step of 1h has been used to simulate the building behavior.

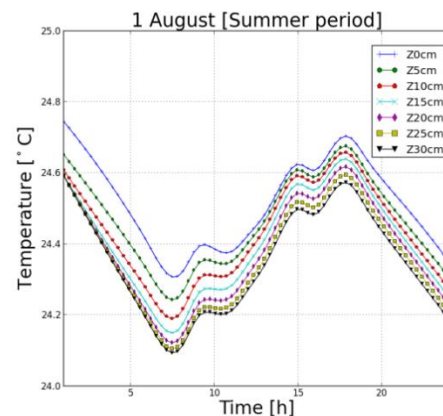
**RESULTS AND DISCUSSION**

**Preliminary simulation: evaluation of the massive layer thickness for the 1D model**

Because of limitations of the modeling tool regarding implementation of the algorithm of the heat conduction transfers, high inertia layer such as 10m soil cannot be simulated (Delcroix et al., 2012). However, there is actually no need to model the whole depth of soil as no variations in the prediction obtained by the 1D model are observed for depth higher than 25cm for the studied case (Figure 5). The results presented in the next section for the 1D model have been obtained using 30cm of massive layer.



a. Winter period

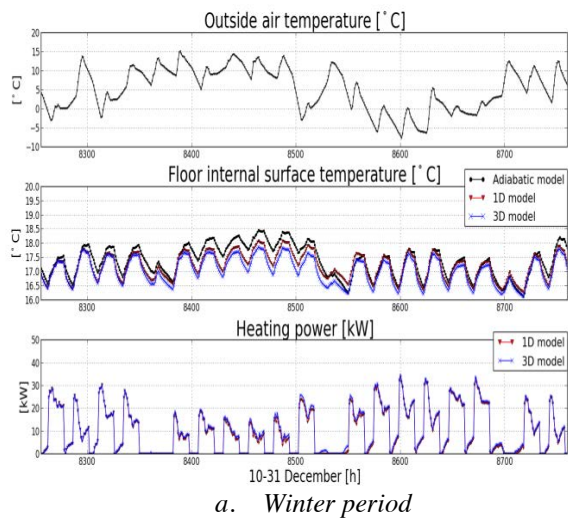


b. Summer period

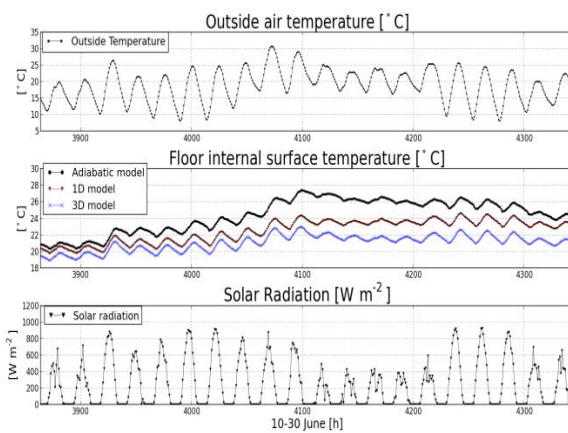
Figure 5. Indoor surface of slab temperature according to the massive layer thickness (1D model) for one typical day in winter (a) and in summer (b)

**Comparison of the ground-coupled models**

Figure 6 presents the evolution of the internal surface temperature of the slab versus time for the winter (a) and the summer (b) period along with the outside temperature and solar irradiance. In contrast to the other two models, the adiabatic model provides higher slab temperature in winter. This result comes from the fact that the heat from the indoor air cannot be transferred down to the ground due to the model hypothesis, which artificially increases the slab temperature. As a consequence, the slab temperature for this model does not depend on the outdoor temperature but only on the indoor air temperature set. The surface temperatures for 1D and 3D models are almost the same in winter. There is a slight temperature deviation when the outside temperature drops down. The average reduction from the adiabatic model in winter is 0.62°C for the 1D model and 1.15°C for 3D model. The heating energy demand computed with the 3D model (65.6 kWh/m<sup>2</sup>.year) is greater than the result of the 1D model (55.85 kWh/m<sup>2</sup>.year).



a. Winter period



b. Summer period

Figure 6. Internal surface temperature of slab

Higher differences regarding the slab internal surface temperature are observed for the summer period. Indeed, no cooling system is operating during summer, and the indoor air temperature is free-floating, strongly depending on the outdoor air temperature, solar irradiation and thermal inertia of the ground. The adiabatic model gives higher temperature whereas the 3D model predicts the lowest one. This is due to a better representation of the thermal inertia of the ground by the 3D model that acts a heat sink and lower down the slab temperature; in comparison with the 1D model that partially accounts for thermal inertia and the adiabatic model that does not.

