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Purely Agent Based Control of Building Energy Supply Systems

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Abstract:

Poorly designed and badly working control systems in buildings are leading to a high waste of primary energy in the building sector. In literature many approaches use agent based control (ABC) in order to facilitate the configuration of these systems and thus reduce the error rate at commissioning processes. These approaches increase the energy efficiency of buildings without any additional installation efforts. Nevertheless, the implementation of software agents is thereby usually limited to small parts of the system such as data monitoring or room temperature control.

On the other hand, in the industrial sector there are already purely ABC architectures for large and complex processes. This means that no superordinate control level is needed. Thus, the advantages of ABC such as ability to plug & play of new components as well as self configuration of processes are used efficiently.

This paper describes an approach to apply a purely ABC for building energy supply systems. The control system needs no pre-configuration and can be set into action without commissioning efforts. Therefore, different components of the building supply system are equipped with decentralized software agents. Each agent has a virtual cost function in order to estimate the operational costs of its corresponding component. Each agent is independently responsible for the control of its component. The agents communicate with each other and evaluate which components have to be activated in order to reach the users' comfort conditions most efficiently.

The functionality of the approach is tested in a test bench in combination with simulated components. The test bench consists of a central air handling unit with both heating and cooling devices as well as four office rooms which can be supplied with heating and cooling energy. The system is extended with additional simulated heat supply units which are integrated into the test bench using the Hardware-In-The-Loop method.

In this paper, negotiation processes of different agents in order to evaluate the most cost efficient components are shown and described. Furthermore, it is shown, how the virtual simulated components are integrated into the test facility. First test results prove the basic functionality of the described system.

Keywords:

Building Automation System, Agent Based Control, Test Bench, Hardware-In-The-Loop, JADE

1. Introduction

In the European union, 40% of the total energy consumption is used in buildings [1]. In order to reach the political goal of reducing greenhouse gas emissions by at least 20% until 2020 referring to 1990, increasing the energy efficiency of buildings, residential as well as non-residential, is considered to be one of the most cost efficient opportunities [2].

Energy consumption of buildings depends on the building structure and the components used for heating, cooling and ventilation [3]. On the other hand, control strategies and algorithms of the building supply systems largely influence the efficiency of the systems. In many buildings, these building management systems (BMS) are very poorly designed or implemented. In Europe, up to 50% of the energy used for building purposes could be spared by the use of appropriate BMS [4]. Thus the improvement of BMS provides a huge potential for increasing the energy efficiency of buildings at low investment costs.

The main difficulty regarding the commissioning of BMS is the adaption of the control system to the real building including the building supply system as well as the users' needs. In most buildings, this adaption is rarely done in order to save costs at the commissioning process [5]. Thus, an approach, which guarantees an automated and self-learning commissioning process could help to improve buildings' energy efficiency at a large scale. The use of purely agent based control (ABC) systems appears to be a promising technology to meet these requirements.

In literature examples are known to use ABC in buildings. However, the implementation of software agents is thereby usually limited to small parts of the system such as data monitoring or temperature control optimization [6–8].

In the industrial sector there are already purely ABC architectures for large and complex processes. That means that no superordinate control level is needed. Thus, the advantages of ABC such as ability to plug & play of new components as well as self configuration of processes are used efficiently [9, 10].

This paper describes an approach, how a purely and holistic agent based control system for buildings can be designed. The functionality of this approach is shown in a test bench in combination with simulated components.

2. Design of an ABC for buildings

In the industrial automation standard, an agent is defined as "an encapsulated (hardware/software) entity with specified objectives. An Agent aims to reach these objectives through its autonomous behaviour, in interacting with its environment and with other Agents. (…) A multi-Agent system (MAS) consists of a set of Agents interacting to fulfil one or more tasks." [11]

Using this principle, components of building supply systems can be equipped with such decentralized software entities. Thus, the whole building control structure can be based on such entities. In the following, an approach is described, how such a system can be designed and how it works.

2.1. Basic structure and cost functions

In order to implement a purely agent based control system, each entity or component of the building supply system has to be assigned to a software agent. Agents are basically decentralized control units. They have to be able to communicate and negotiate with each other in order to find the best operation condition at any point in time. There have to be negotiation standards which allow every single agent and thus every single component to be integrated into the system. In our approach, we are using the operating cost of the components in order to establish such a negotiation standard. Each agent is able to estimate the operation costs of its assigned components. The agents are therefore able to determine the most cost efficient component to meet the current heating or cooling demand.

