Multi agent building study on the control of the energy balance of an aquifer

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Abstract

A heat pump in combination with an aquifer has high promise generating heat and cold for user comfort efficiently within buildings. To guarantee favourable annual performance of the heat pump in future, it is important that the energy supplied to the aquifer is in balance. This paper demonstrates how a multi-agent approach can be applied to preserve this balance while delivering the exact amount of energy demanded at any time. In this simulation study, the data of an actual building with a heat pump, district heating and an air handler unit is used. This design exploits the ability of a multi-agent approach to trade two or more commodities at any given time.

Where a conventional centralized climate control system has failed, a multi-agent system demonstrates the possibility of preserving balance without infringing user comfort. The main difference between the two techniques is by using district heating only when necessary. When starting with a certain energy unbalance it is also possible to regain energy balance again. The share of renewable energy devices to produce heat can be increased as compared to centralized climate control systems. On a day-by-day basis, to deliver cold to the building, the air handler unit provides extra flexibility by using cold outdoor air when there is a demand of cold.

Introduction

In the Netherlands more than one third of energy consumed is within the built environment. It is expected that in future, approximately 2050, the number of devices for heating and cooling of a building will increase to achieve an energy neutral built environment [1]. Such a build environment may include photovoltaic thermal hybrid systems (PVT), a heat pump, district heating, solar blinds and an air handler unit. A buffer for heat storage may also be present as well as mechanical ventilation to guard the concentration of CO_2 in each room. With this increase of supply possibilities, there is a higher risk of one device counteracting the other. Further, the energy from certain sustainable energy sources is supplied at different times than when energy is demanded. In such a case, the system needs to decide whether to store the energy in a buffer or not. In addition to air flows in the building, new device properties need to be controlled. An example being, the annual balance of the energy supplied to an aquifer by a heat pump. As a lot of simultaneous processes occur in a building, this may lead to unnecessary loss of energy.

Another goal is to heat or cool the building in the most efficient way. To achieve high energy efficiency, the share of energy generated by renewable energy devices should be optimized. It is becoming harder for conventional comfort control systems to satisfy the objective: ‘provide thermal comfort at the lowest energy use’.

In the design of these systems, the capacity of the resources is calculated according to a standard reference situation. This means that the designed capacity is not always completely exploited. This creates an opportunity for improving the utilization of the aquifers capacity over time. Multi-agent systems for climate control can offer a number of advantages in this field due to their bottom-up modelling principle starting from the low-level primary process, in this case comfort control. A multi-agent market approach can coordinate the energy flows to achieve global optimization and obtain decentralized control.

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Multi-agent markets

The multi-agent approach localizes and confines data, processing and controlling in a bottom-up fashion, without an omniscient top-level. In comfort control this has several benefits, such as 1) the generic description of installations 2) plug and play behaviour of appliances 3) adaptation to the circumstances instead of predefined behaviour and 4) no need for complex flow diagrams. For coordination of devices to match supply and demand in an electricity network, there has already been developed and tested a successful technology, ‘the PowerMatcher’.

The PowerMatcher is a general purpose coordination mechanism for balancing supply and demand in electricity network [2]. This technique implements supply and demand matching (SDM) using a multi-agent systems and market-based control approach. SDM is concerned with optimally using the possibilities of resources (electricity) producing and consuming devices in order to alter their operation in order to increase the over-all match between resource production and consumption. Within a PowerMatcher cluster, the agents are organized into a logical tree. The leaves of this tree are a number of agents representing something or someone (in this case a device or an energy demand from the user). This agent tries to operate the process it is associated with in an economical optimal way. The agent coordinates its actions with all other agents by buying or selling the resource on an economic market. In order to do so, the agent communicates its latest bid (see below) to a so-called auctioneer and receives price updates from the auctioneer. Its own latest bid, together with the current price, determines the amount of power the agent is obliged to produce or consume. The auctioneer agent performs the price forming process.

The communication between device agents and an auctioneer is very limited. The only information that is exchanged between the agents and the auctioneer are bids. These bids express to what extent an agent is willing to pay for or receive a certain amount of power. As bids are constructed in a process of weighing the profits versus the costs, and thus are a projection of the utility function of the agent. As a response, the market clearing price is communicated to the agents who respond appropriately, i.e. start producing (consuming respectively), or wait for the next event to happen and adjust its bid. The electricity market will try to balance demand and supply, taking into account the bids of all agents (see Figure 1).