To provide a broader view of the differences between the three modeling levels, trends regarding the internal surface temperature of the slab have been plotted against the outdoor temperature (Figure 7). The slopes of these trends show that this slab temperature and the differences between the model predictions increase strongly for high outdoor temperatures. For outdoor temperatures below 5°C, the three models are equivalent. The 1D and 3D models gives almost the same responses for outdoor temperature below 15°C so that energy analysis for heating season can

be performed by both models. For higher outdoor temperatures, differences between the models are important. This suggests that thermal comfort analysis for the summer period requires the use of the 3D modeling for unconditioned spaces.

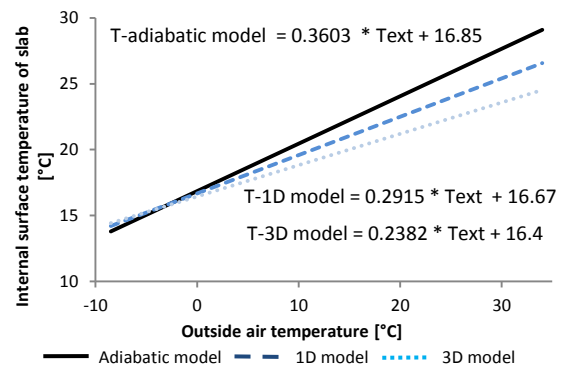


Figure 7. Internal surface temperature of slab on outside temperature function for different model

In addition to the modification of the slab temperature, the thermal inertia acts on the time values corresponding to the maximal and minimal temperatures. This time shift is essentially important for thermal comfort in summer as it can delay too high temperatures at the end of the day, when the building is unoccupied. Table 1 presents the time shift between the time of day of the maximal temperature obtained by the 1D and 3D models and that of the adiabatic model. The values presented in this table are averaged over the whole winter and summer seasons. There is a different time shift for both models. In particular, for the summer period, the time shift of the 3D model is twice the one of the 1D model, and is mainly due to the higher complexity of heat transfer flow path. For the winter season, the 3D model value is slightly higher than the 1D model time shift, supporting the previous observation of similarity for the heating period.

Table 1 Maximal temperature's time shift for 1D/3D model from reference (adiabatic model)

Time shift	1D model [min.]		3D model [min.]	
	Summer	Winter	Summer	Winter
T-max	22	47	47	61

### Computing time

Simulation time depends on the calculation process for each model. We assess the computing time for 3 tested models (adiabatic, 1D and 3D models) and an additional one without floor/ground element for comparison. Figure 8 presents the computing time of those 4 approaches for the main Types of the simulation. Similar simulation times ranging between 56-59 seconds are observed for the simplest models; there is no notable computational cost of integrating the adiabatic and 1D models. Conversely for the last-one

(3D mono zone ground coupling), its simulation time is about 23 times longer than the other models.

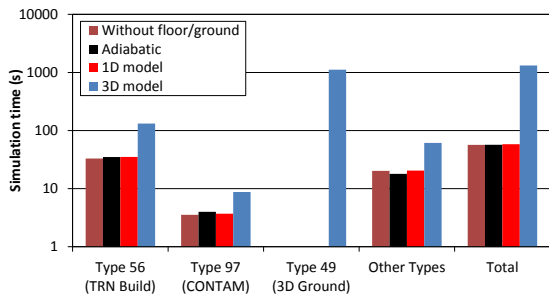


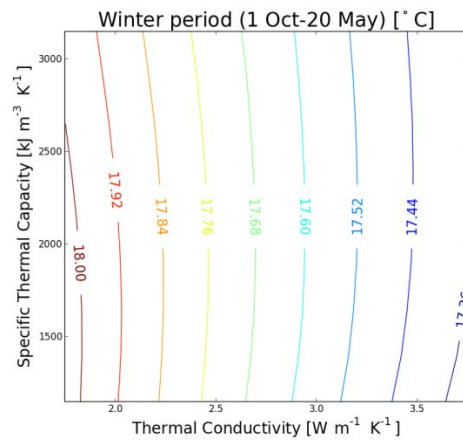
Figure 8. Computing time for the different modeling approaches