In our system, we are using two types of agents: consumer agents and supply agents. The single components are aggregated to operational entities. Each entity is assigned to at least one agent.

Consumer agents recognize heating or cooling demand of their corresponding building entities (e.g. office rooms) and estimate the required heating or cooling power in order to fulfill the current demand. Furthermore, they have to provide control signals for activation and deactivation of supply units.

Supply agents are designed to estimate the operating costs of the corresponding supply units using individual cost functions of these units. In our system, the cost functions are calculated in (€/h) and describe the estimated change of operating costs needed for adapting heating or cooling power.

The cost functions include supply costs (ΔC_sup) for heating, cooling or electrical power, startup costs ($\Delta C\_startup$) and maintenance costs (ΔC_main). The different parts of the cost functions can be either constant (e.g. ΔC_main) or can for their part be functions contingently provided by another agent of a different providing level (e.g. ΔC_sup) [12]. The cost functions are calculated as equation (1).

$$\Delta C\_comp = \Delta C\_sup + \Delta C\_startup + \Delta C\_main \qquad (1)$$

In addition to the mere cost functions, the supply agents have to know about their power adaption range. That means they have to know about their ability to either provide negative power for cooling or reduction of heating and positive power for heating or reduction of cooling. All supply agents are designed totally similar for both heating and cooling components. The only difference between them is the structure of the cost functions.

As an example, Fig. 1 shows the cost function of the CHP unit ΔC_CHP at two different operation points. The cost functions describe, what additional costs or savings would occur, if the heating power output of the CHP changes. The costs thereby depend on the current operation status. If the CHP is already in operation, the supply agent can offer an increase of power (with a positive price) or a decrease of power (with a negative price). If the CHP is switched off at that moment, only an increase of power is possible.

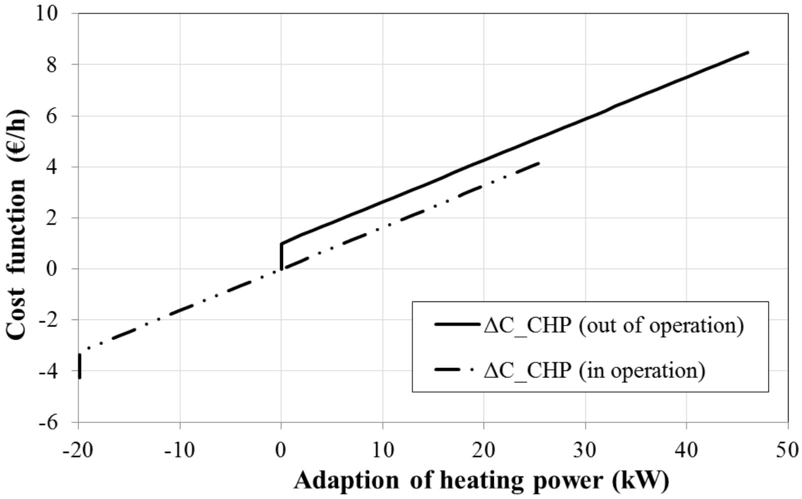


Fig. 1 Cost function of CHP unit [12]

The estimation of the cost function of the CHP also includes the current electrical price. At some other point in time with a different electrical price, the cost function changes. A price forecast is not yet included.

2.2. Negotiation process

Supply and consumer agents communicate with each other. They negotiate in order to determine the most cost efficient entity or component (or combination of entities and components) to fulfil the thermal request of the building.

If a consumer agent detects a thermal demand (adapting of heating or cooling power), the negotiation process starts. First, the affected consumer agent sends a request message to all supply agents whose components are connected to the consumer agent's entity. The called supply agents estimate their cost functions, calculate the power adaption ranges of their assigned components and pass the information to the requesting consumer agent. The consumer agent then decides according to his own estimation of power demand, which supply agents are called to activate (or deactivate) their supply unit. Fig. 2 shows an example of the negotiation process for a heating request.