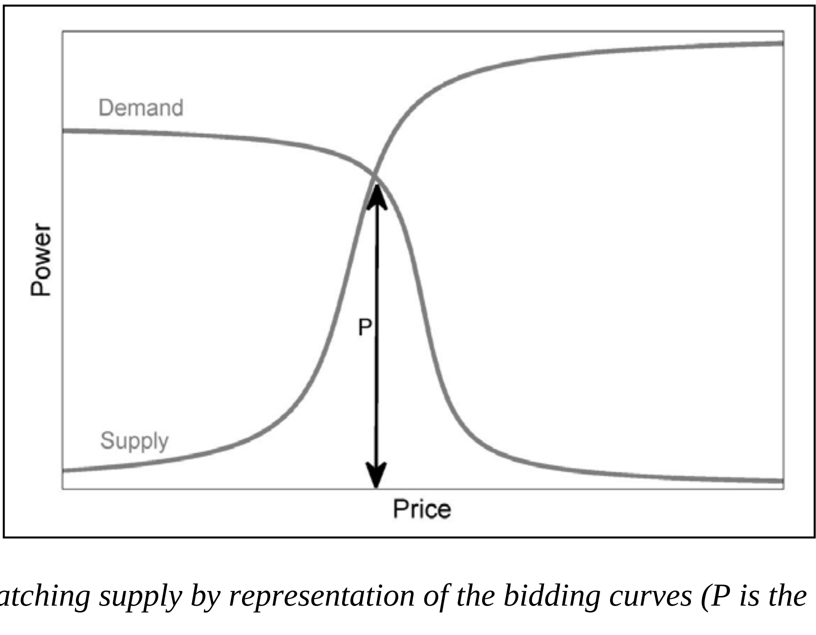

Figure 1 Matching supply by representation of the bidding curves (P is the exchanged power)

The auctioneer searches for the equilibrium price and communicates this price back whenever there is a significant change. The PowerMatcher system thus optimally uses the possibilities of power producing and consuming devices to alter their operation in order to increase the over-all match between supply and demand real-time. It has been shown that a PowerMatcher cluster acts very well as a virtual power plant control [3].

The same concept can also be used for coordination of heat flows. Huberman & Clearwater [4] have claimed success with a multi-agent system for the climate control of large buildings with many office rooms. Based on their work, Ygge & Akkermans [5] proposed an alternative market design which was formulated as a quasi equation: “local information + market communication = global control”.

Before describing our test case, some general remarks must be made. A major difference between the electricity and heat market is the need of scheduling. Where electricity is almost immediately available, with heat there is time delay due to the heat capacity of the building and the installations. Although this is not discussed in this study, one of our goals is to find a design which incorporates a solution to this problem. This study describes the design and the results of a simplified multi-agent climate control system which preserves the energy balance of an aquifer connected to a heat pump by exploiting the PowerMatcher to trade two or more commodities [6]. Further, the share of energy generated by renewables is increased, and inherently the energy efficiency of the building does as well. The bidding strategies of the agents are explained and it is shown that delivering energy for the comfort need of the users of the building is possible, while preserving the energy balance. The possibility of a free cooling air conditioning unit is exploited and satisfies the goal of returning to energy balance again.

The importance of an aquifer energy balance

The expectations of heat pumps with respect to smarter heating of buildings are quite high nowadays. Assuming a coefficient of performance (CoP) of 4, their heating efficiency will reach 180-185% [7] levels. Heat pumps can be configured in various ways. Air-source heat pumps using outdoor air are possible as well as different kinds of ground source related heat pumps. As the temperature of the ground is 11 °C, the ground is theoretically a better place for a heat pump to grab its heat than the air, which in midwinter may be 10 or 15 °C colder than the ground. This is because heat pumps work less efficiently when there is a big difference between indoor temperature and the temperature of an external source. As ground is not a very good thermal conductor, when sucking heat from the ground it is at the risk of the formation of ice. In the Netherlands, there is an alternative because in most places groundwater, which has better thermal conductivity, is available as a source of heat or cold. When winter heat is released into the building, cold is transported to the cold well of groundwater as part of the aquifer. During summer, the flow is reversed and heat is transported to the heat well of the aquifer. For the aquifer, in this study, both wells are insulated by a clay layer. It is possible to pump the ground water of the aquifer through the heat exchanger system without turning the heat pump on, this is called free cooling. Free cooling is another possibility to cool a building yet attractive as it has a large CoP of almost 10 [8].

The flow of groundwater in the Netherlands typically is about 1 m/year. So heat or cold that is released is likely to stay at or near the wells. Imbalance may result in a gradual increase or decrease of well temperature in the aquifer. An increase of temperature would imply a decline in the opportunity to operate the system in free cooling mode, resulting in bad performance. Within the Flexergy project context [9] it was observed that the demand for cold in a building, representative for the Netherlands, exceeds the demand for heat. As cold is supplied by a heat pump connected to an aquifer, a temperature raise of the aquifer may be expected and was actually observed, deteriorating the reliability of future cold demand. The need for control of the aquifer energy balance was stressed and multi-agent climate control was suggested. The opportunity of increased usage of cold outdoor air with the air conditioning unit was suggested as well to gain efficiency and flexibility within the system.

