Comparison of performance of simulation models for floor heating

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SUMMARY*:*
This paper describes the comparison of performance of simulation models for floor heating with different level of detail in the modelling process. The models are compared in an otherwise identical simulation model containing room model, walls, windows, ceiling and ventilation system. By exchanging only the floor construction, the differences can be directly compared. In this comparison, a two-dimensional model of a slab-on-grade floor including foundation is used as reference. The other models include a one-dimensional model and a thermal network model including the linear thermal transmittance of the foundation. The results from the comparison show that there are large differences in both heat loss to the ground, energy consumption and temperature distribution in the room. Differences of nearly a factor two are found for the heat loss to the ground, mainly due to the inclusion or omission of the foundation. The result can be also be found in the energy consumption of the building, since up to half the energy consumption is lost through the ground. Looking at the different implementations it is also found, that including a 1m ground volume below the floor construction under a one-dimensional model does not alter the results. Further, the differences between a hydronic and electrical inclusion of the floor heating pipe can be seen to affect the results. The main differences are found in the fact that the heat supply from the hydronic pipe depends on the temperature of the surrounding floor construction, which is not the case for an electrical (or heat flux) inclusion of the pipe. Finally it has been found, that a simplified lumped resistance/capacitance model can adequately model a floor construction with floor heating and foundation when compared to a two-dimensional model of a slab-on-grade floor.

1. Introduction

When performing building energy simulations a problem that will always arise is the level of detail needed for obtaining sufficiently accurate results for temperatures and energy consumption. This requires a large number of considerations. This is of course also the case for floor heating systems. Especially the inclusion of the heat source in hydronic floor heating systems can be troublesome. The pipe can be included either by a simple heat flux term or as a very complex inclusion of the pipe with fluid flow in the hydronic system.

In all cases it is important to consider the purpose of the modelling. A preliminary assessment at an early stage in the design process requires only a simple model, whereas more detailed models are required to find the influence of the floor heating system on the heat loss to the ground and through the foundation. Several commercially available building energy simulation programs, such as BSim, EnergyPlus, IDA, have included some sort of floor heating modules. These models normally include the floor heating system as a heat flux supplied directly to the concrete layer. A few also include a hydronic system, where the heat is supplied through a heat sink with a given temperature, which is found based on the supply temperature and fluid flow in the system. Typically only the one-dimensional heat loss to the ground is included, thereby neglecting the two-dimensional heat loss through the foundation.

The simulation models of the floor with floor heating can range anywhere from a simple resistance-capacitance thermal network with just a few nodal points to a multi-dimensional finite difference, finite control volume or finite element model with thousands of nodal points including detailed geometry as well as different boundary conditions, all of which will combine to give different results.

In this work, a comparison is made between different implementations of a floor with floor heating keeping the rest of the simulation model of the building unchanged. Therefore, only the difference in the implementation of the floor heating will affect the results, which means that the different models can be directly compared to find basic differences in their functionality.

This paper presents the results from comparing six different simulation models of the floor with floor heating system. Based on this comparison, the differences between an electrical type implementation and a hydronic type implementations for a slab-on-grade floor are compared and the results are analysed.

2. Simulation model

2.1 FHSim

The simulation model used for these analyses is called FHSim for **F**loor **H**eating **Sim**ulation (Weitzmann et al, 2002; Weitzmann, 2004). The main features of the program are dynamical calculation based on a Design Reference Year, internal split of radiative and convective heat transfer in the room and between internal surfaces, where the radiation is based on view factors, and the floor construction with different types of floor heating. All building envelope models, excluding the floor models, are based on one-dimensional finite control volume models. The floor models are described in detail below.

2.2 Building model

A room model of 30m² is used. The room has two windows of 4m² and 2.5m² with a U-value of 1.5W/m²K and a solar transmittance of 58%; the largest facing south and the smallest facing west. The outer walls (south and west) with a total area of 21m², have a U-value of 0.18W/m²K. The ceiling has a U-value of 0.10W/m²K. The value for the floor is shown below.

A simple balanced mechanical ventilation system with an air change rate of 0.5ACH and a heat recovery efficiency of 80% supplies fresh air to the room. Further an infiltration/exfiltration rate of 0.1ACH is assumed. In case the temperature is above 26°C, the windows are opened to give up to 4.0ACH.

