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Exploring the novel software Hysopt: a comparison of hydronic heat distribution systems of an apartment building

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Abstract

Space conditioning and domestic hot water production in buildings account for a large amount of the global primary energy consumption. The type of system that supplies the demanded energy can affect this energy consumption. This paper considers two types of systems that are used in apartment buildings. In the first system, each apartment unit supplies its own heat using a combi boiler (individual production system or IPS). In the second system, the heat is produced by a central boiler (the central production system or CPS). Pipes circulate the water and substations connect apartment units to these pipes. While the CPS facilitates the implementation of sustainable energy sources, it also loses energy due to the distribution circuit. Therefore, a comparison between these two systems seems necessary. This paper compares an IPS and a CPS within an apartment building. This comparison is based on simulations, using the software 'Hysopt'. Results show that the CPS scores 6.9 percentage points lower on efficiency, compared to the IPS. However, the number of startups per boiler is 3.3 times less for the CPS (which has only one boiler while the IPS has 11). This system also shows a higher controllability. Some further steps should be taken to complete the comparison, as the results of the energy consumption are questionable.

Keywords - Collective heating, Individual heating, building simulation software, Hysopt

1. Introduction

The European Union has set ambitious and necessary targets regarding energy and climate issues [1],[2]. In this context, the building sector is predominant. Indeed, buildings in the EU account for 37% of the total primary energy consumption. Most of it is used for space conditioning and domestic hot water production [3]. Following the trias energetica approach, producing the demanded energy efficiently is a final step in reducing this energy consumption. In this paper, the focus is on hydronic heating systems to provide that energy. The doctoral thesis of Vandenbulcke [4] already highlights the importance of hydronic optimization. From this and other research projects [5][6], the company Hysopt NV was founded in 2013 as a spin-off of the University of Antwerp (Belgium). This company commercializes the software 'Hysopt' for the optimization and simulation of hydronic systems.

The scope of this paper is to compare two hydronic heating systems for domestic hot water (DHW) production and space heating (SH) in an apartment building by using Hysopt. In the first concept (individual production system or IPS) each apartment unit has its own production unit: a combi boiler. The second concept consists of a centralized boiler and a collective heat distribution circuit (central production system or CPS). Local substations connect each apartment unit to that circuit.

2. Problem statement

Comparing central and individual production

The CPS system is penalized in the calculations of the Energy Performance of Building standards in Europe due to the distribution heat losses (which are absent in the IPS). However, based on dynamic simulations it was shown by Himpe et al. [7] that these simplified calculations are an overestimation of the distribution losses. Also, among other advantages, the collective system enables a more practical integration of renewable energy in buildings. This integration is far more difficult in IPSs. Hence, a comparison between individual and collective heating seems to be necessary.

Cholewa et al. [8] made a comparison between two types of CPSs, based on measurements in buildings. One system is the same as the CPS as described above. The other CPS system also produces the heat centrally, but the DHW and water for SH are distributed in separate pipes and no substations are used. It was shown that the CPS with substations scores 10.5 percentage points higher on efficiency than the CPS without substations because of the lower distribution losses. They also compared it with an IPS, but under a constant boiler efficiency assumption (i.e. not based on measurements). Unfortunately, no measurements were done inside the living units. This makes a comparison between an IPS and a CPS difficult. Hence, the question remains whether an IPC or a CPS is more efficient. This comparison, among other criteria, is elaborated in this article. The CPS with substations will be referred from now as just CPS.

Comparison criteria

The two systems are compared based on different criteria. The total amount of gas consumption Q_{fuel} (kWh in higher heating value), the total amount of energy centrally delivered from the boiler to the collective distribution system Q_{centr} (kWh) and the total amount of energy uptake at each apartment unit Q_{ind} (kWh) are calculated. The position of measurement of Q_{centr} and Q_{ind} in the CPS are indicated by '3' in Fig. 1B. For the IPS is Q_{ind} equal to Q_{centr}. To characterize the boiler and collective distribution system, the 'seasonal' efficiencies of the production system (boiler) η_{prod} and distribution system η_{distr} are defined as:

$$\eta_{prod} = Q_{centr}/Q_{fuel} \tag{1}$$

$$\eta_{distr} = Q_{ind}/Q_{centr} \tag{2}$$

η_{distr} obviously equals 1 for individual systems. Note that η_{prod} is a mean efficiency, in contrast to the instantaneous boiler efficiency η_{boiler} in (9) (10).