Figure 2 Representative building used for this study and schematic drawing of aquifer

Figure 2 presents the building configuration[2] and Table 1 contains the suppliers for heat and cold of an actual building at Utrecht. The heat pump is designed as the main supplier. District heating should only be used as a backup for days when the power needed (heat demand) is larger than the heat supplied by the heat pump. The air conditioning unit, located on the roof, offers the opportunity to load cold at hours when the outdoor temperature is still low, whereas there is also a cooling demand of the building.

	Main supplier	**Backup**	**Flexible**
Heat	Heat pump 60 kW	District heating 60 kW	
Cold	Heat pump 60 kW + free cooling power		Air conditioning unit < 20 kW

Table 1. Suppliers for the energy of the building

The building demand data may secure whether solely heat or cold is demanded respectively. In the left part of figure 3, allocation for heat takes place; in the right part allocation for cold takes place. The technical design of the building will in near future incorporate a bypass from the air-conditioning unit to the heat pump, enabling the possibility of loading cool outdoor air without warm air entering the building. This offers the opportunity to load cold during the night when the outdoor temperature is low. Such operation is, of course, at the expense of the energy efficiency of the building, as electricity is consumed by the pumping devices.

[2] The drawing is used with courtesy to Kropman Installation Company and drawing of the aquifer with courtesy to Installect Company

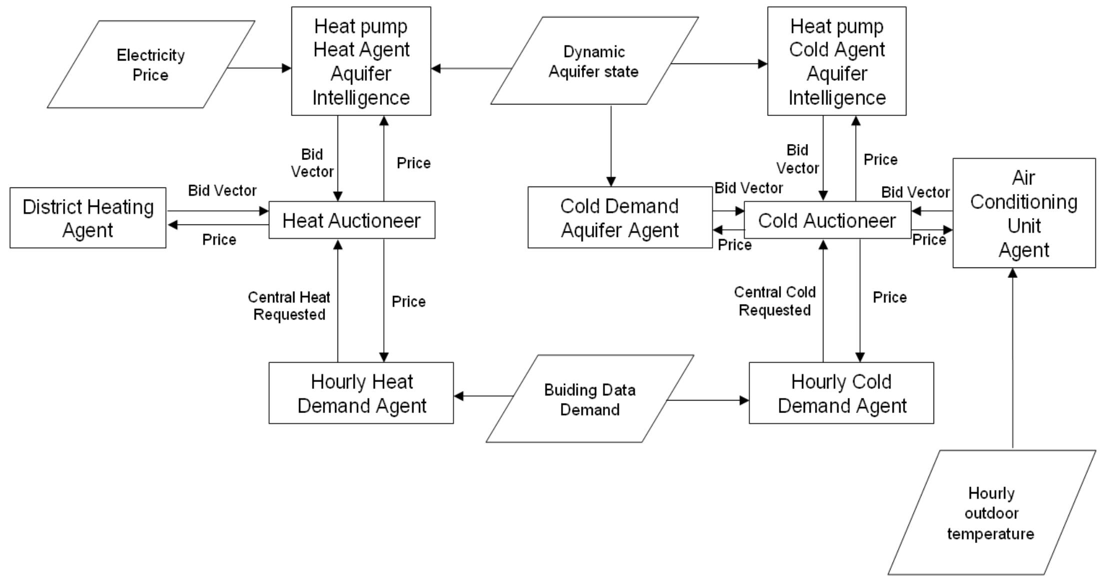

Figure 3 Design of a energy balance study for an aquifer using two commodities

Design

The design for this energy balance study is shown in Figure 3. Two types of building blocks are visible, the rectangular one representing an agent and the parallelogram representing input data. Two types of agents are present, auctioneers and agents representing a device or (user) demand. Between the agents the communication is simply confined to a bid vector containing bids, stating how much power is requested or supplied for each price within a certain price range, sent to the auctioneer and market price downward to the agent. In figure 3, the bid vectors from the hourly heat/cold agents are already translated to Central Heat/Cold Requested, for convenience. Generally, information from the input data is transferred towards the agents as shown by a single headed arrow. In the next sections, the design will further be elucidated.

Two electronic markets for commodities heat and cold

In the design, discrimination can be made between the left part in figure 2, where the trading for the heat demand of the building occurs, and the right part in figure 2, where the trading of the cold demand occurs. Therefore, there are two electronic markets and hence two separate PowerMatcher networks for two commodities: heat and cold, which are simultaneously trading. As can be seen, the “District heating agent”, “Heatpump Heat agent”, “Heat auctioneer” and “Hourly Heat demand agent” balance their supply and demand by trading heat.