All simulations have been carried out for a floor construction with three different insulation thicknesses. For each the thermal transmittance of the floor construction (U-value) and the linear thermal transmittance of the foundation (ψ-value) have been calculated based on the description in DS418 (DS, 2002). This is shown in Table.1, representing constructions that are in accordance with the present building standard as well as expected future constructions.

In general, a supply temperature of 35°C is used to the hydronic floor heating system when it is turned on. For the electrical system a maximum of 80W/m² is used, limited by a maximum allowed floor surface temperature of 27°C. When the room temperature is less than 1K below the set point, only a part proportional to the temperature difference between room temperature and set point is supplied.

In all simulations a room air temperature set point of 21° has been used in the simulations with a dead band on the temperature control of 0.25 K. During the summer period from May 13 until September 24 the system is never turned on.

2.3 Floor heating models

In this section the, different types of models are shown. Common for the simulation models are (except for

TABLE. 1: U-value and linear thermal transmittance in the floor models.

Insulation thickness [mm]	U-value [W/m²K]	ψ-value [W/mK]
150	0.17	0.15
250	0.12	0.13
350	0.09	0.12

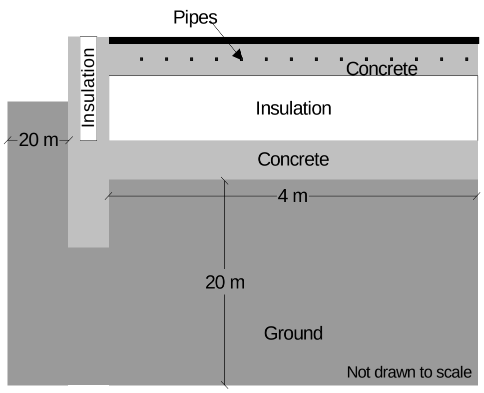

FIG. 1: Floor construction used for the simulation models.

the RC thermal network), that they are based on a Finite Control Volume (FCV) method for calculating heat flows and temperature distribution. The modelling approach has been described in detail in (Weitzmann, 2004).

2.3.1 Floor model

The floor construction used in the modelling is shown in Fig. 1, representing a double deck floor with the insulation layer between the decks. The floor heating system is placed in the upper deck. The floor covering is made of a wooden parquet floor.

The floor models, shown in Fig. 2 are

- One-dimensional FCV model with an "electrical" inclusion of the pipe. The heat supply to the floor is given as a heat flux term supplied directly in one of the nodal points rather than a temperature sink. This approach is similar to that used in typical building energy simulation programs.
- RC thermal network model with hydronic pipe included. The fluid temperature is calculated based on the actual flow rate, supply temperature and concrete temperature. In the model, resistances and thermal capacities are lumped to simplify the modelling as much as possible. Compared to the other models, this model uses fixed convective surface resistances to the room. A version both with and without foundation is modelled.
- One-dimensional FCV model with a hydronic pipe. The hydronic 1D model with floor heating pipe uses a FCV model. The pipe has been included as an extra nodal point which can interact with one of the nodal points in the 1D mesh. A thermal resistance is included between the pipe and the concrete.
- Two-dimensional FCV model with a hydronic pipe which uses the lines of symmetry around the pipe. This model is also called a "1.5D" model, since it does not include the foundation.

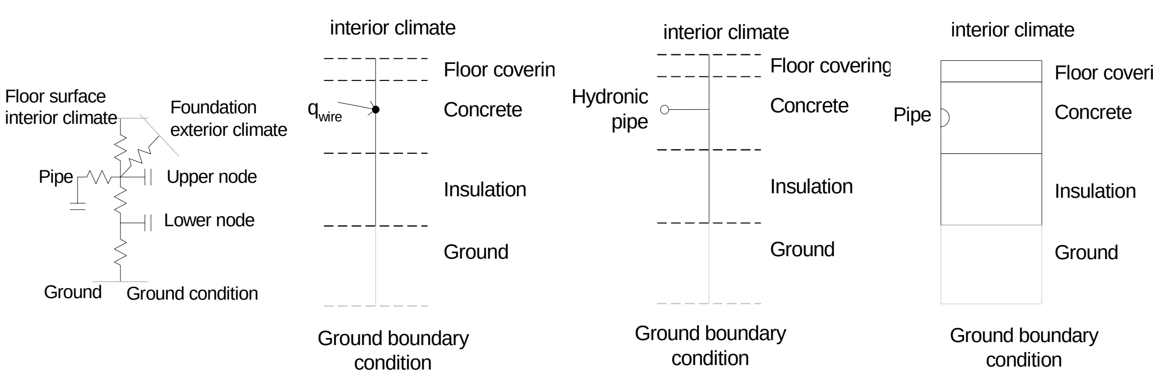

FIG. 2: Floor simulation models used for the comparison, representing RC-model, 1D electrical, 1D pipe and 1.5D pipe, while the 2D model shown in Fig. 1.