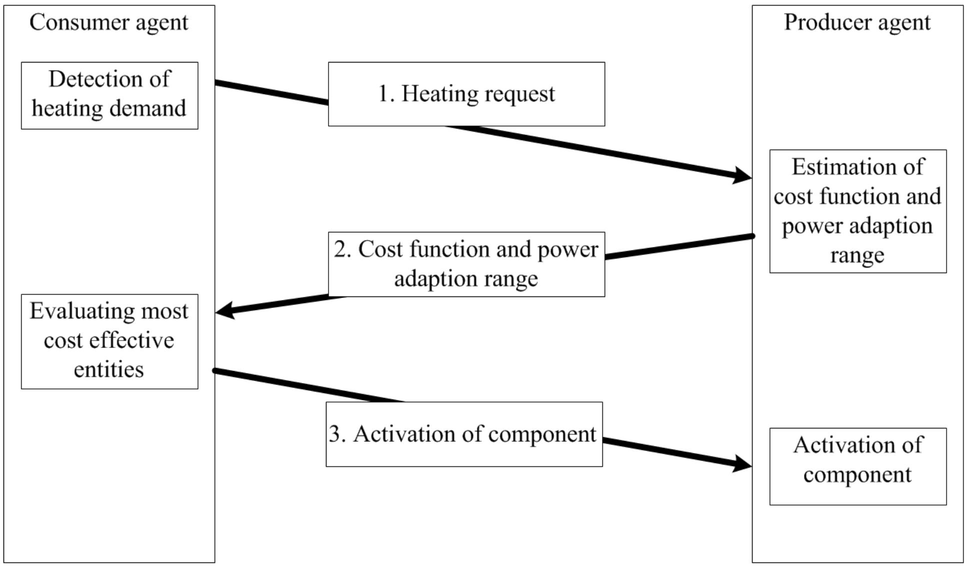


Fig. 2 Example of negotiation process of the ABC system

If the component of the supply agent for its part also needs to be supplied from other components (for example a heating circuit), the agent of this component acts also as consumer agent and sends a request to the supply agents of a superior level. The obtained cost functions from the agent of the superior level are then integrated into the cost function of the first agent. Thus, the result is a cascaded arrangement of agents, which can theoretically be used for the control of even very small entities of the building supply system.

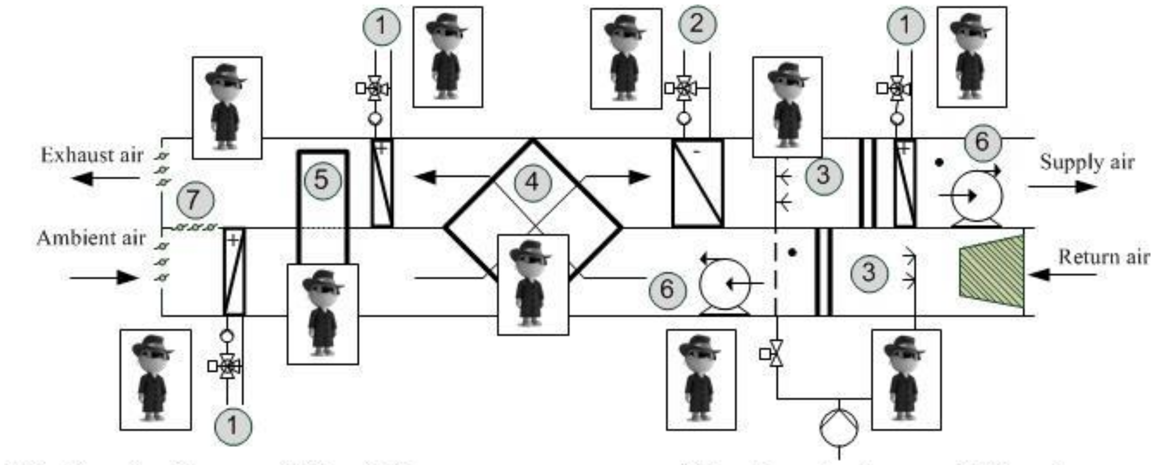
In our test, the agents are programmed using the platform JADE [13]. For practical reasons, the agents are hosted by a central server. Nevertheless, they are acting independently and each agent only gets direct information about his assigned component. Thus, the agents are acting as they would be placed on decentralized units and could be deployed on multiple machines.

3. The test bench

The test bench consists of a HVAC system (heating, ventilation, air conditioning) with both heating and cooling devices as well as four office rooms which can be supplied with heating and cooling energy. The system is extended with additional simulated supply units which are integrated into the test bench using Hardware-In-The-Loop method.

3.1. HVAC-System

The HVAC system used for the experiments (shown in Fig. 3) consists of several components. Heat exchanger with connection to heating (1) and cooling circuits (2), two humidifiers (3) as well as a cross-flow heat recovery unit (4) and sorption wheel (5) can be used for the adaption of the air temperature. The volume flow of the air can be controlled via two speed adaptive fans (6). An adaptive air valve (7) is used for controlling circulation air.