Building data

Central in the design, is the building data. This contains the heat and cold demand of the building which is inferred from the raw building data of 2008. Figure 4 depicts the heat and cold hourly demand which is representative for the building. In the simulation, it is obliged that exactly this amount of energy is delivered, to realise user comfort as the employers of this building actually worked here under conditions with a certain required comfort level. Also, the sine function shown was fitted to this data and used to define the utility of the heat pump.

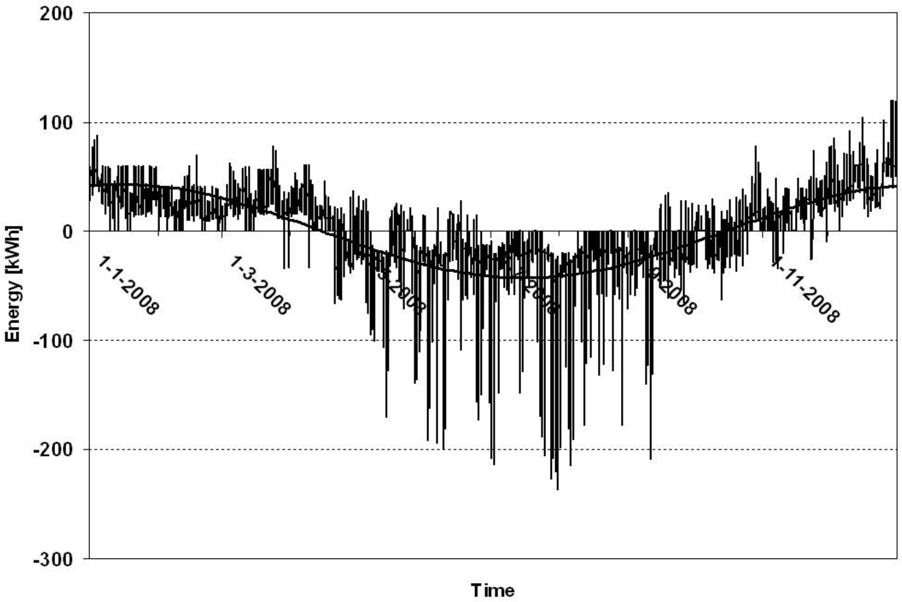

Figure 4 Heat (positive values) and cold (negative values) demand of the building used for this study. Also a sine is shown which is fitted to the building data by least squares method.

Aquifer

As already stated, a parallelogram in Figure 3 represents input data. However, an exception is the “Dynamic Aquifer state” which is also offers an output. Here, the heat pump agents can write the amount of energy they have consumed (heat) or have loaded (cold). The data in the “Building Data demand” is able to secure whether there is only heat or cold demanded, thus preventing the conflicting state where both the “Heatpump Cold agent” and the “Heatpump Heat agent” offer energy. However, the design offers the possibility to have heat and cold demand as well. This is assured by including the current (and former) state telling whether it is used for cooling or heating to the dynamic aquifer state. By inspecting the value of this state the agent can determine whether it is permitted to offer the resource.

Demand Agents

The “Hourly Cold demand agent” for the cold commodity and the “Hourly Heat demand agent” for the heat commodity are agents which accept any price for their consumption. Optimisation is provided by the market mechanism as the supplier offering power at the lowest price is still preferred. So for heat, either the “District Heating agent” or the “Heatpump Heat agent” will supply. When the aquifer has a shortage of cold, the “Heatpump Heat agent” is eager to deliver and the agent has to adjust its bid finally resulting in a price that is just below the price of the “District Heating agent”.

Supply of cold to the building and the aquifer

An interesting part of the design is in the network for the cold commodity. The heat pump can offer cold depending on the state of the aquifer. With the knowledge of historic data in the “Dynamic Aquifer state”, it can calculate how much power at each price can be offered, depending on the season and the expected price developments. The “Air conditioning Unit Agent” can offer cold only when the outdoor temperature is low; at low prices. This occurs mainly in the spring and autumn during early morning hours. The aim, of course, is to cool the building with outdoor air, avoiding further heating of the aquifer.