TABLE. 2: Boundary conditions towards the ground and/or foundation used in the simulation models.

Boundary condition name	Linear thermal transmittance of foundation	Ground temperature	Ground thermal resistance
Simple	-	10°C	1.5 m²K/W
1 m ground volume	-	10°C	1.0 m²K/W+0.5m²K/W from ground
Foundation	As described in DS 418	10°C	1.5m²K/W
Full 2D model	Included in model	Not applicable	Not applicable

- Two-dimensional FCV model with hydronic pipe and foundation and ground volume around the building.

One floor section is used to model the conditions, which means that the section represents average values for the entire floor construction. In the hydronic models, the temperature of the fluid in the pipe is calculated as the mean temperature of supply and return, based on the flow rate and the temperature in the concrete next to the pipe.

The floor models are set up to model the floor construction with as many details as possible in that particular model. Four types of boundary conditions towards the ground are applied, shown in Table. 2.

Notice, that the influence of the foundation can be included in the RC thermal network model by adding an extra resistance to the outside. This is based on EN ISO 10211 (CEN, 1994; CEN, 1995), where the heat flow from a given construction can be split into three components; one-, two- and three-dimensional for areas, linear and point heat losses. The one-dimensional part is the heat loss to the ground, while the two-dimensional part and the heat loss to the foundation. Concerning the three-dimensional part, the corners, investigations (Anderson, 1991) have shown that a three-dimensional building can be reduced to a two-dimensional case by introducing the characteristic dimension defined as the area divided by half the perimeter as the width of the two-dimensional section. Later this has been shown also for slab-on-grade floors with floor heating (Weitzmann et al, 2005).

3. Results

3.1 General results

Yearly simulations have been carried out for the six models described above to find the differences of the models. Fig. 3 shows the energy consumption and heat loss to the ground. The most detailed model, the

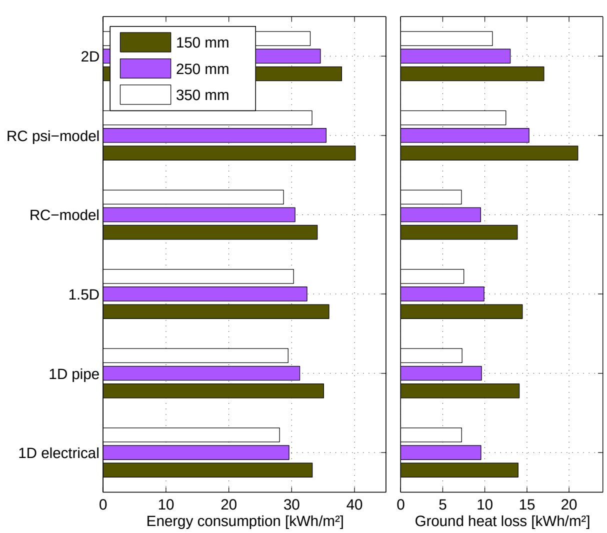

FIG. 3: Simulated heat loss to the ground and energy consumption

two-dimensional, is considered the reference. Looking at the results, the 2D model has larger energy consumption and heat loss to the ground than the other models except for the RC-model with the foundation. For the heat loss to the ground, the difference between the smallest and largest value is nearly 50% compared to the maximum value (or 100% compared to the minimum value), comparing the RC and RC psi-model with 350mm insulation. If the RC model is compared to the 2D model instead, the difference drops to around 35%. However, this is still a large discrepancy, which results in an underestimation of the ground heat loss if the foundation is not included in the simulation models. The electrical inclusion of the floor heating system gives lower values in both categories than the hydronic inclusion. This will be discussed below.

For the energy consumption, the relative differences in the values are smaller, yet still noticeable. This is of course due to the fact that the rest of the model is the same, so that the rest of the model reacts in identical manner to the conditions from the floor and surroundings.

The figure shows the different insulation thicknesses. As expected, all models have decreasing values for increasing insulation thickness, but the rate of decrease is very different in the models indicating different thermal behaviour.

