District Heating Systems:
case study development using Modelica

T.P.C. Pimentel, Master Student in Energy and Environmental Engineering
January 2014

T.P.C. Pimentel[1,2], J.L.M. Hensen[1], J.I. Torrenz[1], G.C. Graça[2]

(1) Dep. Building Physics and Services, Eindhoven University of Technology, The Netherlands

(2) Dep. Geography, Geophysics and Energy Engineering, Faculty of Sciences of University of Lisbon, Portugal

1. ABSTRACT

As countries in Europe are focusing in reducing their CO_2 emission levels, district heating systems (DHS) are considered to be feasible solution due to their ability to re-use heat that would otherwise be wasted and their compatibility with renewable energy sources (RES).

When sizing these systems, building energy simulation (BES) programs are often used as they allow a time-practical analysis of the district's consumption needs. However, conventional BES programs were primarily designed address buildings at an individual scale; hence the need for next-generation programs which can integrate larger scale building systems is clearly recognized. For this matter, Annex 60 (IEA EBC) is developing new computational tools for building and community energy systems using Modelica, an object-oriented language for modelling of large, complex and multi-domain physical processes.

This project is inserted in subtask 2.2 of Annex 60 and evaluates different ways to approach the heating and cooling needs of a neighbourhood case study. The implementation in Modelica is described in this report and a sensitivity analysis carried out regarding the levels of detail applied in four fields that influence the annual demand: Number of thermal zones considered, internal gains, ground temperature and the heat transfer between adjacent buildings.

It was concluded that the heat demand was more sensitive to the sub-zoning of the living space and the heat exchange between the buildings, while the cooling demand proved to be more sensitive to the way the internal gains are modelled. Ultimately, the use of Modelica for this application was also evaluated.

Keywords: Annex 60, District Heating and Cooling Demand, Building Simulation, Modelica

2. INTRODUCTION

Buildings in the EU are responsible for 36% of the CO_2 emissions and 40% of the final energy consumption (European Commission, 2012) most of which is used for space heating. Natural gas is the main heating source, while DH systems provide 13% of the heat supply (David Connolly et al., 2014). Furthermore, almost 50% of EU's primary energy supply is lost before reaching the end use, mainly due to heat losses in electricity production (David Connolly, Nielsen, & Persson, 2013), mainly through co-generation (IEA, 2014). If more DH networks are implemented, some of these losses can be recycled and re-used to heating buildings, improving the overall energy efficiency of the system. In addition, 57% of EU's population live in regions with at least one DH system, suggesting that a much higher share of DH could be used to meet the buildings' heating needs (David Connolly et al., 2012). While it is recognized that renewable heating and cooling (also through DH systems) is vital to decarburization (European Climate Foundation, 2010), studies also conclude that a 50% share of DH in EU by 2050 would reduce fuel consumption by 40%, since it would replace a big share of coal, oil and natural gas used by individual boilers (David Connolly et al., 2013)

When sizing DH systems, one of the most important aspects to take into account is the heating and cooling needs of its users, since they will determine the amount of energy that the system will have to provide and when. To address this issue, BES tools are often used, as they can process the dynamic and complex interactions between the building's systems in a time-efficient way especially in larger scale systems (Hong, Chou, & Bong, 2000). Furthermore, these tools can be applied in the design-phase, in order to determine which options are more attractive in terms of construction materials, design and HVAC system, but also during operation and maintenance (e.g in order to identify possible failures in the building system).

However, when modelling the thermal behaviour of larger scale building systems, many assumptions need to be made in order to simplify and abstract from the complexity of reality. In that sense, and motivated by Annex 60 (subtask 2.2) this study compares and analysis how different assumptions influence the annual demand of a neighbourhood case study. More specifically, this paper focuses on the implementation of a district heating/cooling demand system using Modelica/Dymola and quantifies the difference in the annual demand in the form of a sensitivity analysis regarding the following aspects: number of thermal zones per building; ground temperature; internal gains and surroundings (the buildings are considered to be isolated, or connected to each other).

3. IEA ANNEX 60

3.1 Overview

Recent changes in the requirements for buildings, such as the 2010 Energy Performance of Buildings Directive and the 2012 Energy Efficiency Directive of the European Commission on reducing the energy consumption, bring new challenges to BES tools, as future research will be based on the development and implementation of renewable energy generation and distribution on a community level (Taylor, Saelens, & Schijndel, 2014)**.**

Conventional simulation programs focus mainly on the energy analysis on an individual building level and are therefore not suited to investigate the interaction between buildings and district energy systems (Wetter, Treeck, & Hensen, 2013). Furthermore, they're integration with models from different BES tools or models created by different team members is unpractical, which also makes it difficult to analyse existing buildings with unconventional systems and control logic implementation.