The apartment unit-specific performances are quantified based on temperatures of the zones (i.e. the rooms in an apartment unit) and of the DHW. The real value (also called process value, PV) are compared with the set point (SP) temperature at each moment. The profiles of those set points are discussed below under the case study description. Based on the PVs and the SPs, the temperature lacks (TL, in Kelvin seconds) and temperature excesses (TE, in Kelvin seconds) can be calculated. For DHW, it is called Sanitary Temperature Lack (STL) and –Excess (STE). For SH, it is called Room Temperature Lack (RTL) and –Excess (RTE) [1]. For a period $t_2 - t_1$, this gives in general:

$$\begin{cases} TL = \int_{t_1}^{t_2} (\mathrm{T_{SP}} - \mathrm{T_{PV}})\, dt \qquad if\ \mathrm{T_{SP}} > \mathrm{T_{PV}} & (3) \\ TE = \int_{t_1}^{t_2} (\mathrm{T_{PV}} - \mathrm{T_{SP}})\, dt \qquad if\ \mathrm{T_{SP}} < \mathrm{T_{PV}} & (4) \end{cases}$$

The equations are valid for both DHW production and SH performance if respectively $\mathrm{T_{DHW}}$ and $\mathrm{T_{SH}}$ are used for set points and process values. Those variables are a measure for how fast and stable the set points can be reached. RTL and RTE also quantify the thermal comfort. At each moment, the RTL and RTE are related to resp. an underconsumption or overconsumption of energy of a zone to reach its set point. This relation depends on the outdoor temperature and the wall temperature of that zone at that moment. For that reason, the RTL and RTE can only approximate the energy over- and underconsumtion. STL and STE lack potential to quantify the DHW comfort of the end users. Indeed, the set point of the DHW temperature is 55°C, but a temperature of 40°C would not affect the comfort of an end user. Again, these variables only approximate the energy over- and underconsumtion. Indeed, the amount of heat depends also on the water flow of the DHW. An alternative for the quantification of over- and underconsumption of energy would be the net heat demand, necessary to resp. remove or add to reach the set point temperatures of SH and DHW. For SH, this is used in reference [2]. This comparison will be done using the software Hysopt, based on an elaborated case.

3. Hysopt

The software

Hysopt is a graphical-based software. It allows the user to select 'Base Circuits' (BC) [3] and interconnect them with pipes and control signal connections in the GUI. BCs are commonly used combinations of basic components. Examples are given in Fig. 1. The model behind each BC, describes the hydronic and thermal behavior of that BC. The structure of the mathematical equations cannot be adjusted. However, parameters in the equation can be adjusted by selecting a BC.

Two public versions of Hysopt exists: 'Master-dev' and 'Secure'. For this simulations, the latter was used. It enables the use of some extra BCs and a shorter simulation time step (5s), compared to the other version. This enables a better analysis of DHW systems. However, the implementation of DHW in Hysopt is still in its infancy and will evolve the coming year.

Hysopt is a cloud-based software. The calculations are done by a central server and speed up the simulations. A maximum simulation period of 4 days can be selected if the original data is required, as only a limited amount of samples can be saved by the server. If a longer simulation period is selected, the data will be subsampled, while the simulation time step stays the same [4]. The software provides some useful features for the design of heating/cooling systems. Moreover, the user can run through a workflow that supports the design process.

Models

Most of the models and their validity are discussed by Vandenbulcke [1]. Each BC can affect the pressure loss and/or temperature of the water that flows through it. The pressure losses are given in hydraulic models. They include pipe friction, balance valve, control valve and pump models, but will not be discussed here. The effect on temperature is described by thermal models. For the radiator model a lumped capacitance model is coupled with an LMTD model [5]. The heat output P_{emit} can be coupled to a zone. For heat exchangers the ε-NTU method [5] is used. The heat transfer coefficient of the heat exchangers relates to the primary and secondary water flows. The structure of this relation was validated by Hysopt NV for a plate heat exchanger. It was found to be the best fit among a series of model structures (personal communication [4]). Thermal pipe loss P_{pipe} is also modelled by a ε-NTU method. The heat transfer coefficient of pipes can be calculated by Hysopt for a given insulation class, according to EN 12828 [6]. Pipe loss can be coupled to a zone. Each zone in the building is modeled separately. The model does not allow for heat exchange between zones. No internal heat gains, originating from e.g. electronic devices or solar radiation, are accounted for. Zones are modeled as two lumped capacitances: the internal air with temperature T_{zone} (°C) and the wall with temperature T_{wall} (°C). Heat transfer between those two capacitances is characterized by a resistance R_{int} (K/W). R_{ext} (K/W) characterizes the heat transfer from the wall capacitance to the outdoor (temperature T_{ext} in °C). This is shown by the set of equations:

$$\begin{cases} C_{wall}\dfrac{dT_{wall}}{dt} = \dfrac{1}{R_{int}} * (T_{zone} - T_{wall}) - \dfrac{1}{R_{ext}} * (T_{wall} - T_{ext}) & (5) \\ C_{zone}\dfrac{dT_{zone}}{dt} = P_{pipe} + P_{emit} - \dfrac{1}{R_{in}} * (T_{zone} - T_{wall}) & (6) \end{cases}$$

C_{wall} is the heat capacity of the wall (J/K) and depends on the wall structure. In this paper, the wall structure is set to 'rather light' (with $C_{wall,rather\ light} = 6700\ V_{zone}$ and $C_{zone} = c_{air}\rho_{air}V_{zone}$). The software calculates R_{int} and R_{ext} by using a given set of design parameters of that zone (see Table 1 below). Note that this model is not intended to emulate a real zone. However, the model is able to approximate the zone dynamics. Indeed, a comparable model was experimentally validated in [7]. The dynamics of the boiler are modelled using a lumped capacitance (C_{boiler}) model with an ideal burner. The model is a combination of the TESS [8] boiler model and a static boiler model for the efficiency $\eta_{boiler}(T_{ret}, \dot{V}, PLR)$ [9]. Refinements were made which will be described in an upcoming paper [10]. More information can be found in [11]. The model is described as:

$$\begin{cases} C_{boiler}\dfrac{dT_{sup}}{dt} = P_{boiler} - P_{boiler,sup} - P_{boiler,loss} & (7) \\ P_{boiler,sup} = c_{water} * \rho_{water} * \dot{V} * (T_{sup} - T_{ret}) & (8) \\ P_{boiler,loss} = UA_{boiler} * (T_{sup} - T_{ext}) & (9) \\ P_{fuel} = P_{boiler} / \eta_{boiler}(T_{ret}, \dot{V}, PLR) & (10) \end{cases}$$

The heat taken up by the boiler P_{boiler} is directly controlled through a demanded Part Load Ratio (PLR) by the boiler control. $P_{boiler,sup}$ is the heat flow 'through' the lumped capacitance. $P_{boiler,loss}$ is the skin loss of the boiler and can be characterized in Hysopt by the constant value UA_{boiler}. As can be seen in (9), the skin loss depends on the outdoor temperature T_{ext}. Therefore, $P_{boiler,loss}$ cannot be coupled with a zone. Electric consumption of the electronics and ventilator of the boiler are neglected.

4. Case study

Description

The elaborated case in this article is based on a real apartment building in Antwerp (Belgium). During the renovation of the building, the IPS and CPS were both studied as alternatives to replace the central DHW production system. The apartment building consists of 59 apartment (living) units. However, for simplicity only 11 apartment units are considered in this study. The building has four types of apartment units. The types 'North', 'East' and 'South' are three times repeated, the type 'West' two times. See Table 1 for the zone specific parameters. In this table, the heat loss of each zone in each apartment unit were determined using NBN 62-003 standard [12]. Radiators are selected according to [13]. The theoretically energy demand for SH depends on the set point temperature of a zone $T_{zone,SP}$ and the outdoor temperature T_{ext}. $T_{zone,SP}$ at day differs for the different zones, as can be seen in Table 1. 'Day' is defined as the period between 7am to 10pm. At night, $T_{zone,SP}$ is 14°C and is equal for all the zones. For T_{ext}, a test reference year of Uccle (Belgium) is used.