1 Heating circuit
2 Cooling circuit
3 Humidifier
4 Cross-flow heat recovery
5 Sorption wheel
6 Fan
7 Air valves

Fig. 3 Basic scheme of the HVAC system

Each component is assigned to a software agent which controls the corresponding component. The whole HVAC system itself is also assigned to an agent. If heating or cooling is required from the HVAC agent, the agents of the different components are estimating their cost functions including costs for their own consumption (e.g. heating costs, electricity costs etc.) necessary to meet this requirement. The HVAC agent then decides which components are activated or deactivated.

In this paper, we present a proof of this concept regarding the negotiation process of the heating circuit.

3.2. Heat supply as Hardware-In-The-Loop test bench

The heat supply of the test bench is provided by district heating. In order to enlarge the variety of test scenarios, the test bench is extended by a virtual heat supply system. Therefore, a simulation setup of different heat supply units has been created. The physical behavior of these components is simulated in Dymola/Modelica [14, 15]. The internal control structure of the virtual components as well as the combined system is simulated in Simulink [16].

For our paper, we use a heat supply system consisting of a combination of combined heat and power plant (CHP), heat pump, solar thermal system and condensing gas boiler. A thermal hot water storage tank ensures the decoupling of generation and consumption. Fig. 4 shows the hydraulic setup of the simulated heat supply system.

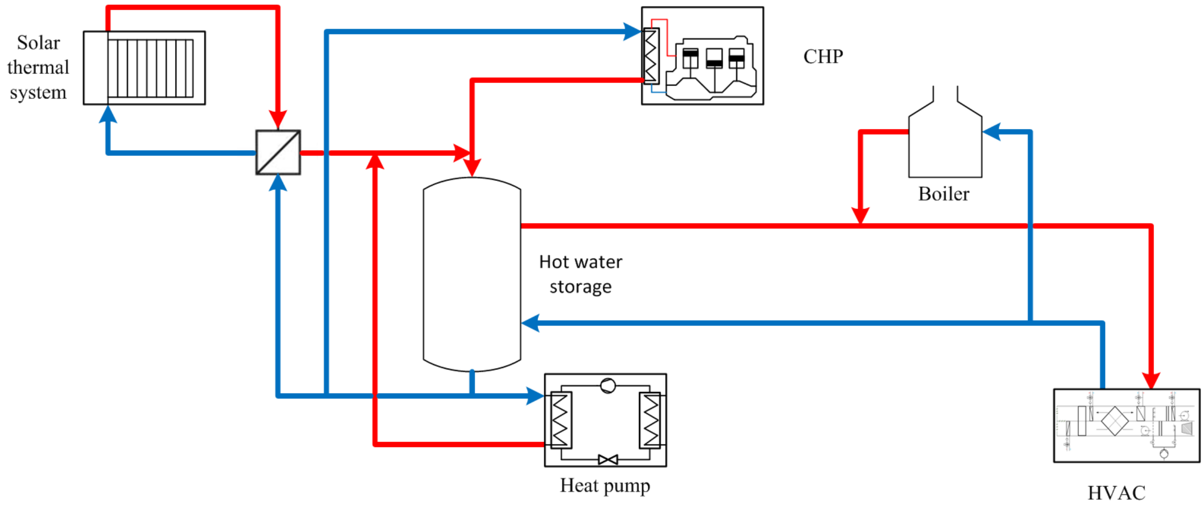


Fig. 4 Hydraulic setup of the simulated heat supply system

The simulation performs in real time and is interconnected to the HVAC test bench as well as to the MAS-software in a Hardware-In-The-Loop system. The measured values of the return temperature as well as the volume flow rate of the HVAC heating circuit are used as constraints for the simulation. The flow temperature of the simulation is used as a set point for the heating circuit of the HVAC system. The basic principle of the used Hardware-In-The-Loop system is shown in Fig. 5.