Finally, the ratio of the heat loss to the ground to the total energy consumption is between 0.25 and 0.5. A heat loss of up to 50% through the ground and foundation of the total energy consumption in new buildings with low energy demand is comparable to findings in other works (Claessson and Hagentoft, 1991).

3.2 Simulation time

The simulation time is another factor, which is included in the comparison. The 2D model is by far the most time consuming, with a simulation time of around 45 minutes using a 3.4GHz Pentium 4 processor. The fastest are the RC models, which use around 5 minutes. The 1D models are nearly as fast and the 1.5D model is 20% slower. When only the part of the simulation time used by the floor model is considered, the differences are much larger. Here the 2D model is more than 100 times slower than the RC- and 1D models, and 70 times slower than the 1.5D model.

Notice that the large difference between the relative simulation times for the entire model and just the floor model is due to the fact that the rest of the simulation model is identical in all cases.

3.3 Comparison of Electrical/hydronic

A common simplification for modelling floor heating is to use an "electrical" inclusion of the floor heating system where a heat flux is supplied in the floor construction instead of using a floor heating pipe with a fluid with a given temperature.

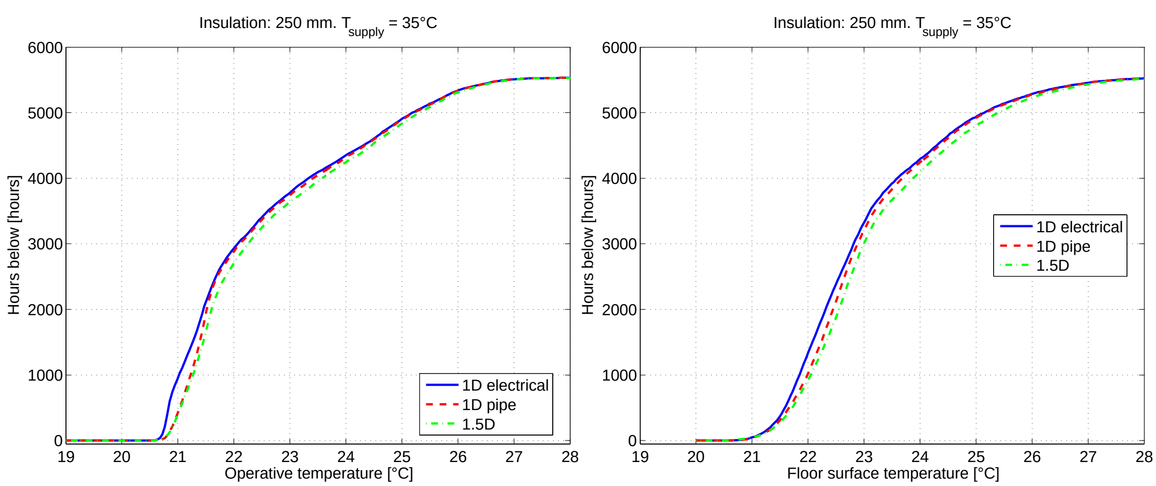

FIG. 4: Comparison of 1D model with electrical inclusion of pipe, 1D with hydronic inclusion and 1.5D model.

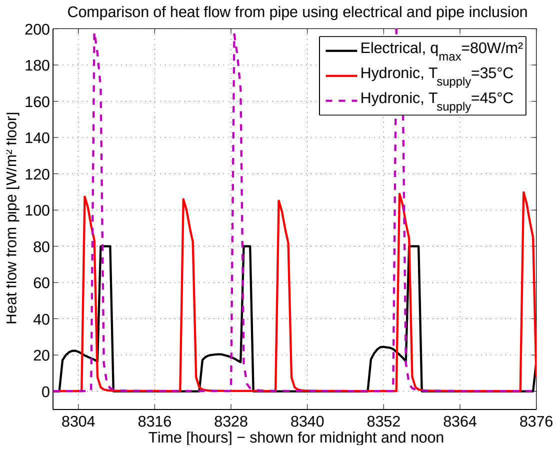

FIG. 5: Heat supply from floor heating system using electrical and 1.5D pipe inclusion of the pipe during a three day period in early December.

