Model-based assessment of cost-effective retrofit solutions for a District Heating System extension

Carine Tran[1,2], Luyi Xu[2], J. Ignacio Torrens Galdiz [2], Jan L. M. Hensen [2], Vincent Lemort[1]
[1]Thermodynamics Laboratory, University of Liège, Liège, Belgium
[2]Unit Building Physics and Services, Eindhoven University of Technology, Eindhoven, The Netherlands

Abstract

This contribution aims to investigate the viability of a district heating system (DHS) on the long-term, by studying a method to extend an existing DHS with new buildings while keeping the same generation and distribution facilities. The study is conducted by simulating the DHS. The models are developed in Modelica.

Simulation results show that extending a DHS is possible under scenarios. Retrofitting the envelope of some buildings and applying a centralised control over every customer's thermostat both give satisfying results. On the other hand, decentralised storage manages to improve indoor comfort but slightly increases the energy demand. Centralised storage proves to be very dependent on its sizing and control strategy, and only provides poor results when non-optimal.

Introduction

District heating systems (DHS) have made their way through history. Early examples go as far as the 14th century, with the establishment of district heating in the village of Chaudes-Aigues in France (Bloomquist (2003)). Some major cities, such as New York and Moscow, have been supplied by district heating for more than a century (Çomakli et al. (2004); Rezaie and Rosen (2012)). In Europe, the development peak took place after the Second World War (Iacobescu and Badescu (2011); Benonysson et al. (1995)).

Today's world has introduced a new need for district heating. According to the United Nations World Urbanization Prospects, in 2010, around 73% of all 502 million EU27 residents lived in urban areas (Connolly et al. (2014)). A decarbonisation of those areas is therefore needed. Furthermore, in 2008 the European parliament and council agreed on the 2020 package – a set of binding legislation – to guarantee that the EU can meet its climate and energy target by the year 2020. The aims are to reduce by 20% the greenhouse gases (GHG) emissions compared to 1990 levels, have 20% of EU energy from renewable sources, and to improve energy efficiency by 20% (European Commission (2016)). These targets, combined with the rise of fossil fuel prices, emphasize the urgency to develop more efficient, greener energy systems.

In this regard, district heating can play an important part. Indeed, half of the energy consumption in the EU is due to cooling and heating (European Commission (2012)). Additionally, most of our heat comes from burning fossil fuels, and it is hence responsible for a big part of the EU GHG emissions (Benonysson et al. (1995); Greater London Authority (2013)). An improvement of these issues could be achieved via the development of centralised heat production; the optimum use of fuel and the cleaning of exhaust gases in that case is easier to achieve than in private boiler units (Åberg and Henning (2011)). Higher efficiency, and thereby lower heating costs, can also be obtained when producing heat in a few large heat plants rather than small individual plants (Benonysson et al. (1995)).

Expanding district heating also allows the use of local renewable resources that cannot be used on an individual basis, such as waste, biomass, geothermal energy or industrial waste heat as a source for heating (Rezaie and Rosen (2012); Euroheat (2012)). However, aside from the environmental benefits, DHS provide a series of advantages for the local community and society in general. Having no fuel in the dwelling improves the safety of building owners and tenants, while the installation of the technology is labour intensive and likely to provide local employment. Moreover, the energy security increases through the reduced dependence on imported fuel and the flexibility in choosing heat sources (Rezaie and Rosen (2012); European Commission (2012)). District heating thus answers the three major challenges that the European Community is facing within the energy field, that is sustainability, security of supply and competitiveness (European Commission (2007)).

It is then understandable that district heating is a growing market (Ecoheatcool (2006)). As shown is Figure 1, the current market share for district heating in European buildings is only 13%, which represents approximately 6000 different systems all over Europe (Connolly et al. (2014)). Yet both shares and the number of systems installed are increasing. Nevertheless, the market penetration of district heating differs from one country to another. It is close to zero in some countries while it can reach up to 70% of the heat market in others (Euroheat (2012); Münster

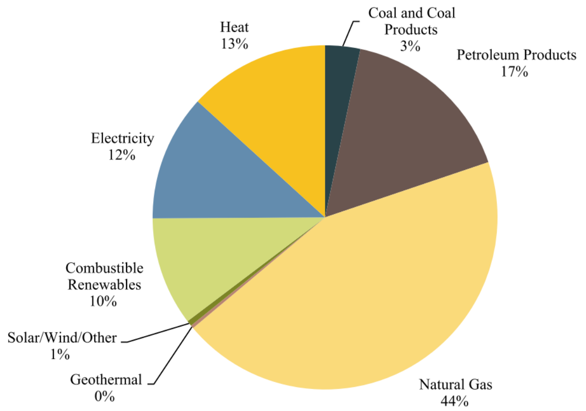

Figure 1: Composition of the origin for heat supply to residential and service sector buildings in EU27 during 2010. Heat denotes mainly heat from district heating systems. (Connolly et al. (2014))

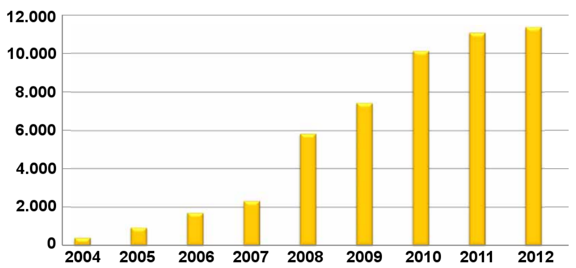

Figure 2: Evolution of the installed power of district heating in Belgium, in kW. (Fédération Rurale de Wallonie (2012))

et al. (2012)). Figure 2 shows the growth of district heating in Belgium in the past few years.
This evolution highlights the underlying logic of DHS, which is that of a system allowing extension. In Denmark, many municipal DHS are currently expanding, echoing a steady consumer demand and an attractive investment environment (Chittum and Østergaard (2014)). Still, DHS are an evolving technology, be it on the demand, distribution or supply aspect. Indeed, not only are building and pipe insulations getting more efficient, but heat sources are also moving forward, with the improvement of fossil fuel exploitation and the integration of renewable energies, as mentioned earlier. This extension thus raises the question of knowing how flexible an existing DHS can be towards newer technology.
Extensive research has already been conducted on the area of DHS design. However, only a few studies can be found on the evolution and the adaptation of older DHS in today's world (Connolly et al. (2014)). It is an important issue, as in some cases district heating and planned low energy buildings have turned out to be incompatible, due to the cost of district heating turning out being too high. Other examples have shown that connecting low energy buildings to a DHS is possible (Åberg and Henning (2011)). Studying a mean to reduce the time gap between older and newer