As such, the objectives of Annex 60 are to develop and demonstrate next-generation computational tools '*that allow building and community energy grids to be designed and operated as integrated, robust, performance based systems*' (IEA EBC Annex 60, 2012). To address this issue, Modelica and the Functional Mockup Interface (FMI) standard have been selected, '*as they are industrial-strength, non-proprietary, industry-driven standards that allow technology transfer between the building performance simulation community and much larger dynamic modelling communities from controls, automotive, power-plant, electrical system and chemical plant modelling*' (IEA EBC Annex 60, 2012). Annex 60 will be conducted through three subtasks: Subtask 1 will validate and further develop the technology required (modelling libraries and tools for co-simulation), Subtask 2 explains and applies these technologies to a case study and finally Subtask 3 will develop a guidebook. This study is focused on Subtask 2 - Activity 2.2, which deals with the demonstration in Modelica of buildings' integration into a community-level energy grid.

3.2 Subtask 2.2 – Neighbourhood case study

The case study designed by IEA's Annex 60 consists of a 24 buildings' neighbourhood, which are combined to describe a street section. The buildings are classified in five layout typologies: detached (D), semi-detached (S) and terraced (T) dwellings, one five storey apartment building (A) and one five storey office (O) building. Furthermore, the buildings are can have one of two insulation typologies: state #1 (more insulated) and state #2 (less insulated, more common in older buildings).

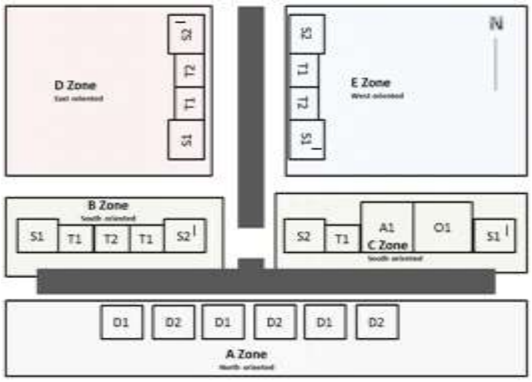

Figure 1 - Neighbourhood case-study layout. In some semi-detached dwellings (S1' and S2') the side facades were switched due to windows that were on the facades that are adjacent to other buildings.

The residential dwellings are characterized by one ground floor (daily-zone), one floor with bedrooms (night-zone) in the detached and semi-detached, two floors with bedrooms in the terraced dwelling and one unheated attic. Each floor of the apartment building has a daily- and a night-zone in opposing facades and an unheated hallway between them. Regarding the office building, it has the same geometry as the apartment but in this case the hallway belongs to the "night-zone".

Regarding the heating needs, a constant temperature set-point for heating is defined as 21 ^{o}C for all buildings, meaning that whenever the inside temperature drops below this value, heat will be injected into the building.

Given the considerable amount of buildings, the neighbourhood was divided into five zones, according to their orientation. The orientation is determined assuming that each building is street oriented.

4. METHODOLOGY

The simulations were carried in two different sets. The first set was used to address the first common exercise of Annex 60-subtask 2.2, which considers the assumptions mentioned in the case study (**3.2**), while discharging cooling needs, internal gains and shading control. For this one, a comparison was conducted between assuming buildings separated from each other (a) and in contact with each other (b), exchanging heat through conduction.

1st set:	(a) Ref. Case	(b) Comparison
Heating	Tset-point for heating = 21 (constantly, for all buildings)	
Cooling	Not considered	
Ground Temperature	Tground = 10.3	
Internal Gains	Not considered	
Shading Control	Not considered	
Thermal Zones	Day/night zones	
Surroundings	Buildings are isolated	Buildings are connected

Table 1 - 1st simulation set assumptions.

For the second set, more parameters were included (occupancy schedules, cooling needs and shading control) and five cases were defined for comparison (a-e). On each case, the detail level of a specific parameter (ground temperature, internal gains, number of thermal zones and surroundings) was individually increased and compared against the reference case (a), in order to perform the sensitivity analysis. The four parameters in study were modelled in two levels of detail each. These cases are summarized in the table below.