Fig. 4 shows the duration curves for the operative temperature in the room and for the floor surface temperature, comparing the 1D electrical, 1D pipe and 1.5D pipe model s. The duration curve shows the number of hours below a given temperature during the heating season, which lasts from mid-September to mid-May, or around 5500 hours. The two models with hydronic inclusion of the floor heating system have almost identical duration curves, while the electrical model tends to have lower temperatures, yet still above the temperature set point of 21°C. The influence of the lower room temperatures in the electrical model can be seen in Fig. 3. The 1D electrical model has lower energy consumption and heat loss to the ground. The energy consumption is typically around 5% lower than the 1D/1.5D model with pipe. Since the heat loss to the ground is mainly influenced by the temperature of the concrete deck, as this will almost always be the highest temperature in the floor construction, the average concrete temperature is therefore lower for the electrical model indicating a more efficient control.

Another difference is that the peak value of the heat supply to the room is limited by the allowed maximum peak value, where the maximum heat supply from the pipe is limited by the actual temperature difference between pipe and surrounding concrete. This difference is shown in Fig. 5, where the heat flow from the pipe is shown for two different supply temperatures and for the electrical model. The heat flow using the pipe inclusion has different peak values depending on the actual conditions, while this is not the case for the electrical type. In addition, where the electrical system has a constant maximum heat flow to the floor during heating periods, the pipe inclusion starts with a peak value which drops during the heating period because the surrounding concrete is heated. In fact, the high supply temperature of 45°C gives 5-10% higher energy consumption than the 35°C case, however this difference can mainly be assigned to higher room temperature. Finally, when the heating system is turned off, the heat flow from the electrical system immediately returns to zero, where the pipe inclusion requires some time before the temperature of the fluid in the pipe has dropped to that of the surrounding concrete.

It is also worth to mention, that the system is only turned on around once a day for a few hours after which the concrete deck is heated sufficiently to heat the room for the rest of the day.

3.4 Ground volume in 1.5D model

Two different types of inclusion of the ground volume are compared in this section. They are the models with no ground volume and a thermal resistance to a fixed ground temperature and the model with 1 m of ground volume and a fixed (but smaller) thermal resistance to the same fixed ground temperature. This corresponds to the first two boundary conditions in Table. 2. Fig. 6 shows the duration curves of operative and floor surface temperature.

As it can be seen from these figures, the temperature distribution is almost identical in the two models. The same is the case for the heat loss to the ground which differ less than 1% regardless of the insulation

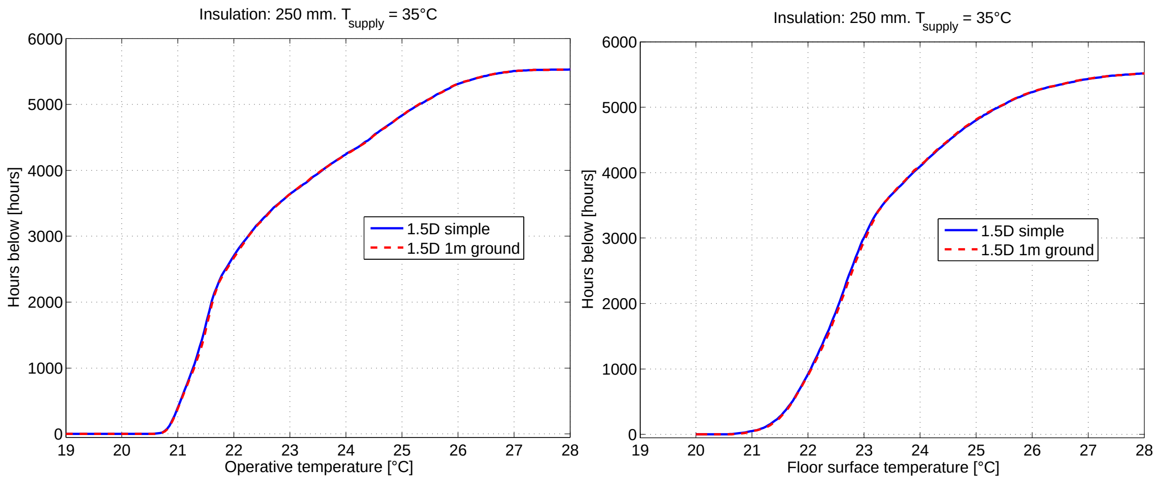

FIG. 6: Comparison of different inclusion of ground volume with no ground volume and with 1 m ground volume

thickness. It can therefore be seen that the inclusion of a 1 m ground volume in the simulation model does not alter the results in any significant way. This is also the case for the energy consumption.

3.5 Comparison of 2D/RCψ

The two models where the linear thermal transmittance is included are the 2D model and the RCψ-model. The two models are very different, one detailed with correct representation of the actual floor construction, while the other simply uses the linear thermal transmittance as an input to the system of lumped resistances and capacitance. The linear thermal transmittance must consequently be found outside the model.