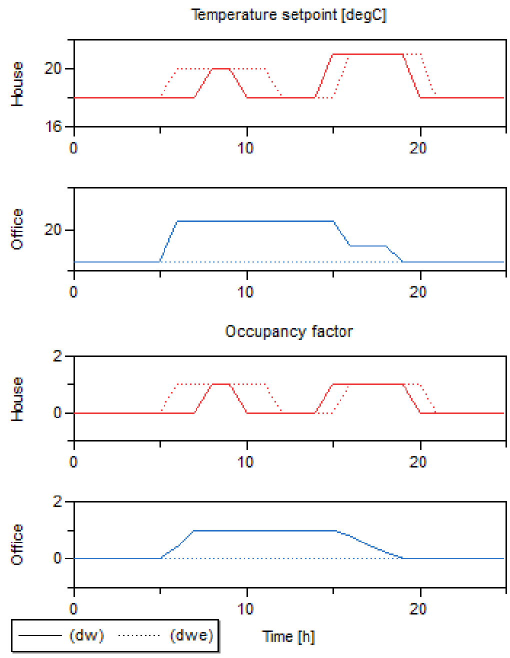

Figure 3: Example of the occupancy schedule for one of the houses and for the office buildings. The occupancy factor represents the fraction of the nominal occupancy at a certain point in time.

DHS is then necessary to ensure the energetic and economic viability of district heating.
Therefore, the scope of the present study is the investigation of the adaptability of such an existing DHS in the long-term. This was achieved by researching an efficient method to extend the DHS while keeping the same generation source and distribution network. To this end, the current energy performance of the studied neighbourhood and the most cost effective retrofit opportunities were evaluated.

Methods

DHS feasibility study

The research was carried on a model of a fictional neighbourhood, whose characteristics are based on typical Flemish houses, as described in IEA BBC Annex60-A2.2 (AIT, IK4, KUL, Masdar, RWTH Aachen, TUe, and ULg (AIT et al.)). The occupancy schedules - which describe the variation of the number of occupants, of the domestic hot water (DHW) consumption, and of the temperature setpoint – were based on data collected in residential buildings in Belgium (Georges (2013)). Another occupancy schedule was used for the sole office building of the district, based on average behaviours in offices (Lemort (2016)). Example of the schedule is shown on Figure 3.
The case-study consists in the extension of an existing district with several low energy buildings. The initial district, assumed to be from the 70s, has a low thermal efficiency: heat losses through the building

envelopes and throughout the distribution network are non-negligible, with values ranging from 470 to 660 W/K in the buildings (Arnaut (2015)) and 2 to 10 W/K in the pipes (resulting in a drop of 4K on 100m). The district heating network (DHN) operates with hot water at a temperature of 100°. The neighbourhood includes a majority of residential buildings – 17 of them – and one office building, for a total of 80 inhabitants and 75 employees in the district. Four types of residential buildings typologies were studied: detached (D), semi-detached (S), terraced (T) and apartment block (A or O, for apartments and offices). It was also assumed that the municipality owned the district; they operate the DHS and both the social-housing apartment block and the office building.

The district is then to be extended by the addition of houses with high thermal efficiency, which would be working as a low temperature district (LTD). These buildings denote a level of insulation required by the EPB 2010 in Flanders. The addition would consist in 6 more residential buildings, resulting in 24 more inhabitants. Figure 4 represents the studied district. The upper part indicates the initial district, which is directly fed by the boiler, whereas the lower part shows the branch to be added, which will be fed by the return water of the initial DHN. Some buildings of the initial district are assumed to belong to the municipality (also owner of the DHS). The numbers on Figure 4 indicate the buildings level of insulation, #1 corresponding to a high thermal efficiency and #2 corresponding to a low thermal efficiency.

The possibility of extension was studied in a demand point of view. It was then necessary to assess the overall heat supplied to the district as well as the effect of the extension on the consumer. The generation aspect, in the form of the boiler, was modelled to study the ability of the DHS to supply the users. Besides, building models had to be implemented to evaluate the internal temperature, allowing an estimation of the occupants comfort. A model of the DHN was implemented to obtain a realistic representation of the heat losses in the distribution network.

In order to find the most efficient solution to extend the district in an effective way, the study was restricted to a set of retrofitting scenarios that were proven to be cost-effective. Furthermore, we assumed that these measures were limited to the buildings and infrastructure owned by the owner of the DHS for them to invest in their own assets:

#1. Retrofit of the envelope of the municipality buildings (ExtIns)

#2. Decentralised storage in each of the new buildings (DSto)

#3. Centralised storage on the municipality buildings (CSto)

#4. Limitation of the internal setpoint temperature (TCtrl)

DHS model development

The models were developed under Dymola (Version 2016 FD01; Dassault Systèmes) using the ThermoCycle library (Thermodynamics and University of Liège Energetics (2016)) and the Modelica Buildings library (Berkeley Lab, ORNL, UC Berkeley and Modelon Inc. (2013)). The full DHS model comprises of three main parts interacting together to better represent the DHS behaviour: distribution, demand and generation side.

Distribution model

Pipe model

A pipe model compatible with wide hydraulic networks had to be implemented (Sartor et al. (2015); Sartor (2016)). It was developed by the Thermodynamics Laboratory at the University of Liège. The pipe model delays the fluid temperature signal with a time-varying delay (Velut and Tummescheit (2011)). It takes into account convective heat transfer and pipe conductivity, but ignores fluid conductivity. This assumption is valid in the case of a low temperature variation of a fluid cell, which corresponds to the insulated pipes modelled in this study (Sartor (2016)). Heat losses throughout the DHN are thereby simulated. A ground temperature of 10°C was used to simulate the losses.