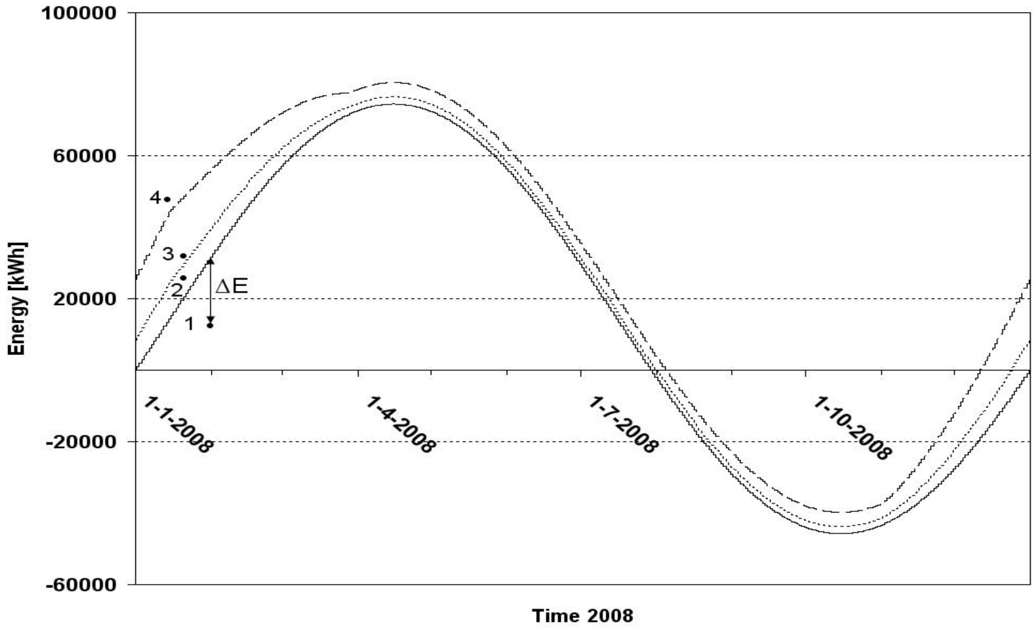

Figure 5 Energy balance curve of the aquifer inferred from the building data as shown by the solid line. Two more curves, constructed from certain design perspectives as explained in the text, are shown and are used by the agents to base their bidding upon

Another way for the aquifer to retain its heat balance is introduced by an extra agent called "Cold Demand Aquifer Agent". Outside working hours, depending on the state of the aquifer the agent may demand cold. Especially during the night when outdoor temperatures are low there is good opportunity to load cold to the aquifer. Of course this is only possible when the building has no heat demand. Results based on this agent are not available yet and will be published later.

Two heat pump agents

There are two agents controlling the same device, the heat pump. The question may rise, why are two agents being used to represent a heat pump? The only reason for this is a limitation of the PowerMatcher software. It is currently not technically possible for an agent to register and perform biddings on two markets. A software update to enable this capability is pending.

Strategy implemented in bid curves of devices

Each agent representing a device which can deliver cold or heat has a certain bidding strategy. The bidding strategy of the heat pump agents is based on maximizing the utility of the heat pump and taking into account the marginal costs; i.e. the electricity price. The electricity price in this study is considered to be constant, resulting in static marginal costs.

To determine the utility of the heat pump, a sine function was fitted to the building data as shown in Figure 4. This sine contains the average values of energy requested by the building during one hour, denoted by n. The energy for each hour denoted by E_n was used to calculate the energy of utility Eu_n represented by the solid curve in figure 5, where $Eu_n = E_1 + E_2 + \dots + E_{n-1} + E_n$. This solid line represents the expected state of the aquifer. Note that at the end of the year, for this line, the content of the aquifer has returned to its original value. To maximize the utility of the heat pump the expected state is used as a guide for the agents of the heat pump. If they follow this curve enough close, than at the end of the year the chance is likely that the energy content of the aquifer has returned to its original value and balance is preserved. To support this further, a model has been designed, in which two more curves were added, as is shown in figure 5. They mark certain energy areas in time with an associated bidding strategy. The shape of these curves was tested and after some optimization