2nd set:	(a) Ref Case	Comparison
Heating	Tset-point for heating in residential buildings = 21 (constantly) Tset-point for heating in office building = 20 (occupied), 16 (unoccupied)	
Cooling	Tset-point for cooling in office building = 24	
Thermal Zones	1 per building	**b)** day/night zones
Internal Gains	Constant annual mean gains	**c)** Variable gains based on schedules
Shading Control	Shading Threshold = 300 W/m2	
Ground Temperature	Tground = constant	**d)** Tground = f(depth)
Surroundings	Buildings are isolated	**e)** Buildings are connected

Table 2- 2nd simulation set assumptions.

The subsection below describes in more detail how the models were developed and implemented in Modelica and how the levels of detail applied differ from each other.

4.1 Implementation in Modelica

The model was structured in two layers. The bottom layer contains the building's envelope related parameters, such as geometry and construction materials' properties. As can be seen **Figure 2** (left), the infiltration was also included in this layer, assuming 0.1 ACH for state #1 buildings and 0.5 ACH for state #2 ones. The heat balance between the building and the other components is calculated here, using the model ***Rooms.MixedAir*** from the Buildings library (described in **4.1.1**). In the top layer, the implementation of control based components allow relevant information to be added to the building(s), e.g regarding its occupancy schedules, shading controls and the ground temperature. The heating /cooling demand meter is also connected to the building in this layer. In order to evaluate how the representation of the parameters in study influences the heating/cooling needs of a building, each parameter was modelled separately as a sub-system. This provides independency between the sub-systems, guaranteeing that by changing their level of detail one does not have change the whole system.

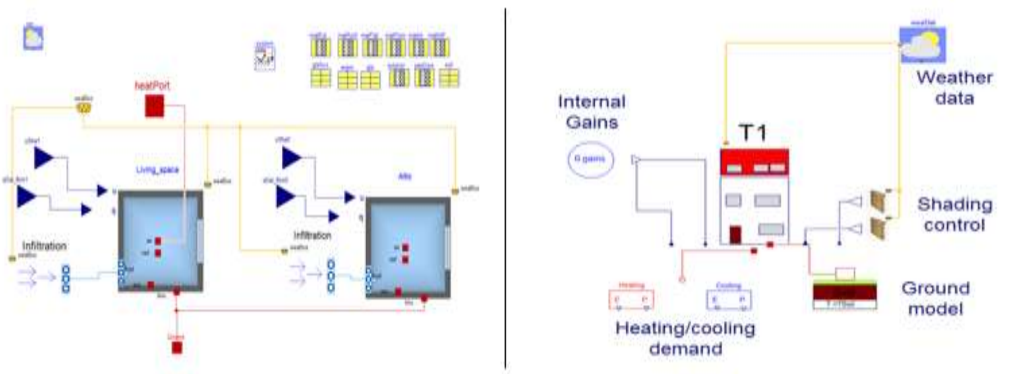

Figure 2 - Model structure in Modelica. Bottom layer (left) and top layer (right). Dark blue lines refer to controls (internal gains and shading control), light blue to fluids (infiltration), red lines to heat transfer (W) and yellow lines to weather related data.

In addition, it allows one sub-system to connect to any number of buildings as long as they have the same layout typology. For example, the internal gains defined for the terraced dwellings only need to be processed once, passing the information to all terraced dwellings. Not only this saves simulation time but also makes the model more user-friendly.

4.1.1 Thermal zones

Each building was defined using one (or more) thermal zones. In order to represent each zone, a ***mixedAir*** room model from the Buildings library was used, where the constructions and surfaces that participate in the heat exchange processes were defined. A complete overview of the model is provided by Wetter, Zuo, & Nouidui, 2011.

As mentioned in **4.1**, two levels of detail were considered regarding the number of thermal zones used to represent the buildings: The first level considers each building as one single zone (plus an unheated attic in the residential dwellings). In the second level, the single zone assumed in the first level is divided in daily- and night zones (as mentioned in **3.2**). This division of the living space allows a more realistic characterization of the heat transfer inside the building, as it separates two zones that are different in terms of occupancy. An accurate sub-zoning for residential buildings in building simulation is described in (Peeters, Dear, Hensen, & D'haeseleer, 2009), taking into account different thermal comfort bands for three distinctive zones: bedrooms, bath rooms and other rooms. It concludes that the adaptation to the outdoor temperature plays a major role in the thermal comfort inside the building and defines a strong dependency of the comfort bands on the recent outside temperature values. However, such sub-zoning would increase the number of ***mixedAir*** models needed to represent each building, which would result in an unpractical simulation time. For the same reason, the second simulation set only considers one thermal zone per building, since it includes more simulations than the first set.