As heat transfer depends on the fluid temperature, its intensity should vary throughout the pipe (as $T_{in} \neq T_{out}$). However, as the model is valid for a low temperature variation of a fluid cell, heat transfers can be assumed to be of constant intensity throughout the pipe. Therefore, heat transfers in the pipe are modelled as local events instead of diffuse events (Sartor (2016)).

Three operations are thus applied to the supply temperature signal T_{in} in order to compute T_{out}. In the following equations, T_{itm} and $T_{itm,Q}$ are intermediate expressions of the temperature.

The time-varying delay on T_{in} was expressed in the following equations, where τ is the time-varying delay and ν is the fluid velocity (Velut and Tummescheit (2011)):

$$T_{itm}(t) = T_1(t - \tau(t)) \tag{1}$$

$$\frac{d\tau}{dt} = 1 - \frac{\nu(t)}{\nu(t-\tau)} \tag{2}$$

Convective heat transfer is simply expressed as the following, where h is the fluid specific enthalpy, $\dot{m}$ the mass flow rate, $\dot{Q}$ the convective heat transfer and $c_{p,w}$ the fluid specific heat capacity:

$$\dot{m}\ h_{itm,Q} = \dot{m}\ h_{itm} + \dot{Q} \tag{3}$$

$$T_{itm,Q} = (h_{itm,Q} - h_{itm})/c_{p,w} + T_{itm} \tag{4}$$

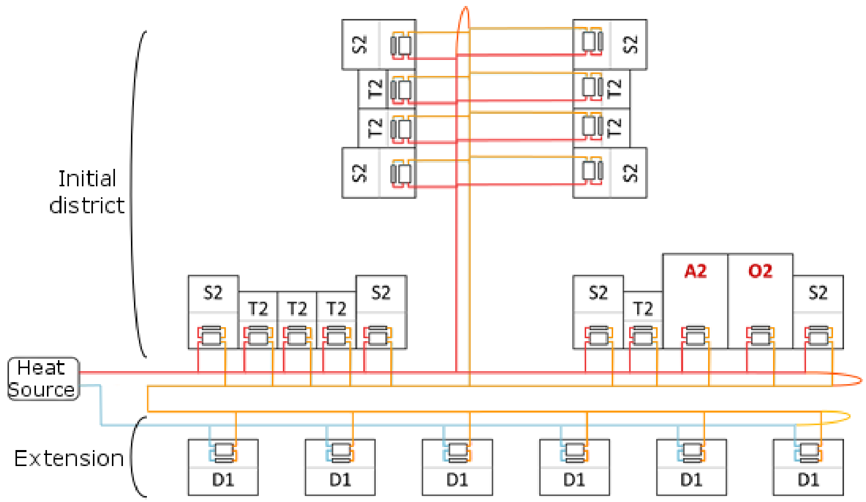

Figure 4: Diagram of the studied district (based on IEA BBC Annex60-A2.2). Red lines represent the supply flow, orange lines the intermediate flow, and blue lines the return flow. Buildings A2 and O2, in red, are assumed to belong to the municipality. The curves connecting supply and return lines represent the bypass valves.

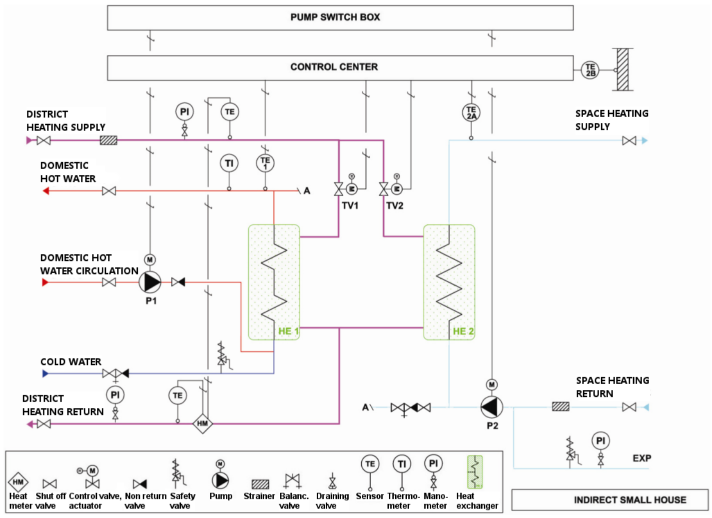

Figure 5: Diagram of the substations used for the buildings with indirect connection to the DHN. Domestic hot water is provided by an instantaneous heat exchanger. (Euroheat & Power (2008))

Pipe thermal inertia (conductive heat transfer) was modelled as the following, where ρ_m is the pipe material density, $c_{p,m}$ the pipe specific heat capacity and V_{pipe} the fluid cell volume:

$$\rho_m \, c_{p,m} \, V_{pipe} \, \frac{d}{dt} T_{out} = \dot{m} \, c_{p,m} (T_{itm,Q} - T_{out}) \quad (5)$$

DHN model

The pipes had been sized for pressure losses of 100 Pa/m along the main lines and 250 Pa/m for network branches (Greater London Authority (2013)). The nominal mass flow rate in the DHN was set according to the buildings' nominal demand. The pipes used for the initial DHN were mineral wool insulated steel pipes, a material used for DHN in the 70s (Marechal (1967)). On the other hand, the new LTD uses CALPEX pipes, which are much better insulated (Jonas (2015)).

It has to be noted that while the CALPEX pipes had clear, defined sizes for the LTD, no precise data could be found for the initial district insulated steel pipes. The steel pipe dimensions were then based on modern insulated steel pipes (HILINE STEEL) and the insulation thickness was estimated so that the heat losses in the DHN would belong to the range of 5-10%, a value often met in DHN (Çomakli et al. (2004); Narjot (1985)).