Table 1: Zone-specific parameters of the different apartment types used in the simulations: volume of the zones (V_{zone}), set point temperatures during daytime ($T_{zone,SP}$), the zone heat losses at design conditions ($P_{zone,des}$), the emissions of the radiators at design conditions ($P_{emit,des}$)

Type	Zone type	V_{zone} [m³]	$T_{zone,SP}$ [°C]	$P_{zone,des}$ [W]	$P_{emit,des}$ [W]
North	Living room	90.7	20	2400	1370 x 2
	Bedroom 1	33.4	20	582	819
	Bedroom 2	22.7	20	528	819
	Bathroom	11.1	23	1062	1260
East	Living room	90.7	20	2356	1370 x 2
	Bedroom 1	33.4	20	708	819
	Bedroom 2	22.7	20	540	819
	Bathroom	11.1	23	1088	1260
South	Living room	77.0	20	2000	1202 x 2
	Bedroom 1	34.0	20	680	819
	Bathroom	11.7	23	1050	1260
West	Living room	90.7	20	2326	1370 x 2
	Bedroom 1	24.1	20	578	819
	Bedroom 2	33.3	20	435	819
	Bedroom 3	33.6	20	713	819
	Bathroom	15.1	23	1309	1480

For the DHW demand, a Medium Ecodesign tapping cycle [14] is used to define the consumption pattern. Every day, the same cycle is applied to each apartment unit. For the IPS, the DHW consumption in all apartment units starts at the same time (7am). For the CPS, the start of the DHW tapping cycle in each apartment unit is spread between 6 am and 8 am. The reason for that, is to emulate a variation in DHW consumption of the inhabitants. The tapping cycle includes 19 deliveries of 40s at 3l/min, one tapping of 90s at 4l/min, one tapping of 211s at 4l/min and two times a tapping of 268s at 6l/min spread over the day. Note that the four latter described tappings account for 65.9% of the daily DHW energy demand. The demanded temperature of the DHW $T_{DHW,SP}$ is 55°C for all deliveries. The domestic cold water is 10°C for all simulations. Four periods of four days are simulated, each starting the first day of the month (Table 2).

Table 2. Summary of energy demand for SH and DHW, and mean outdoor temperature for the four simulation periods

	1-4 Jan	1-4 Apr	1-4 Jul	1-4 Oct
$T_{ext,mean}$ [°C]	6.9	6.1	15.4	10.3
SH [Wh]	1870586	2011269	468297	1308426
DHW [Wh]	256014	256014	256014	256014
Total [Wh]	2126599	2267283	724311	1564440
DHW/total [%]	12.0	11.3	35.3	16.4

Implementation in Hysopt

Two different types of heating systems are compared as discussed before: a system with individual production (IPS) and a system with central production (CPS). The two systems are schematically represented in Fig 1. In the IPS, each apartment unit produces its own heat using a combi boiler. The hydronic configuration of a standard combi boiler can be found in [15]. The simulation model of a West-type apartment unit, including the control logics, as implemented in Hysopt can be seen in Figure 1A. A boiler with a maximum heat flow of 35 kW is used with a minimal PLR of 15%. In the CPS, the heat for all apartment units is distributed by collective distribution pipes. The implementation of it in Hysopt is partly shown in Fig. 1B. A central pump circulates the water. A central boiler with a max heat flow of 146 kW and minimal PLR of 15% tries to keep the supply water at 75°C. It has to be said that this temperature can be further optimized, resulting in lower distributions losses. Between each floor, the pipes have a length of 4m. At the end of a riser, the pipes are connected. The flow through the end of the risers is controlled to keep the hot water flowing (0.1 m³/h) in the risers even if no heat demand is present. Each apartment unit is equipped with a substation without storage.

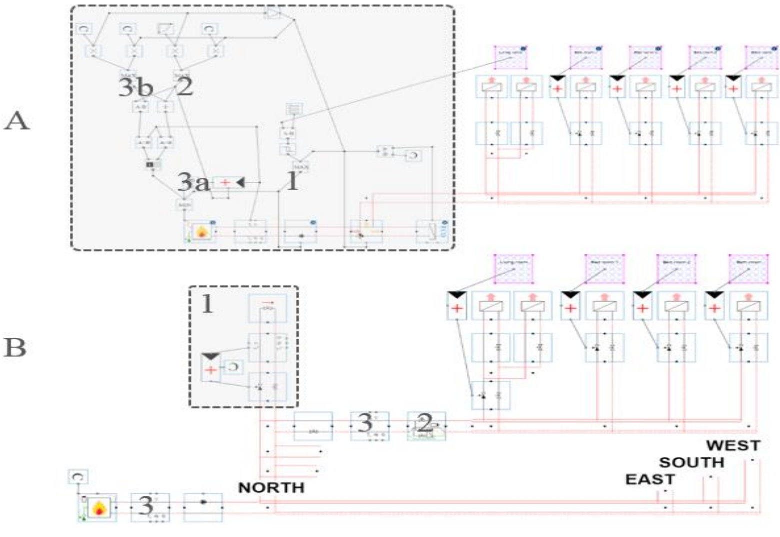

Fig. 1 A. The simulation model of a West-type apartment of a IPS as implemented in the GUI of Hysopt. The dotted line defines the boundary of the combi boiler. 1: on-off signal based on energy demand of DHW and/or SH. 2: set point temperature of boiler $T_{sup,SP}$. 3a: PI-control signal for modulation of the boiler. 3b: hysteresis temperature difference of DHW and SH. B. Only one of the eleven apartment unit is shown. 1: dotted line includes the flow control at the end of a riser. 2: BC of a substation. 3: BCs that can measure heat flow.