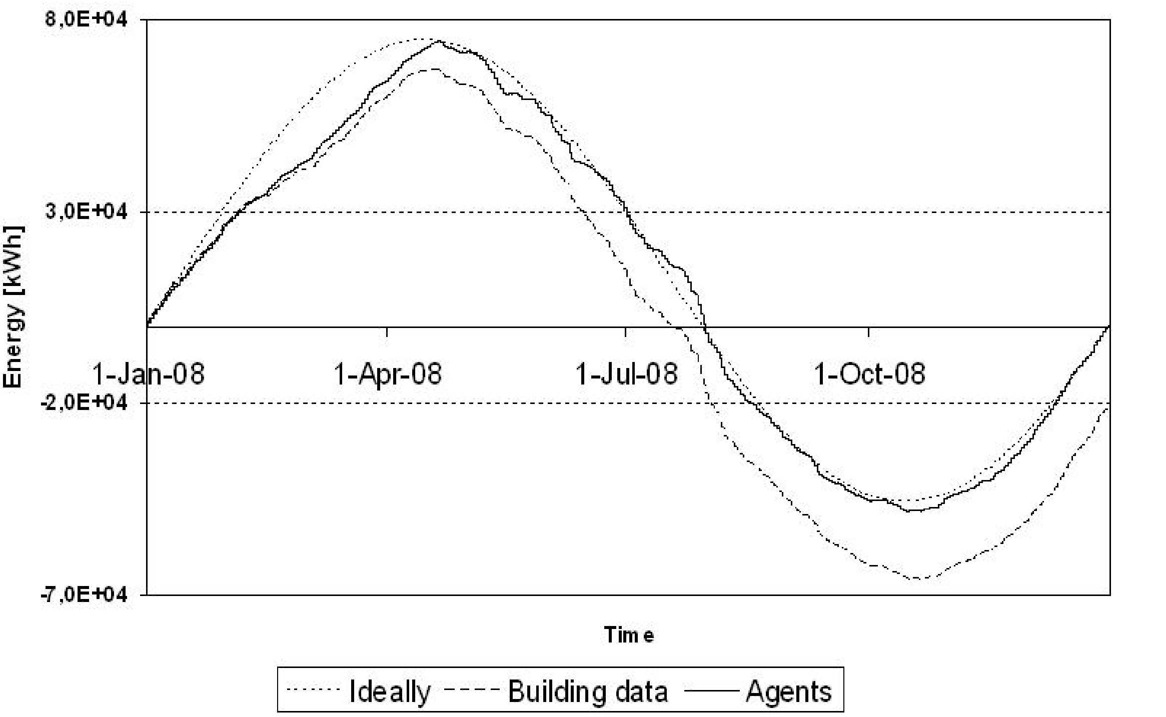

Figure 6 Aquifer energy balance curves for a building with actual data and simulated with agents.

the one that proved to be most successful in preserving the balance was chosen. However, further improvement of the curves and their associated bidding is still possible.

When heat is offered and the current state of the aquifer is below the solid curve (situation 1) the heat pump is eager to pay for production of cold. However, in situation 2, although there is enough cold in the aquifer, heat is offered at a low price because a shortage of cold may be expected. In situation 3, heat is offered at higher prices proportional to the energy deviation of the corresponding value to the solid curve (ΔE). In situation 4, above the dashed line, heat is only offered at the highest price. When offering cold the bidding process of the heat pump is in principle identical, but based on a reverse kind of reasoning.

In this study, the expected state of the aquifer is based on data from 2008. Depending on the weather each year and a shift or variation of internal loads, this state will change. To comply with this, the expected state will continuously be updated with recent values. For domestic heating, as the price of energy is constant throughout the whole year, the bidding curve is chosen to be constant, offering no power at relatively low prices and 60 KW at higher prices.

However, for the air conditioning unit, the energy flow is characterized by a mass flow and a temperature. As the mass flow is constant in this study, the output can be expressed in the outdoor temperature T_{out}, since $Q = \alpha \cdot m \cdot c_p \cdot (T_{out} - T_b)$, where Q is power, m is mass flow, c_p is the heat capacity of air, T_b is the temperature of the building and α is a factor <1 accounting for incomplete mixing of outdoor with indoor air. For the purpose of energy efficient cooling, it is required that cooling power was only offered when $T_b - T_{out} > 5$ °C, with increasing willingness to pay at larger temperature differences.

Results

Figure 6 shows the results of a simulation preserving the energy balance of an aquifer with agents for the year 2008. Three curves are shown. The dotted curve which has the shape of a sine is the ideal balance curve which the agents should follow quite closely to have a yearly balance. The dashed line displays the balance curve which is derived from the actual building data. The normal