Substations work as an interface between the DHN and the buildings, allowing the transferring of the heat carried by the DHN to the buildings. Two types of connection exist for these (Euroheat & Power

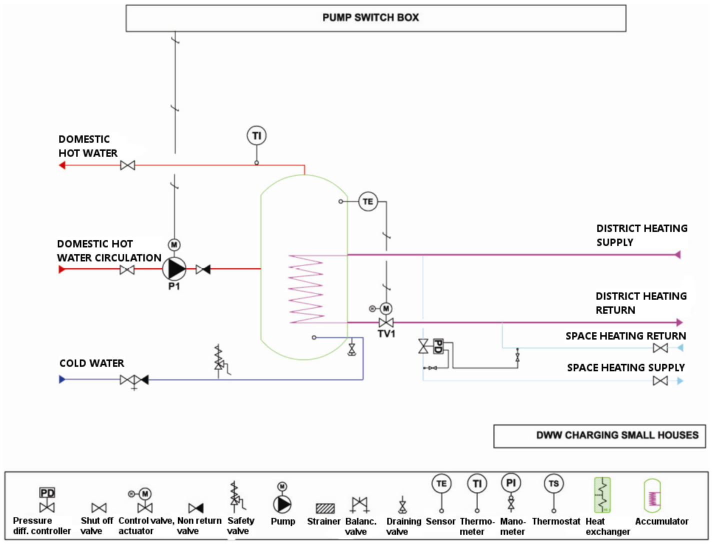

Figure 6: Diagram of the substations used for the buildings with direct connection to the DHN. Domestic hot water is provided via a tank. (Euroheat & Power (2008))

(2008)). Indirect connection ensures hydraulic separation in the form of a heat exchanger. On the contrary, direct connection permits the primary system DHN water to circulate around the consumer building. Connection also varies for DHW. It can be provided either via an instantaneous heat exchanger, or through an accumulator. This theoretically leaves us four options. The models were limited to two types of substations following guidelines: indirect connection with instantaneous heat exchanger and direct connection with DHW accumulator. Most of the substations modelled for this research were of the first type, the second being used only for the LTD in retrofit scenario #2. Schematic representation of the substations can be found on Figure 5 and Figure 6.

The heat exchangers at the substation are supposed to work on a temperature regime similar to that of the houses they supply, that is, 100°/80°for the initial district and 60°/30°for the LTD. However, in order to simplify the computations under Dymola, the heat exchangers were assumed to work at constant efficiency and the primary fluid was assumed to sustain the same temperature drop as the secondary fluid (consumer side).

The DHN also required the implementation of a bypass valve, in order to redirect excess flow coming from the supply. These were put at the end of each line. Nonetheless, this is not their only role. The bypass valves from the initial DHN also work as thermal bypasses, in order to guaranty an exploitable return temperature from the initial district. Indeed, a return temperature that is too low would prevent the LTD from working correctly. Therefore, control was implemented in order to have a return temperature of 60°from the initial district when working with the full district (i.e. initial district and LTD).

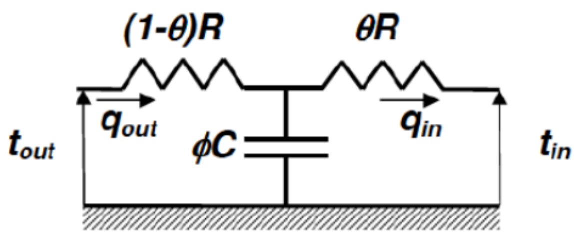

Figure 7: Diagram of the wall model implemented in the buildings. Lemort (2016)

The pipe models also brought about another limitation: the necessity for a minimal flow to circulate in the DHN. Thus, it was assumed that the pipes would carry a fluid with a minimal velocity of 0.5 cm/s at all time.
Finally, pumps should be present in the DHN to ensure fluid circulation. However, as these do not bear significant importance from a thermal point of view, a proper pump model was omitted from the distribution model. Circulation in the model was ensured by the use of fluid sources for perfect control in the branches.

Demand model
The building models are based on previous research by the Thermodynamics Laboratory at the University of Liège (Arnaut (2015)). Influence of external temperature, solar gains and internal gains are taken into account. Heat transfer between adjacent buildings has been neglected however. Party walls have thus been considered adiabatic.
Each building was represented by a single thermal zone for ease of computation. A constant volume of air, modelled in the Buildings library, is at the core of the zone model. External and internal walls have been modelled as shown in Figure 7. A full diagram of