### Effect of thermal ground properties

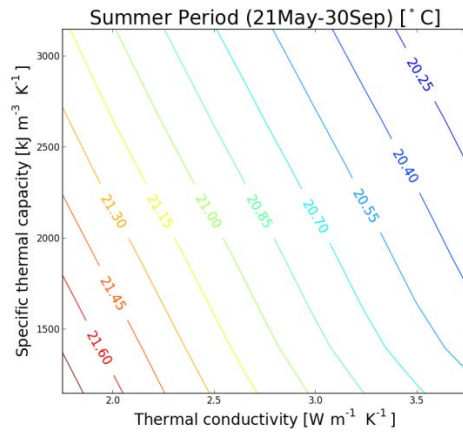
In order to investigate the impact of ground thermal properties on the thermal building performance and thermal comfort, additional simulations have been performed using the 3D model alone. The soil thermal conductivity represents the soil's ability to transfer the heat to the environment and specific thermal capacity (i.e. the product of its heat capacity by its density) indicates the ground's capacity to store the heat per unit volume. In the previous section, sand was selected as the reference soil with a thermal conductivity of 2.0 W/m.K and a specific thermal capacity of  $2 \times 10^6$  J/m<sup>3</sup>.K. A parametric study has been carried out by varying the value of the conductivity from 1.75 to 3.75 W/m.K and the specific thermal capacity from  $1.14 \times 10^6$  to  $3.43 \times 10^6$  J/m<sup>3</sup>.K. 81 simulations have been performed for the present study.

Figure 9 presents the slab internal surface temperature obtained with the 3D model according to the thermal conductivity and specific thermal capacity for the winter and summer seasons. The obtained slab surface temperatures for the winter period (Figure 9-a) only depend on the thermal conductivity and not on the specific capacity. The temperature of the indoor air is actually kept to a higher value than the 10m depth boundary condition's temperature below the slab. Thus, the heat transfer is always one-directional, from the building air to the ground. Therefore, in this one-direction heat transfer, the thermal conductivity alone influences the temperatures change and heat balance. In case of high thermal conductivity, the temperature of internal surface of slab will be smaller (as observed in Figure 9). Both thermal properties contribute to the temperature changes in summer. As the building air temperature is left free-floating i.e. without a cooling system, this temperature is periodically higher and lower than that of the ground. In this way, the heat transfer is alternatively from and to the ground. Consequently, thermal inertia (i.e. the specific thermal capacity) plays the role of delaying the effects of the outdoor tempera-

ture and solar irradiation fluctuations on the building air temperature. As observed in Figure 9, grounds with large thermal capacities absorb more heat from a slab that becomes subsequently colder.



a.



b.

Figure 9. Average temperature [°C] of the slab internal surface versus ground thermal properties

Figure 10 presents the time shift versus the ground thermal conductivity and specific thermal capacity for the summer period. Both ground properties are important here, the expected shift ranges from 42 to 77 minutes for the present studied case.

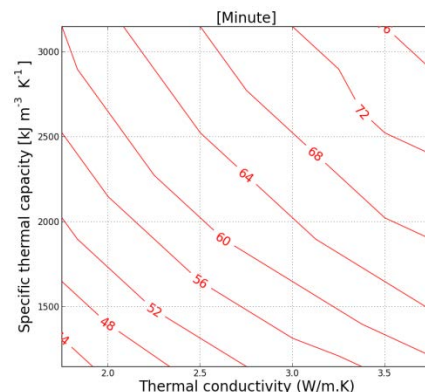


Figure 10. Maximal slab temperature time shift versus ground thermal properties

Regarding the heating energy variations, the building heat losses through the slab are clearly depending on the ground conductivity. High thermal conductivity increases the heat transfer through the ground to the outside air. This effect is highlighted in Figure 11. Along with the increase the conductivity value, there is a significant linear increase correlation to heating energy demand and the thermal inertia does not play a noticeable role.