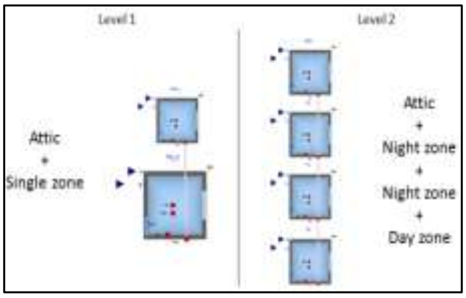

Figure 3 - Thermal zones using the *mixedAir* room model. Comparison between less detailed (left) and more detailed (right) levels.

4.1.2 Heating/Cooling demand

The heating and cooling demand of one building is defined as the amount of energy that it needs to maintain the inside temperature between a given limit, as if there was no heating/cooling equipment. As such, instead of considering real heating/cooling sources (e.g boilers, heat pumps, chillers), an ideal one was assumed in this model. Furthermore, models of such real sources were already developed in other Modelica libraries (e.g Ideas library) but the interaction with the Buildings library (version 1.5) led to simulation problems and were consequently left out.

In the first simulation set, an annual constant temperature set point for heating of 21^{o}C was assumed for all buildings. In the second set, this value was kept for the residential buildings, while for the office building a thermal band between 20^{o}C (for heating) and 24 ^{o}C (for cooling) was established during occupancy hours. When unoccupied, the heating in the office is switched on if the inside temperature drops below 16^{o}C.

The component *Heating/cooling demand* in **Figure 2** (right) is responsible for the heating and cooling. Using PID controllers from the Buildings library, the temperature inside the rooms are adjusted given their present value (through a temperature sensor) and the desired set-point, injecting the required load (W) into the room (when heating) and taking the required load outside the room (when cooling) through a prescribed heat flow. The difference between the PID's in the Modelica Standard library and the Buildings library is that in the second one a reverse flux is allowed, which is useful when modelling the cooling needs. The annual load distribution is calculated using the component ***Modelica.Blocks.Math.Mean***, which outputs the hourly mean load value. To determine the yearly amount of energy, the component ***Modelica.Blocks.Continuous.Integrator*** was used. For the office building, two extra components (***Buildings.Controls.SetPoints.OccupancySchedule*** and ***Modelica.Blocks.Logical.Switch***) were introduced in order to distinguish between occupancy and non-occupancy hours, since these differ in their temperature set-point for heating in the second simulation set.

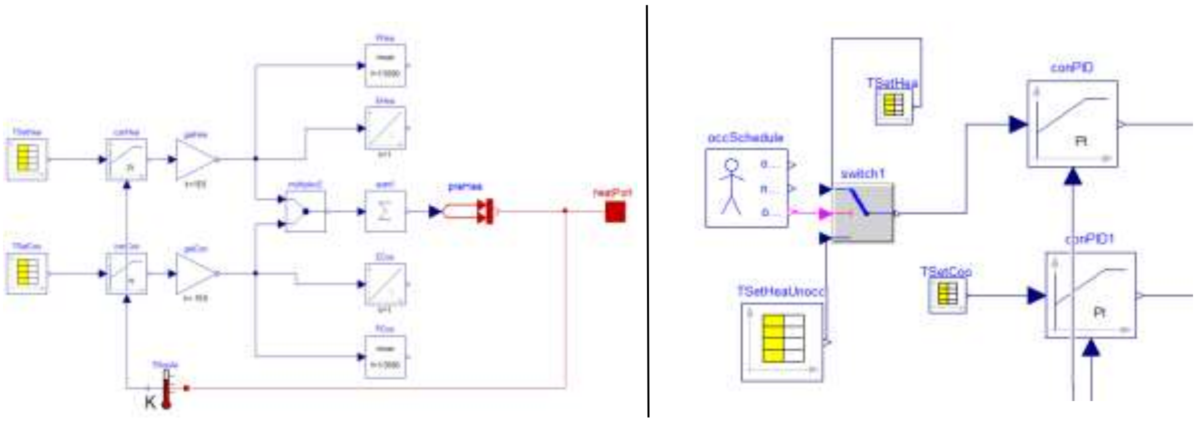

Figure 4 - Heating/Cooling demand component in residential buildings (left) and in the office building (right).