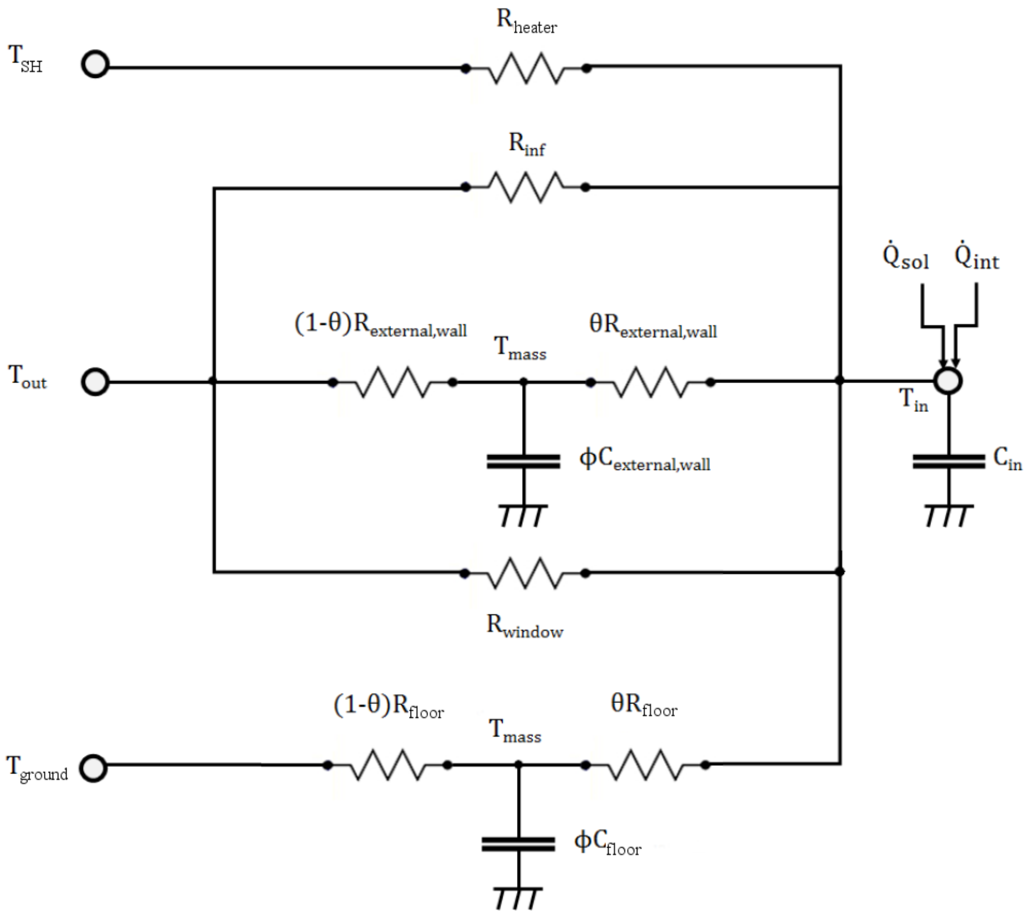

Figure 8: Schematic of the building model. T_{SH} is the water temperature inside the heater, $\dot{Q_{int}}$ represents the internal gain, and $\dot{Q_{sol}}$ represents the solar gains. External walls also represent losses through the roof.

the building can be found on Figure 8. The thermal resistance R of the wall reflects its level of insulation, while the heat capacity C represents its inertia. As it is not fully accessible throughout a daily cycle of 24 hours, the heat capacity C is bounded by a factor φ. The factor θ expresses the ease of access to the wall thermal inertia. On the contrary, the thermal inertia of windows is negligible. The windows were hence modelled as pure thermal resistance.

Parameters R and C were given with the characteristics of each walls in the definition of the IEA BBC Annex 60 exercise (AIT, IK4, KUL, Masdar, RWTH Aachen, TUe, and ULg (AIT et al.)). Masy provided an EES model to allow the evaluation of parameters φ and θ (Arnaut (2015)).

Space heating is provided through radiator. They worked with a temperature regime of 90°/70°for the lower insulation buildings. The radiators for the LTD had a different regime depending on the type of connection; for direct connection, 60°/30°; for indirect connection, 55°/25°(Kaarup Olsen (2014)). Heating control is achieved through a thermostatic valve at the radiator, controlling the flow going through it, and a three-way valve working with a heat curve to modulate the fluid temperature at the radiator supply (Cellule Architecture et Climat (2016)).

As mentioned before, DHW is provided by the substation, either via an instantaneous heat exchanger or a hot water tank. In the case of instantaneous heat exchangers, a DHW temperature of 50°was set in every one-family houses. A temperature of 55°was set (Euroheat & Power (2008)) for multi-family houses (i.e. the multi-storey buildings A2 and O2). The control of DHW temperature in the case of hot water tanks will be further described in section 2.4.2..

Generation model

The supply of the DHS was done through a conventional gas boiler. Its principle of operation is shown on Figure 8. The combustion was modelled as being complete, with a fuel-air ratio of 0.06. The effectiveness of the gas-water heat exchanger and the water-environment heat exchanger and the efficiency of the boiler are based on laboratory test data. The generation is operated through an ON/OFF control (Lemort (2013)).

The boiler had been sized for a supply temperature of 100°as the initial district buildings operated on a 90°/70°temperature regime and for the peak demand

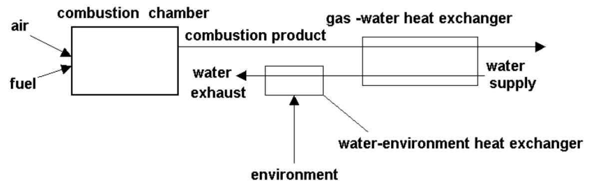

Figure 9: Boiler model principle. One heat exchanger represent the heat transfer between flue gas and water, while the other one represents the losses to the ambiance. (Lemort (2013))

of the district, while considering occupancy schedules. The boiler design considered a 5% security factor over the peak demand.

Retrofit scenarios

In this study, extending the initial district meant adding demand while keeping the same generation. However, simulating the extended district revealed that the boiler was not able to supply the additional buildings in heat. It was thereby necessary to modify the DHS in order to shave the demand peak. The range of studied retrofit scenario was limited by some constraints: bringing the least possible amount of modifications to the original DHS, modifying only infrastructure belonging to the municipality (DHS and buildings A2 and O2), and striving to find the most cost-effective solution.

Retrofit of the envelope of A2

The envelope of the apartment building A2 was retrofitted to have high thermal efficiency, according to the characteristics described in the IEA BBC Annex 60 (AIT, IK4, KUL, Masdar, RWTH Aachen, TUe, and ULg (AIT et al.)).

Decentralised storage

This retrofit measure applies to the additional buildings and not the municipality buildings. Hot water tanks separate the DHW supply from the DHN and the DHW demand from the consumer, and in this way has the possibility of shaving the demand peak (Li and Svendsen (2012)). DHW tanks were implemented in the new buildings (D1 on Figure 4). Their model was based on previous work by the Thermodynamics Laboratory at the University of Liège (Dumont et al. (2015)). It assumes a finite volume stratified tank that allows heat transfer between neighbouring nodes. Figure 10 illustrates the hot water tank operation principle. The tank size allows it to be fully emptied during the peak hot water demand.

Prevention of the development of bacteria and Legionella is achieved by a controller in the water tank that operates the system at 55°via a temperature sensor 1/3 from the bottom of the tank.

Centralised storage

The use of centralised storage in the DHN would allow to shave the demand peak by displacing the heat demand: extra heat would be produced when the demand is low (for example at night), stored, and then used when the demand is high (Verda and Colella (2011)).