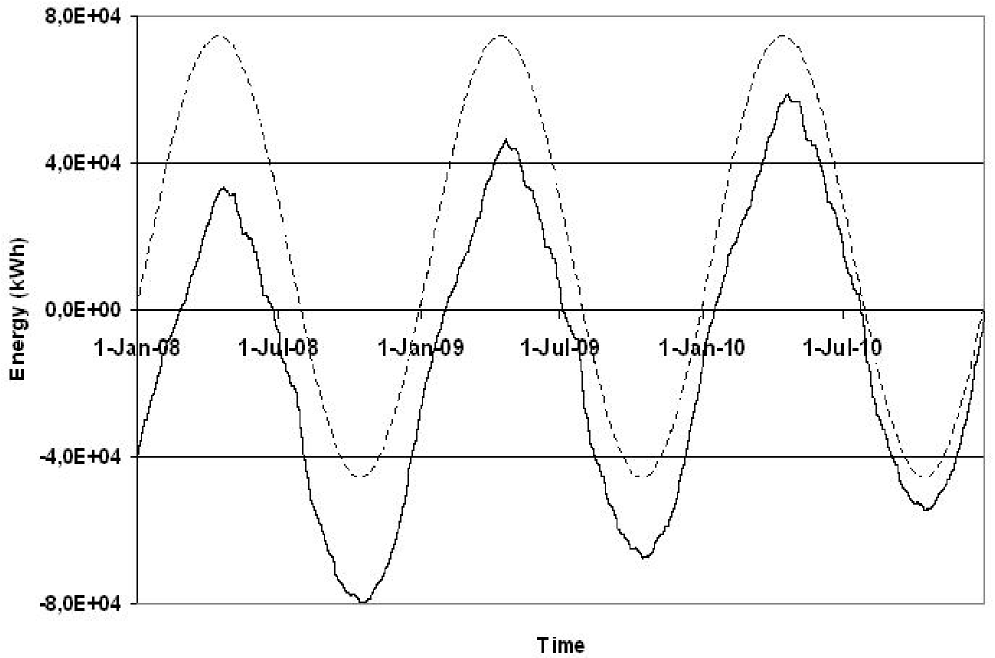

Figure 7 Aquifer energy balance starting with a cold shortage of -40 MWh

curve shows the resulting curve obtained using agent technology. At the end of the year, for the building data, there is a cold shortage of -20 MWh, while with agents there is only a small cold excess of 0.7 MWh. This result was somewhat surprising, as it was expected that the air conditioning unit would not provide enough cold for retaining the balance. Therefore, it was decided to study the agent behaviour starting with an energy unbalance. Values for the unbalance were chosen to be 20 MWh, -20 MWh and -40 MWh. The results of the latter, starting with a rather large cold shortage, are shown in Figure 7. It proves that the agents are capable of retaining energy balance again within 3 years. To perform this study, the same meteorological data was used for 2009 and 2010 as 2008. When starting with -20 MWh the balance was retained within 1.5 years. When starting with 20 MWh the balance returned within a half year. Here it was observed that domestic heating was turned on more often, avoiding cold to be loaded to the aquifer, enabling a swifter return to balance.

To understand why the balance was so easily retained in Figure 6, Figure 8 displays the cumulative power of district heating. As can be seen, there is a large difference of power supplied by district heating in an the actual building as compared to agent simulation. Where power was supplied for the actual building from half February till June, the agents show that no domestic heating was necessary for supplying heat for the comfort of the user. In fact 16 MWh less heat was applied, benefiting the aquifer balance, as only 4 MWh had to be delivered by the air conditioning unit. The air conditioning was able to supply cold with rather small amounts of energy mainly at spring and autumn, as was expected.

Discussion

As Figure 6 and Figure 8 show it is possible to obtain energy balance for the aquifer by simply optimizing the use of district heating. Only a small amount of energy is required from the air conditioning unit, in fact a little more than necessary as there is an excess of 0.7 MWh at the end of the year. The conventional centralized building control system failed to achieve energy balance. Perhaps such a system may be improved for this situation, however one must keep in mind that the task of a future centralized building system will become increasingly difficult due to the enrollment of more renewable energy devices such as sun boilers, sun blinds and heat/cold storage units. Using multi-agents due to its scalability further initiation of such devices will hardly be hampered.

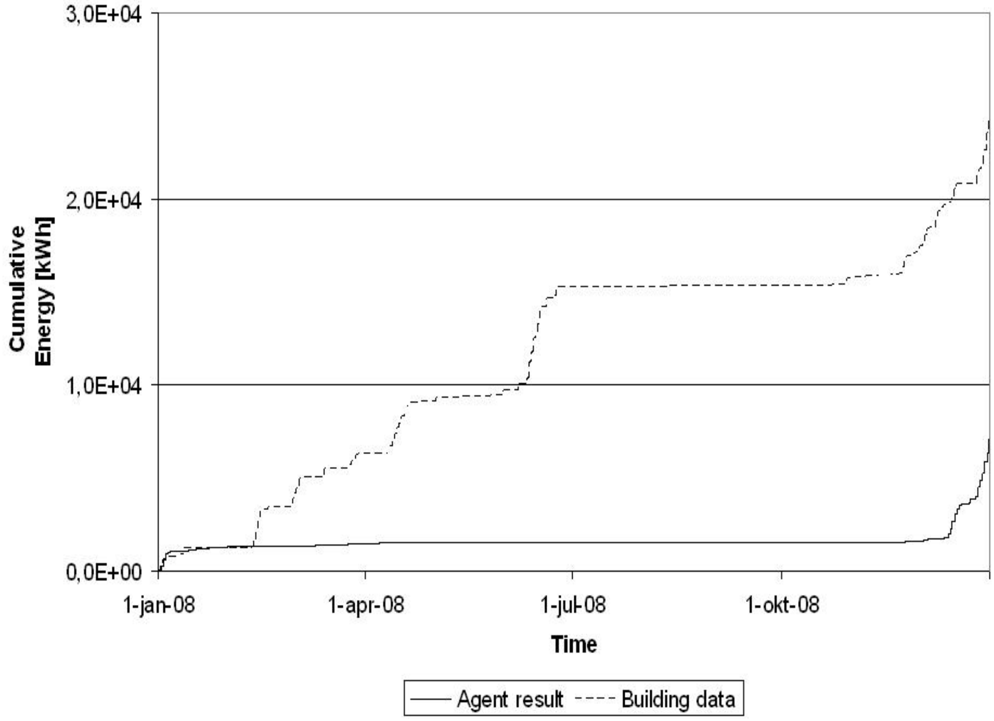

Figure 8 Power supply by district heating inferred from the actual building data and with agents