Returning to Fig. 3, it is interesting to notice, that while the ground heat loss has a discrepancy of up to 20%, the total energy consumption varies by less than 4%. There are many reasons for this difference. Among these are (1) the calculated value of the linear thermal transmittance does not include floor heating, (2) the general modelling simplifications, and (3) different operative temperature in the heated room, which can be seen in Fig. 7. The RCψ model predicts higher operative and floor surface temperature than the 2D model. A final note is that the parameters in the RCψ-model can be tuned using i.e. some type of optimization algorithm. Pedersen et al (2005), describes such a method, the so-called space-mapping technique, for thermo active components. This approach is shown to improve the results significantly compared to the advanced model. The same procedure can easily be implemented for a slab-on-grade floor.

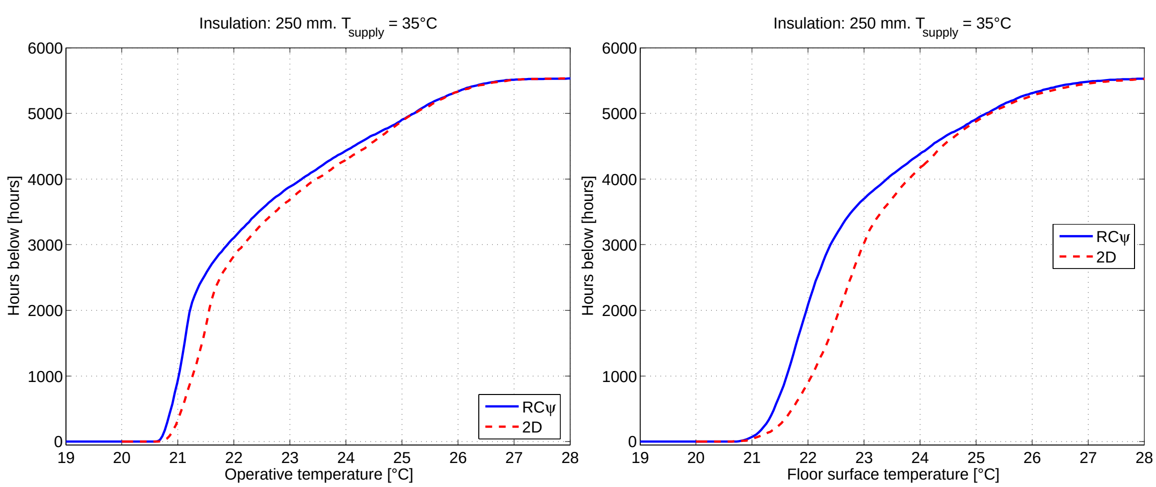

FIG. 7: Comparison of RC-model and 2D model.

4. Discussion

Summing up on the findings in this work, a large discrepancy in the results from the simplified models without the foundation included and the models where it has been included. This goes for both the heat loss to the ground, energy consumption and temperature distribution in the room and on the floor surface. An underestimation of up to 35% on the heat loss to the ground is found between the simplest and most detailed – and therefore accurate – result. This is an important point when modelling buildings with floor heating. For all included models, the difference varies by up to a factor 2 for the heat loss to the ground.

Secondly, comparing a heat flux type (electrical) and a heat sink type (hydronic) of heat flow shows that there are large differences in their functionality. The electrical implementation leads to lower energy consumption than the hydronic implementation. Therefore, while it does include the heated floor surface, the conditions are still not correctly modelled, since it is not possible to model the influence of the supply temperature and/or control strategy, which will also inevitably lead to different results.

Third and finally, a simple lumped thermal network model has been found to reproduce the results from the far more detailed two-dimensional simulation model of the floor satisfactorily. This shows that it is possible to include the influence from the foundation using a simplified model. Of course the simplified model has a very large decrease in the simulation time compared to the more advanced model, but it does require inputs from a detailed model to fit the values of the lumped parameters. However, this work needs only to be done once and therefore subsequent simulations can be carried out much faster, thereby enabling for instance optimization calculations of the building envelope.

What remains is that choosing a simulation model is very much a question of what the results should be used for. The simple models can be used in situations where the ground heat loss is of minor importance, in e.g. investigations on the control system or for simplified calculations and early estimates. The advanced two-dimensional model can be used to help develop new designs of slab-on-grade floors with floor heating and establish detailed information on the heat loss to the ground, for reference to simpler models.

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