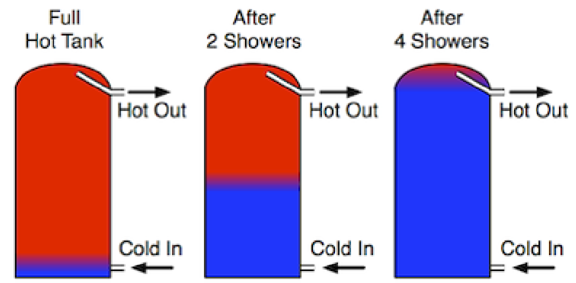

Figure 10: Schematic of the decentralised hot water storage tank operation principle. Four valves isolate the storage tank from the DHN. During the peak demand, the hot water from the tank is fully emptied. (Source: www.apricus.com)

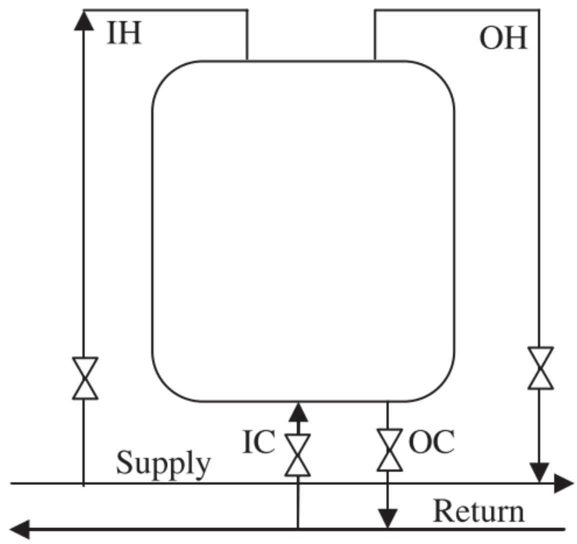

Figure 11: Schematic of the centralised storage tank. Four valves isolate the storage tank from the DHN. (Verda and Colella (2011))

The thermocline storage model from the ThermoCycle library was used to simulate this behaviour. Figure 11 illustrates the thermal storage as it was implemented in the DHS. The storage tank is charged at night when the heat demand is low. In the charging process, hot water from the supply line flows into the top of the tank (IH) while cold water is extracted from the bottom of the tank (OC) and enters the return line. The stored heat is used during the day. During this discharging process, cold water enters the tank (IC) while hot water is extracted from the top (OH) and delivered to the consumers via the supply line. When the tank is not in operation, all four valves are closed and both the supply and return line of the DHN bypass the storage tank.

Sizing of the thermal storage was based on the height-to-diameter ratio of a similar storage used in Torino

DHS (Verda and Colella (2011)). The storage volume used in this paper has been computed according to the least amount of spare energy at the boiler at night (thus on the coldest night of the year) and according to the supply and return temperature of the DHN at the location where the storage was connected.
There obviously are several ways of connecting the storage tank to the DHN. In this research, the only scenario studied consisted of installing the storage near the A2 and O2 buildings (as they belong to the municipality). However, setting the storage near the boiler would also make sense. This option gives an opportunity for future study.

Thermostat control

The idea of intelligent heat control was described in literature according to the smart cities principle (Lund et al. (2014)). In this research, an operator had a certain amount of control over the thermostat in every building of the district. If a building's internal temperature was under a certain threshold, it sent a signal to the operator that it was too cold. The operator then sent a signal to every other building that it had a lower its thermostat to ensure a comfortable temperature throughout the whole district. In this case, the thermostat could be reduced by a maximum of 1 K.

Results

The current system was able to satisfy the new demand through some of the retrofit measures. The extended district model being computationally demanding the simulations were only ran to focus on the ability of the retrofit measures to flatten the demand peak. In other words, only the coldest week of the year was simulated. Figure 12 shows the evolution of the outside temperature of the district throughout the year. The coldest period is on the 43rd day, in mid-February.
The initial district covers 5713 m^2 for a network length of 321 m. The extended district covers 8106 m^2 for a network length of 472 m. Assuming each user has subscribed for the nominal heat power described in Table 1, this results in a DHN density of 67 MW/km^2 and 1.2 MW/km in the first case, and 51 MW/km^2 and 0.9 MW/km in the later. Table 1 indicates the nominal space heating demand for each building type. The values have obviously been rounded up. Table 2 shows the evolution of the heat demand of the district when extending the initial district with the LTD. Note that due to different occupancy schedules, the aggregated demand peak is different from the sum of each nominal demand. As stated earlier, heat losses are significant in the DHN. They cause a drop of the DHS efficiency as well as a temperature drop between the boiler and the furthest consumer, as shown in Table 3. The temperature drop in Table 3 was computed according to the furthest consumer of the initial district to provide a point of comparison. Furthermore, the pipe insulation in the LTD makes the temperature drop between the return of the initial DHN and the last consumer of the LTD negligible.

Table 1: Nominal heating demand for each building type.

Building type	Nominal demand [kW]	Volume [m^3]
D1	6	440
S2	20	440
T2	15	384
A2 / O2	50	1880

Table 2: Heat demand over the coldest week of the year.

District type	Peak demand [kW]	Req. energy [MWh]
Initial	340	35
Extended	370	39

Table 3: Heat losses in the DHN over the coldest week of the year.

District type	Max heat loss [kW]	Mean efficiency [%]	T°drop [K]
Initial	30	93	4.5
Extended	40	90	3.5

These losses change a lot between the initial and extended district due to the implementation of the thermal bypass and the necessity to have a minimal return temperature for the initial district. Indeed, the values of heat loss of the extended district with retrofit are very similar to those of the extended district without retrofit.
The impact of the extension on the whole district was quite small. At the demand peak, the boiler was able to sustain 95% of the whole heat demand, due to the small amount of high thermal efficiency building added. Therefore, the gap between temperature setpoint and building internal temperature is quite small: at most 0.9 K against 0.1 K in the initial district. Figure 13 shows the indoor temperature evolution over the coldest winter day. The outside temperature that day varies from -1°to -9°, hence respecting the winter reference value for Brussels Cellule Architecture et Climat (2016).
Table 4 shows the main results of the study from the demand point of view. A drop of the DHN supply

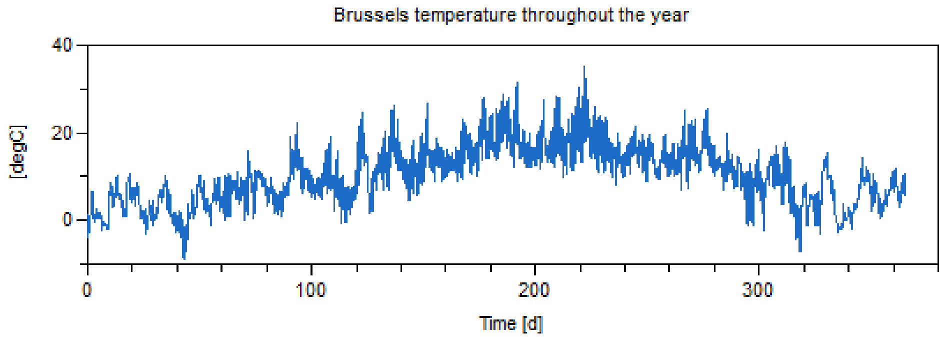

Figure 12: Evolution of Brussels temperature over a year.