4.1.3 Occupancy and internal gains

The internal gains were modelled using mainly the Modelica Standard library. For the second resolution level (more detailed, used in case (c)), it was assumed that the heat gains from people, lighting and equipment were dependant on schedules, resulting in hourly heat flow (W/m^2) values that are put into each zone. For the residential dwellings and the apartment building, a total number of 4 and 3 occupants was assumed respectively and two schedules were considered (weekdays and weekends). Regarding the office building, the number of occupants was based on the assumption that each person occupies 12 m^2. The occupancy schedule was set from 08:00 h -18:00 h and an extra schedule was considered to represent the holidays, consisting in a 50% reduction in all the internal gains in August and the last ten days of December. During the weekend, the office building is completely unoccupied.

PEOPLE

The rate at which heat is generated by the human body (metabolic rate) depends on the level of activity of each person. In this model, different levels of activity were considered, each with a corresponding time fraction: day zones have higher activity levels, while night zones hold the metabolic rates for sleeping and resting. For the same reason, the office building has different activity levels from the residential ones. At each hour, a certain amount of occupants was assumed to release heat according to the activity types in that zone at respective time fractions, as presented in the table below.

	Description	met	time spent [%]
Day-zone (residential)	Reading seated, writing	1	0.25
	Walking about	1.7	0.55
	Housekeeping (cleaning, cooking)	2.1	0.2
Night-zone (residential)	Sleeping	0.7	0.9
	Reading seated, writing	1	0.1
Office	Typing	1.1	0.6
	Walking about	1.7	0.3
	Lifting/packing	2.1	1

Table 3 – Activity type for each zone with corresponding metabolic rate values and time fraction.

Assuming an average skin surface of 1.8 m^2, the resulting met value is converted to W (1 met=58.2 W/m$^2_{skinSurface}$) and divided by the zone area. Finally, the heat is split in radiative and convective shares (latent heat share was considered to be zero) and delivered inside the ***mixedAir*** room model. The figure bellow illustrates how the heat released from people is put into each building in Modelica.

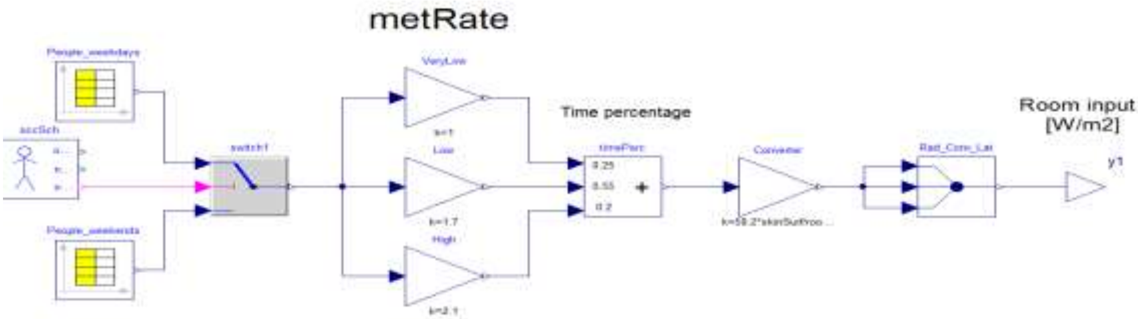

Figure 5 - Implementation of the internal gains released from people used in the more detailed case (case (c)). Example of a daily-zone in a residential dwelling.

LIGHTING/EQUIPMENT

The lighting system of the buildings was considered to dissipate heat at 10 W/m^2. Based on the same occupancy schedules, a certain percentage of light is on (or off), which multiplies by the total heat dissipation rate (10 W/m^2), split in radiative and convective shares and put into the thermal zone. To represent the heat released from equipment, electronic devices such as PC's, screens, televisions and washing machines were considered to dissipate between 40 W (PC) and 100 W (washing machine).

The first resolution level (less detailed, used as reference) for the internal gains takes into account the yearly amount of radiative and convective gains from people, lighting and equipment considered in the second level for each building and defines a mean value for both (radiative and convective heat). In this level, the internal gains output is a constant (as shown in the figure on the right), rather than a variable value, while assuring that the total amount of yearly gains are identical in both levels.

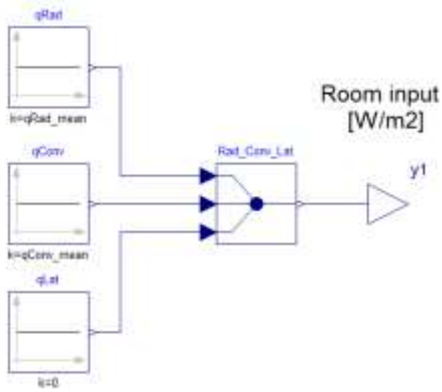

Figure 6 - Implementation of the internal gains released from people, used in the reference case.