Results and discussion

The results of the case study are summarized in Table 3 ($\eta_{tot} = \eta_{prod} * \eta_{distr}$). η_{tot} of the IPS is for all periods higher than the CPS. Two explanations can be given. Firstly, the distribution losses in the CPS are accounted for in η_{distr}, which equals 1 for the IPS. Secondly, η_{prod} is slightly lower for the CSP. This is a result of the skin losses of the central boiler. These losses are neglected in the simulations for individual combi boilers. The reason for that, is the fact that the skin loss is coupled the outdoor temperature in the boiler model (9) (10). For the central boiler of the CPS, these losses are taken into account. This can be justified for a well ventilated central boiler room for the CPS. On the contrary, for a combi boiler that would overestimate these losses as the boiler would be placed within one of the inhabited zones such as the bathroom. For that reason, η_{prod} is overestimated for the IPS. Moreover, skin losses are expected to be relatively lower for a central boiler. Also, η_{prod} is most likely overestimated for both IPS and CPS because of the neglected startup losses. These losses are due to pre-ventilation before ignition and loss of unburnt gas during ignition [16]. These losses or not accounted for in the current boiler model. The number of startups is much greater for the IPS because the boiler is oversized for SH purposes. The effect of oversizing of residential boilers is shown by Peeters et al. [11]. However, for DHW production that size is required if no storage vessel is used. That causes the well-known short-cycling of a boiler.

For periods with a lower SH demand (July and October), it can be seen that η_{distr} of the CPS decreases. The reason for that is the lowered SH demand, while distribution losses remain equal. These findings are in line with the findings of Cholewa et al. [17]. Those same periods, η_{prod} decreases also. Indeed, due to the lowered heat demand the relative amount of skin losses increases (despite the decreased absolute amount of skin losses because of the higher outdoor temperature). Also, an increased return temperature and decreased volumetric flow rate of the distribution water might affect the instantaneous efficiency of the central boiler η_{boiler}. The lowered heat demand also explains the increased number of startups of the central boiler of the CPS during those periods. The effect of a lower SH demand in July and October of the IPS is contrary to the effect on the CPS. Because no constant circulation is required, the boiler stays off more which reduces the number of startups. Also the effect of heat demand on return temperature is eliminated because of the use of a heating curve for the IPS.

Table 3. Simulation results: efficiencies and number of startups (with mean startups = mean per boiler).

Comparison criteria	1-4 Jan	1-4 Apr	1-4 Jul	1-4 Oct	Total
CPS η_{prod}	0.902	0.903	0,871	0.894	0.896
CPS η_{distr}	0.964	0.966	0.921	0.953	0.956
CPS η_{tot}	0.869	0.872	0.802	0.853	0.857
IPS η_{tot}	0.927	0.923	0.918	0.930	0.926
CPS startups	39	47	95	54	235
IPS startups	2550	2514	1312	2149	8525
IPS mean startups	232	229	119	195	775

While the efficiencies of the IPS are higher, the contrary is true for the fuel uptake Q_{fuel} and the heat uptake at the level of the apartment Q_{ind}. This is shown in Table 4. They both are significantly higher for the IPS. Only for the four days in July, Q_{fuel} and Q_{ind} are slightly lower for the IPS (results not shown).