Table 4: Results of the retrofit measures. The abbreviations correspond to the retrofit scenarios described in section 2.

Retrofit		none	ExtIns	DSto	CSto	TCtrl
E. to reach set supply T°	[MWh]	1.40	0.22	1.15	3.90	0.40
Time when boiler at full charge	[%]	3.70	0.00	3.61	10.51	1.89
Longest time at full charge	[h]	4.00	0.00	4.20	5.54	1.55
E. supplied by boiler	[MWh]	48.37	44.33	48.47	54.48	48.34
Maximum heat supplied	[kW]	354.85	341.93	354.68	356.30	353.11
Max ΔT setpoint at peak demand	[K]	0.83	0.05	0.70	1.12	0.30

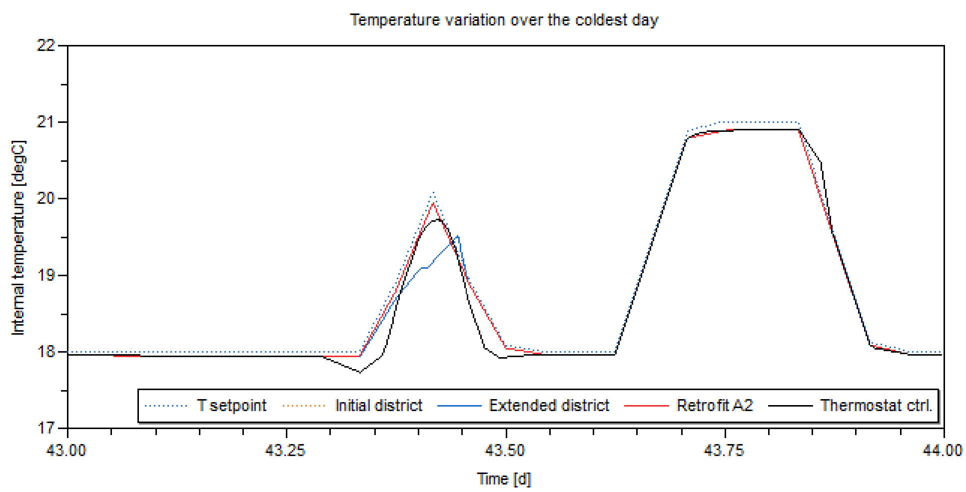

Figure 13: Evolution of the indoor temperature in one of the residential buildings on the coldest day of the year.

temperature resulted from the insufficient heat supply. The first line of Table 4 expresses this lack by quantifying the additional energy needed to reach the set supply temperature. An illustration of the retrofit effects is shown on Figure 14. It has to be noted that the centralised storage was not able to fully charge on the coldest night of the year, despite being sized for the minimal amount of energy available at night. Figure 15 shows the temperature variation in the centralised storage.

Discussion

Among the studied retrofit scenarios, retrofitting the envelope of the apartment building A2 (ExtIns scenario) and using a centralised control of the thermostat (TCtrl scenario) provided the best results, as they allowed an augmentation of the indoor temperature, thus bringing it closer to the setpoint temperature and improving the comfort conditions indoors. The thermostat control is all the more interesting as it doesn't involve any actual cost on behalf of the municipality. The disadvantage is that it provides less

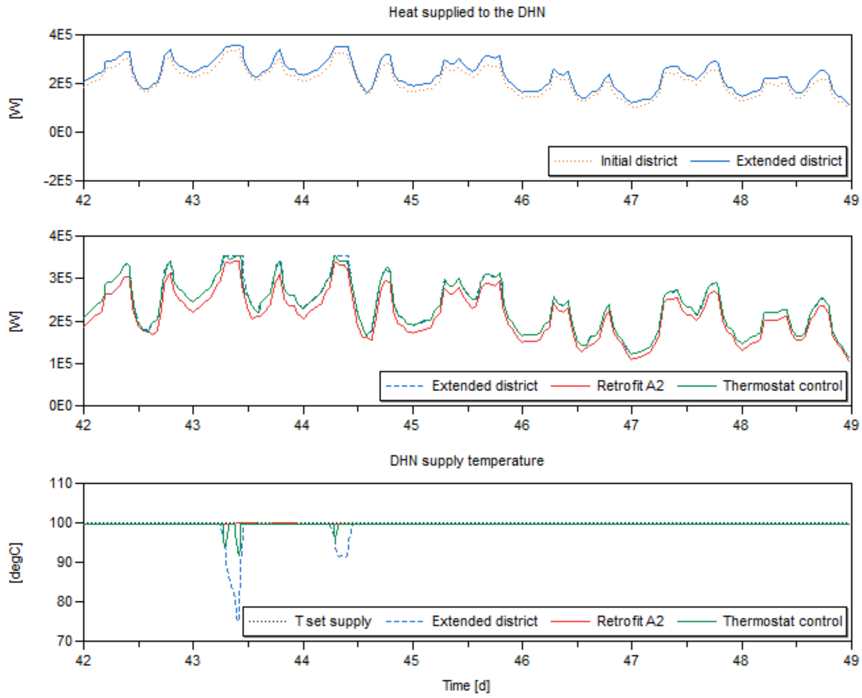

Figure 14: Comparison of the effect of some of the retrofit scenarios on the extended district over the coldest week of the year.