Even when starting with an energy unbalance, regardless of whether there is a shortage or excess of cold, the multi-agent system performs as expected; within a certain time balance returns. Under these conditions still the amount of heat or cold is supplied to the building for user comfort. An error analysis was performed checking differences between the demanded and supplied heat. On average each hour 0.2% too much heat, so about 0.1 of 60 kW was supplied more than demanded. This is not considered to be a problem, as for an actual building, the system will correct itself, in other words the demand will decrease when too much heat is supplied.

It was discovered that during this year the heat and cold demand of the building were equal. In fact, this year, although warmer than average, was the coldest since 2000 [8]. So indeed, during the former years of operation a larger cold rather than heat demand may have occurred as mentioned by the building operators.

When comparing the power supplied by the air conditioning unit and the district heating for each of the three scenarios, it is evident that the amount of supplied heat or cold depends on the unbalance which differs for each starting condition. In case the aquifer has an excess of cold, the air conditioning unit supplies only little energy and district heating supplies a lot of energy, avoiding the aquifer to load cold. When the aquifer has a shortage of cold then the air conditioning unit supplies more energy and district heating supplies less energy than when compared to the former situation.

It was investigated whether the share of energy generated by renewable energy sources increased as well. For heat, as can be seen in figure 9, the energy supplied by district heating is reduced from 24.3 to 7.3 MWh, so this leads to 70% decrease of fuel derived resources. An 8.5% increase of share of heat from renewable sources (the heat pump) was observed. For cold also an improvement of efficiency can also be inferred. As free cooling with outdoor air occurred and the COP of the air conditioning supply at temperature differences of approximately 8 °C ranges from 5-10 [8] which is better than the COP of about 3.5 for a heat pump for cold, an increase of efficiency is accomplished.

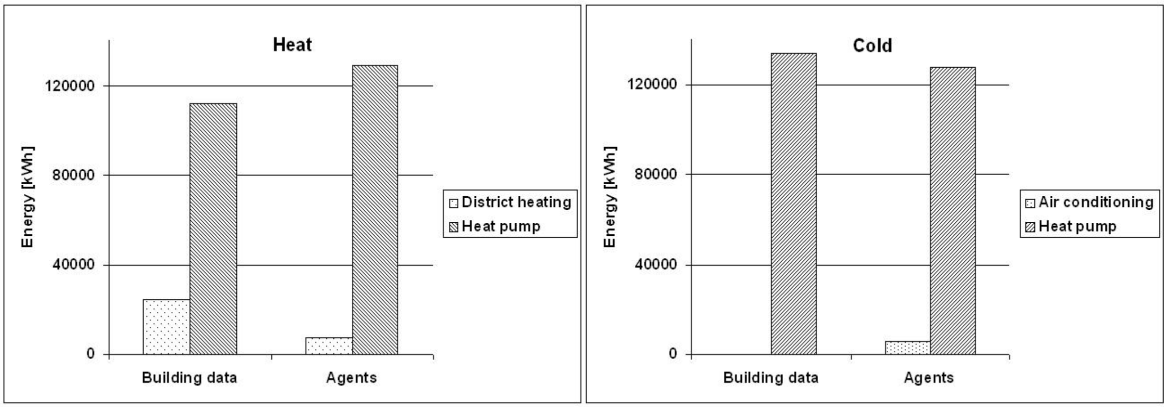

Figure 9 Amounts of energy for heat and cold delivered by energy suppliers as obtained from building data and from simulation with agents

Conclusions

In 2008, the climate building system of the building used for this study was not able to preserve the energy balance of an aquifer. More cold was supplied by the aquifer to the building than heat. The results of this simulation study suggest that a well designed multi-agent system can preserve the balance, while supplying exactly the amount of heat or cold that the building demands for their users comfort.

This is achieved by using district heating on fewer occasions than actually occurred in the building. To test the reliability of the system, simulations were carried out starting with a certain energy unbalance. The results suggest that the cooling capability of the air conditioning unit is sufficient to preserve the balance even when more cooling power is demanded than heat, unlike in 2008 occurred. Meanwhile, the share of energy supplied by renewable energy devices has improved, as a 8.5% increase of use of heat supplied during winter by the aquifer is observed. During winter an efficiency increase due to free cooling with the air conditioning using cold outdoor air is expected as well.

Acknowledgements

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