4.1.4 Shading control

All buildings were considered to be equipped with an automatic blinds system, which computes the direct solar irradiation on the tilted surfaces with windows (using the component ***Buildings.BoundaryConditions.SolarIrradiation.DirectTiltedSurface***) and opens/closes the blinds according to imposed thresholds: a threshold of 300 W/m^2 was assumed, bellow which the blinds are fully opened (output is 0) and above which the blinds are fully closed (output is 1).

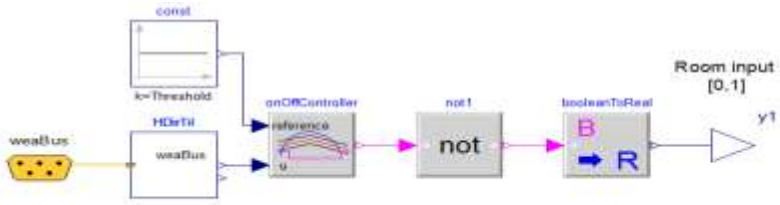

Figure 7 - Implementation of an automatic blinds system for shading control.

4.1.5 Surroundings

When simulating the energetic performance of buildings in a district scale, it is important to consider the geographic position of the buildings and how they stand in relation to each other. For that reason, two levels of deatil were considered for the neighbourhood: In the first level, each building is assumed to be isolated from the surrounding buildings, while in the second level the connection between adjacent buildings (and therefore the heat they exchange through conduction) was taken into account. This was implemented by re-defining the exterior surfaces in the ***mixedAir*** room models as constructions that expose to other-side boundary conditions (instead of exterior constructions) and connecting their heat ports.

4.1.6 Ground temperature

Information on the ground temperature can be very important, since it takes part in the in the heat exchange processes on floors and basements but also for determining at which depth the distribution pipes shall be placed in order to minimize possible heat losses to the ground (Georgios Florides & Soteris Kalogirou, 2005). For the more detailed level (used in case (d)), a model developed by Kasuda, T., & Achenbach, P. (1965) was implemented, which defines the ground temperature as a sinusoidal function of the depth and the climate (thermal surface amplitude). As in the internal gains model, an annual mean value of this function was calculated and used as a constant in the less detailed case (reference case).

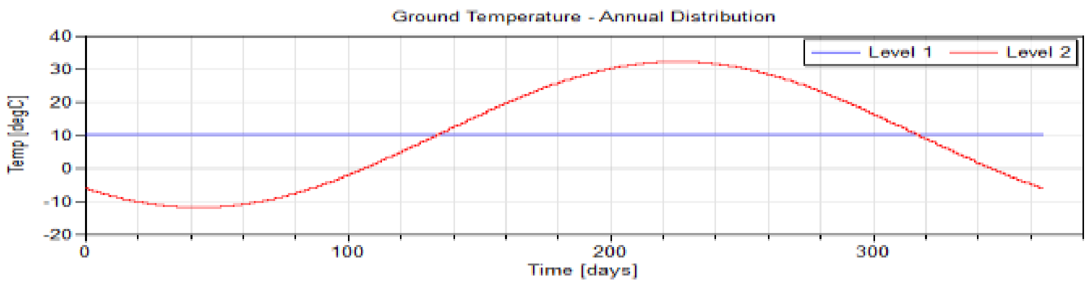

Figure 8 - Comparison between Kasuda ground temperature model (red), assuming 1m depth and its annual mean value (blue).

5. Results

The simulations were carried out for an entire year, using weather data from Brussels, Belgium, with an hourly output interval. Each neighbourhood zone was simulated individually and the simulation time ranged approximately between one and five hours.

5.1 1st simulation set

Assuming the conditions described in the case study, the annual energy demand for heating decreased 12.4%, from 471 MWh in the reference case to 412 MWh in case b. As can be seen in **Figure 9**, the amount of heat decreased for almost each building. This happens because the buildings have less façade contact with the exterior and part of the heat is kept in the walls and transferred back into the buildings when the inside temperature decreases, improving the efficiency of the heating system.