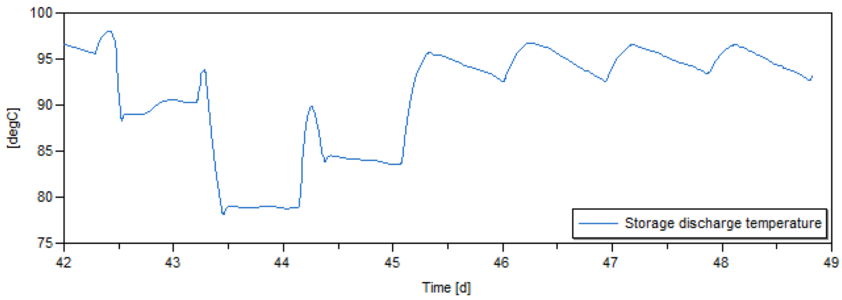

Figure 15: Discharge temperature of the centralised thermal storage over the coldest week of the year.

comfort to the occupants than retrofitting the envelope of the municipality building (TCtrl reduces the gap with the setpoint temperature by 63.9% while ExtIns reduces the gap by 94.0%). On the other hand, at peak demand the boiler of ExtIns scenario only worked at a charge of 97.3%, while it worked at 95.5% in the initial district in the same climatic conditions. However, due to the necessity to ensure a temperature of 60°from the initial district, only two more houses could be added to the LTD with this retrofit measure. (In the initial district, the average return temperature over the coldest week was 45°.) These results prove that the combination of energy efficiency measures on both supply and demand sides of the energy system - namely measures on the heat supply through thermostat control and heat savings by the retrofit of the A2 envelope – provide better heat savings than through sheer heat savings alone (Persson et al. (2014)). Further heat savings on the supply side could also be achieved by reducing the DHN supply temperature, but this would require a change of the temperature regime in the initial district buildings, and thereby for the consumers to replace their radiator. Such a possibility was overlooked in this paper, as it is a solution that would go beyond the reach of the municipality.

Table 3 also reveals that even if the installation of water tanks in the new houses allow a decrease of the temperature gap, they cause an increase of the total energy consumption over the week. This shows the importance of a shared vision between the municipality and the housing company that built the houses on how to develop the local energy system (Åberg and Henning (2011); Chittum and Østergaard (2014)). Comprehensive planning is therefore necessary for the development of cost effective DHS.

Heat losses in the DHN were based on assumptions, given an order of magnitude found in existing DHN. A variation of the heat losses magnitude can bear a great impact on the consumers. Other results have shown that rising the heat losses to an average of 16%, as found in some other sources, yields a much more dramatic impact on the consumer that the studied 8% case (Çomakli et al. (2004)). Not only does the maximum difference with the temperature setpoint rises (2 K), but these differences happen more often (up to 12 hours instead of 3 hours). On the contrary, reducing the heat losses to an average of 5% results in the DHS being perfectly able to sustain the extension (Narjot (1985)). This proves the non-negligible role of heat losses in district heating.

Further study of the centralised storage scenario would be necessary. Indeed, the storage operation relies on a control algorithm. Therefore, its performances should depend of it. This might explain the low efficiency of the CSto scenario. Different control methods could be compared to improve its performances. Implementing the centralised storage so as to bypass the boiler might also prove an interesting enhancement in future studies.

As stated before, the yearly study was overlooked due to technical reasons. Nevertheless, a simulation over the course of a full year would have allowed several opportunities and problems to come into view. Undeniably, the possibility for seasonal storage could have been examined, as the heat demand in summer drops considerably. The impact of the investment in seasonal storage on the heat price will have to be studied however. In addition, the cost of district heat for the users living in the initial district might have risen. The extension of the DHS with the LTD and the necessity for a thermal bypass cause an increase of the boiler use that is disproportional to the number of dwellings added. Operation cost in the DHN might remain more or less the same, but the fuel consumption of the boiler would increase significantly, as the LTD requires a supply temperature of 60°to function. There should therefore be a threshold for the number of additional consumers before the extended DHS proved profitable. In this case, a slight retrofit of the boiler might be considered, for example by replacing the ON/OFF burner with a modulating burner. On the other hand, the decrease of the network density hints a profitability limit for the DHS, as there would be a point where heat sales can no longer cover the DHS cost (Narjot (1985); Lemort (Lemort)). Deeper financial investigation would thus allow to prove the cost-effectiveness of the studied retrofit scenarios as well as uncover the optimal extension size for the DHS.

Remarks on Dymola as a building simulation tool

As mentionned earlier, the district model was computationally demanding (from 6 to 20 hours of simulation on Intel Core i5-4210H @ 2.90GHz CPU, depending on the scenario tested), the most computationally heavy model being the DSto scenario. The main reasons behind this issue are not only PID control - mostly due to small integral time - but also memory management in Dymola. Indeed, we found out that the file format for the different simulation inputs (climate, internal gains, occupancy schedules...) had a great impact on the overall simulation speed. Files under the *txt* format proved to yield a simulation speed two or three times greater than using *mat* files. On the other hand, storing those data directly in the model rather than loading it caused Dymola to crash due to insufficient memory. There further seemed to be some memory leak with Dymola, as sometimes running two simulations in a row caused erroneous results (values of #INF in the later).

An improvement of the models might therefore be necessary to see if those issues could be solved by using the tool in a different way. Simplifying the building models may help the simulation being faster, while an in-depth investigation of the models used might uncover the cause behind those bugs.

Conclusion

District heating is coming to its second peak of development due to the rise of fossil fuel prices and the need for more sustainable heating. As the use of district heating spreads, they are likely to encounter older DHS, working on another technical level than today's constructions.

The aim of this study was to evaluate the possibility of extending an existing low thermal efficient DHS with a new development of high thermal efficiency buildings, in the form of an LTD. This proved to be feasible, through the application of retrofit measures in the DHS. Sole heat savings in the buildings, in the form of a retrofit of the building envelopes, are enough to extend the energy system up to a certain point. Further extension, and hence a better efficiency for the DHS, can be achieved with a centralised control over every consumer's supply. This, along with the fact that installing individual water tanks in houses could increase the energy demand of a DHS, showed the importance of cooperation between housing companies and the municipality for the development of local energy systems.

The research also showed the incompatibility of day-by-day centralised storage with some energy systems. Seasonal storage, however, could be beneficial for the heat demand and allow a greater extension of the district. Still, the significant investment required for the installation of seasonal storage might cause an important augmentation of the heat price, and therefore replace thermal discomfort with a lack of economic interest.

A slight conflict between the operation of LTD and older DHS was revealed. Extending the energy system by using the original return flow to supply the LTD forces the system to provide additional heat to ensure an exploitable temperature for the LTD, resulting in a disproportional increase of the boiler use. This further limits the number of additional houses the DHS can serve.

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