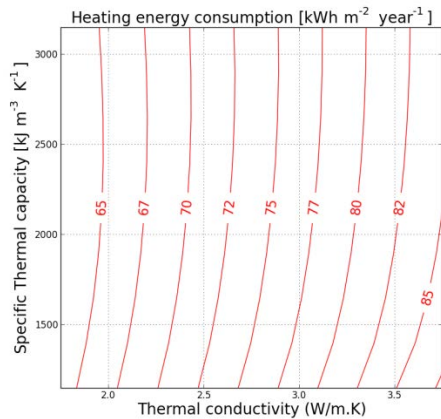


Figure 11. Heating energy (01 Oct-20 may)

In summer, the highest operative temperatures take place when both thermal properties are at their lowest values. Unlike for the winter period, low thermal conductivity ground reduces heating energy consumption, it can represent a risk of overheating in summer. As an illustration, Figure 12 presents the evolution of the indoor operative temperature for highest and lowest values of thermal conductivity and specific capacity of the ground. A difference of 2°C is observed between the two extreme values.

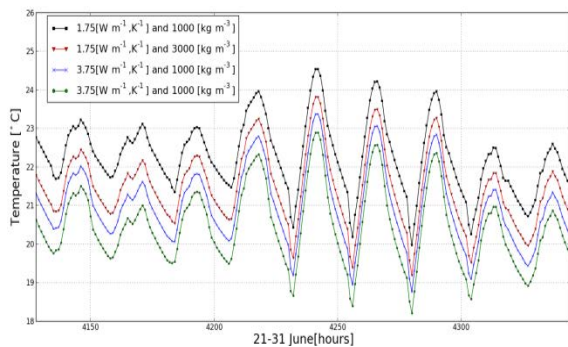


Figure 12. Indoor operative temperature

Figure 13 presents the evolution of the degree hours (26°C-based) representing thermal discomfort and energy demand for cooling system. Maximum indoor operative temperature and thermal discomfort are obtained for low values of thermal properties. However, the degree hour values obtained here are very small, i.e. there is almost none thermal discomfort so the studied building does not need any cooling system.

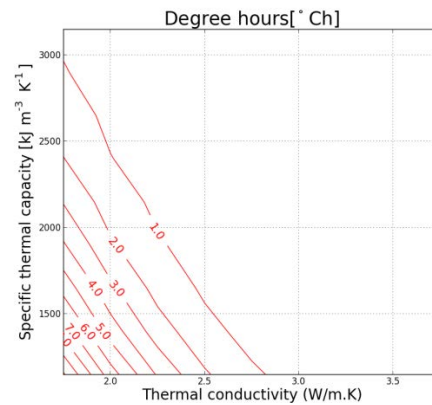


Figure 13. 26°C-based degree hours in summer

## CONCLUSION

The present study aimed at evaluating the effect of the modeling level of the ground-coupled heat transfer on the building behavior. Various results were presented regarding the slab internal surface temperature, heating energy and operative temperature.

The main results shows that the 1D model gives satisfactory predictions for the slab temperature compared to the 3D one when heating system is operating to maintain a constant indoor air temperature. Yet, considering the deviation on the energy demands, about 17%, this is a really important parameter especially for highly insulated buildings. Furthermore, the parametric analysis regarding the thermal properties of the ground illustrated this apparent independency of the slab temperature with the thermal inertia. Similar results would be obtained for a cooling system. As a consequence, 1D model can be used to assess the energy demand with similar precision for air-conditioned building. However, for these buildings without air-conditioning system, the thermal inertia along with the thermal conductivity strongly act on the thermal comfort. In the latter case, the use of the more complex 3D model is required as demonstrated by the detailed parametric study.

The main limitation of the present study lies in the unique tested case and geographical location. Yet, this typical form factor of low-rise building where the effect of the ground is high should be carefully studied. Indeed, most simplified building simulations neglects or make strong hypothesis on these transfers which are less significant for other construction types (e.g. high-rise buildings). A direct perspective of this work is to assess the impacts of the aspect ratio (which was limited to a square here) and to the role of internal thermal inertia such as stored goods. This work is the first step of a systematic analysis of commercial low-rise building's energy performance that will be completed with in-situ measurements.

## NOMENCLATURE

### *Roman symbols*

$T$	= temperature [°C]
$T_m$	= mean surface temperature over the year [°C]
$T_a$	= surface temperature variation amplitude [°C]
$t$	= time [days]
$t_p$	= day of the year when the surface temperature is minimal [days]
$z$	= ground depth [m]

### *Greek symbols*

$\alpha$	= ground thermal diffusivity [ $m^2/s$ ]
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### *Subscripts*

<i>in</i>	= inside
<i>n</i>	= time of the year (days)
<i>out</i>	= outside
<i>s</i>	= surface

## ACKNOWLEDGEMENT

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