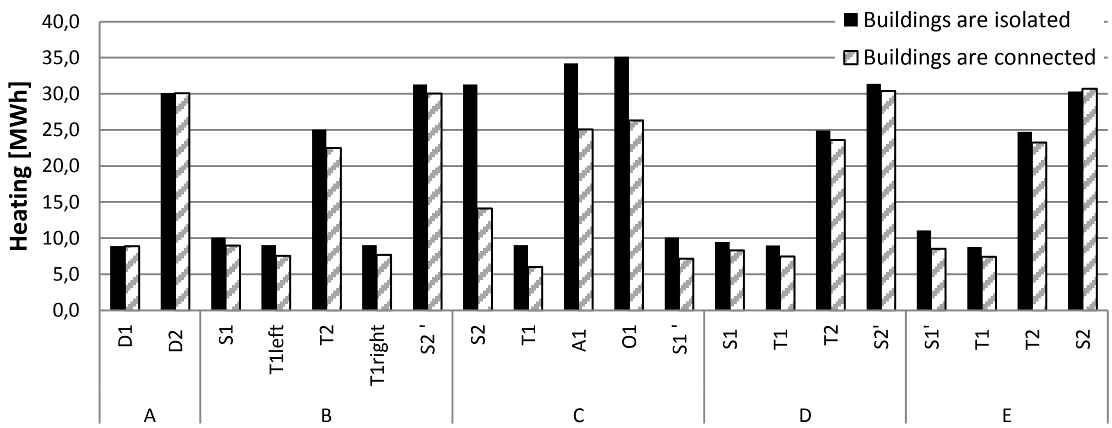

Figure 9 - Comparison of the annual heating demand per building, in MWh between case a) and b).

Regarding the annual heating load (W), the district demand peak achieved 119 kW in the reference case and 108 kW in case b which occurred on 11th February in both cases. By looking at **Figure 10**, it becomes clear that by considering the heat exchange between adjacent buildings, the hourly load values are inferior for almost the whole year, reducing significantly the peak loads.

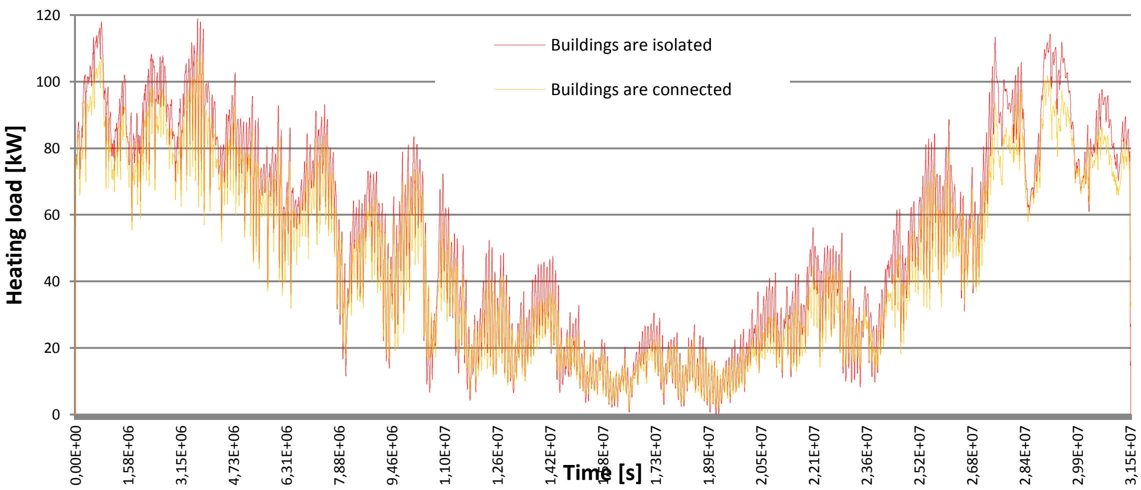

Figure 10 - Comparison of the annual district heating load, in kW between case a) and b.

5.2 2nd simulation set

The reference case for the second simulation set was developed using the reference case in the first set, but considering constant hourly internal gains as well as shading control devices and reducing the number of thermal zones per building to one. By doing so, the annual district heating demand decreased by approximately 22% between both reference cases, reaching a value of 369.2 MWh in the second set. This decrease is justified by the internal gains component and due to energy savings in the office building, which changed its temperature set point for heating during unoccupied hours to 16 ^{o}C. In fact, by looking at **Figure 11** - Comparison of the neighbourhood's annual heating and cooling demand between the cases considered. and comparing the reference case with case b), the heating consumption is rather higher when the number of thermal zones is only one per building (-6.8% in case (b)) compared to the reference case).

When considering internal gains dependant on thermal zones and occupancy schedules (case (c)) instead of constant values during the year (ref. case), the heating needs of each building didn't change significantly, resulting in a district increase of 0.6% in case (c).