Table 4. Simulation results: energy and temperature lacks/excesses for the four simulation periods together

System	Q_{fuel}[kWh]	Q_{ind} [kWh]	RTL [Ks]	RTE [Ks]	STL [Ks]	STE [Ks]
CPS	9065	7766	7537	3888	225987	9876
IPS	11962	11071	54438	3206	2187041	477934

The results in Table 4 show a discrepancy. The higher Q_{ind} for the IPS should result in a higher energy consumption of the apartments. In turn, this should -in general- result in higher RTE and/or STE, and/or a lower RTL and/or STL. However, the latter statement is very disputable. There is no one-to-one kind of relationship between temperature excesses/lacks and energy as discussed above. In fact, two examples can be given that undermine the statement. The first example concerns RTL, which is almost an order of magnitude higher for the IPS. Roughly 50% of the RTL of the IPS originates from bathrooms (results per zone are not shown). The energy that is needed to compensate that lack depends, among other parameters, on the volume of that zone. This is because the volume of a zone is proportional to the heat capacity of the air in it and walls around it, as explained above under 'zone model'. This volume is much smaller for bathrooms than other zones (see Table 1). Because the RTL of the CPS is much more equally spread over the different type of zones, a comparison of energy underconsumption based on RTL is biased. The second example concerns STE, which represents relatively more energy in the case of the IPS. The reason for that, is because most overheating of the DHW occurs during longer tappings, as the boiler needs time to increase its supply temperature to the set point for DHW (60°C). Those longer tappings involve higher flow rates and account for most of the DHW energy demand (Table 1). These two examples can partly explain the results of Table 4.

However, given the large differences, it is most likely that other factors play a role. A possible explanation might be a difference in the BC for DHW production. The heat exchanger of the combi boiler loses heat in SH mode due to leakage in the three-way valve. This heat loss is not taken up by the DHW and is therefore not accounted for in the temperature lacks/excesses. Also, a difference in control signals was found in subsequent simulations of identical simulation models and identical simulation periods. This resulted in changed STL and STE up to a few to 100% and this makes the results for DHW questionable. To date, it remains unclear why subsequent simulations are not identically calculated for the IPS, as no randomness is present. To conclude, the question remains unclear what the higher Q_{ind} is used for in the IPS.

Finally, a note on controllability. Table 4 shows that for both DHW and SH, the CPS can better provide the demanded temperatures (lower lacks and excesses except for RTE). This is a result of the permanently circulation in de CPS. Also, DHW and zone temperatures are controlled based on variable flow. In contrary, the living room and DHW production of the IPS are controlled based on the supply temperature. Therefore, its controllability relies on the control of a boiler, which is much less accurate than a control valve.

5. Conclusion

The dynamic behavior of the two hydronic systems: the individual production system (IPS) and the collective production system (CPS), was simulated using Hysopt. According to the assumptions, it is shown that the efficiency of the CPS is 85.7%. The efficiency decreases if the SH demand is lowered and the DHW demand remains equal. The efficiency of the IPS is 6.9 percentage points higher. The difference is most likely an overestimation because startup losses are not accounted for. The number of startups is (summed for all boilers) 36 times higher for the IPS. Anyway, the efficiency of the CPS could be increased by implementing sustainable energy sources such as cogeneration, heat pumps or thermal solar collectors. The required savings are in a reasonable range. Also, the CPS shows a better controllability of both DHW temperatures and zone temperatures.

Regarding fuel consumption and heat uptake by the apartments, the results are questionable. Both are much higher for the IPS. And yet, the RTL and STL are higher. However, temperature lack and excess are inadequate criteria to make an energy based comparison. For that reason, it is difficult to conclude what happens with the higher heat flow into the apartments in the IPS. However, two other suggestion were made. Firstly, energy is consumed along the primary side of the DHW heat exchanger in the IPS when no DHW is consumed. The energy is not taken up by the DWH and hence ‘disappears’. Secondly, subsequent simulations of the IPS simulation model resulted in changed STE and STL. These inconsistencies are caused by the (initial values of the) control signals.

To complete the comparison, three suggestions are given. Firstly, other criteria than only RTL, RTE, STL and STE should be used for analyzing energy flows and comfort. They are only intended to quantify controllability. The energy flows from the zones to the outdoor and the energy flows through the primary side of the DHW heat exchangers should be possible to extract from the simulation results. To quantify thermal comfort, RTL and RTE are reasonable variables. However, for DHW it is far more difficult to quantify comfort. Indeed, the temperature lack and excesses should be defined for end users, not based on the production of DHW. Therefore, DHW flows and mixture with cold water should be implemented in Hysopt. Secondly, the heat exchanger BC of the IPS and CPS should be compared and should be consistent concerning energy loss. Thirdly, the inconsistencies of the subsequent simulation runs should be fixed.

Nonetheless, Hysopt was found to be a convenient tool for research purposes. In particular the building of a simulation model was found to be user friendly. The BC methodology, fault detection and other design features speed up the implementation in the software.

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