On the other hand, replacing the constant ground temperature model with the model developed by Kasuda (case (d)) led to an increase of 8.2% in the total district heating demand. As expected, the fact that during the winter the ground temperature in case (d) is below the average value (10.3 ^{o}C) results in higher heating needs to keep the temperature within the desired limits.

Finally, as already seen in the first simulation set, the contact between adjacent buildings in case (e) reduced the heating demand, in this case by 7.5%.

Regarding the cooling demand in the office building, the sharpest difference was noticed in case (c), increasing 53% (from 8.6 MWh to 13.3 MWh). The reason is that when assuming variable values for internal gains, these values can achieve much higher numbers than when considering constant mean values and therefore the temperature inside the building reaches the temperature set-point for cooling faster and more often.

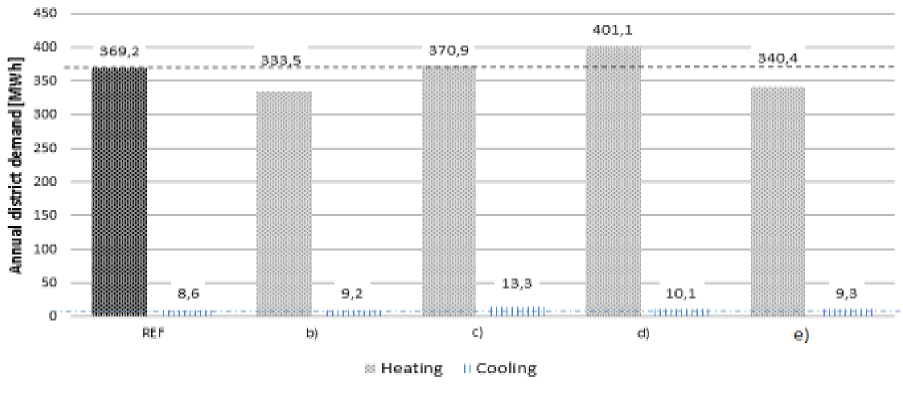

Figure 11 - Comparison of the neighbourhood's annual heating and cooling demand between the cases considered.

6. Conclusion

In this study, the tasks proposed in the first common exercise of Annex 60 – Subtask 2.2 were carried out and a comparison was made between two different assumptions: While the first assumption considered the buildings were separated from each other (more common in similar studies), the second one took into account the heat transfer through adjacent buildings, which is more realistic especially in larger scale systems such as neighbourhoods or districts. The second assumption had a relevant impact on the annual heating demand (-12.4%) and in the annual load distribution, reducing not only the peak load by 8.3% but also the annual mean value.

In a second approach to this exercise, more assumptions were compared against a higher level of detail regarding the internal gains, the ground temperature and the number of thermal zones. The results showed that the neighbourhood was particularly sensitive to the ground temperature (+8.6% heat demand) and to the number of thermal zones (-9.7% heat demand), when more detail was applied. Regarding the internal gains, while showing insignificant impact on the heating needs, a significant increase of the cooling demand was registered in the office building (+53%).

The use of Modelica proved to be a positive choice, as it provides a wide range of possibilities to approach the issue in study. Furthermore, the libraries used are equipped with detailed descriptions of the models, which was very helpful in the early stages of the project. The simplistic representation (acausal modelling) of the models leads to an easier understanding of the processes that are being simulated (heat transfer and controls, in this case) and provides an easy model modification if needed. Regarding the use of the ***mixedAir*** room model from the Buildings Library, although it brings advantages in terms of input ease and thermal zones definition, it requires significant time to process the heat balance, which leads to an unpractical simulation time when implementing larger scale systems.

Finally, this report can be used by Modelica beginners, as it provides a methodology on how to implement buildings and controls that influence the heating and cooling needs of its users. Companies that compute the energy consumption in buildings through simulation may also find valuable information in this study, as it establishes a connection between level of detail applied (and therefore the time invested) and the impact it has on the final results.

7. Acknowledgements

To begin with, I would like to thank Jan Hensen for the opportunity to perform a trainee program in Eindhoven University of Technology under his supervision and for the wise pieces of advice provided. Secondly, to Ignacio Torrens for leading me into such an innovative project and for all the guidance, patience and availability throughout the entire process, and to Guilherme Carrilho da Graça for supervising the project from my home institution. Ultimately, I would like to thank Jan Hensen's research group, especially Fábio Batista and André Leitão for all the support and Jad Al Koussa and Frank Soons for sharing knowledge about the software in the early stages of the project.

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