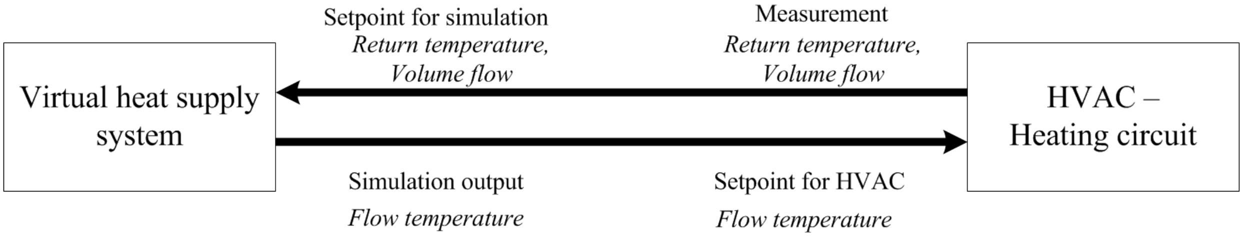


Fig. 5 Interconnection between test bench and virtual heat supply system

4. Experimental setup

In our test, a consumer agent is assigned to each of the four rooms. One of these room agents initialize the negotiation process. The HVAC-unit is represented by a bivalent agent providing both the functionalities of a consumer agent as well as of a supply agent. The HVAC supply agent reacts to requests by the room agents. On the other hand, the HVAC consumer agent requests heating and cooling from the internal HVAC-components. As one of these internal components, the agent of the heating circuit acts as consumer requesting heat from the agents of the heat supply system.

Each of the components of the heat supply system is assigned to a supply agent. As the thermal hot water storage tank can both consume and supply heating energy, it is assigned to a consumer agent as well. Fig. 6 shows an overview of the described agent structure of the experimental setup.

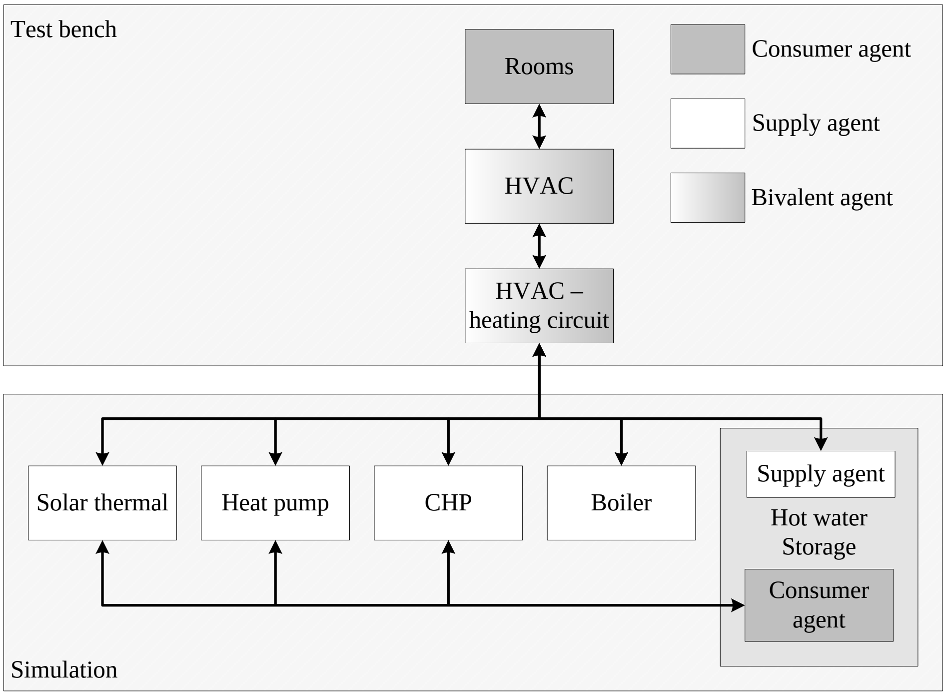


Fig. 6 Overview of the agent architecture of the experimental setup

5. Test results

The following results show a period of time of about half an hour during the test run. During this period, the agents are influencing the behavior of the system. It can be seen, how the test bench and the agents are working, how the cost functions are designed and used and how the agents are interconnected.

5.1 Interaction between test bench and simulation

The interaction between the test bench and the simulation setup has been tested with the described heating system. Therefore, the temperature control of the heating circuit has to control the flow temperaure according to the outlet temperature of the simulated heating system.

Fig. 7 shows the measured results of the test run. It can be seen, that the flow temperature of the HVAC-heating circuit T_HVAC_in approaches the outlet temperature of the simulation T_sim. The difference between both values results from the thermal inertia of the heating circuit as well as from non-optimal parameters of the corresponding termperature control. The measured return temperature of the heating circuit T_HVAC_out as well as the measured volume flow V_HVAC are used as constraints for the simulation of the heating supply system.

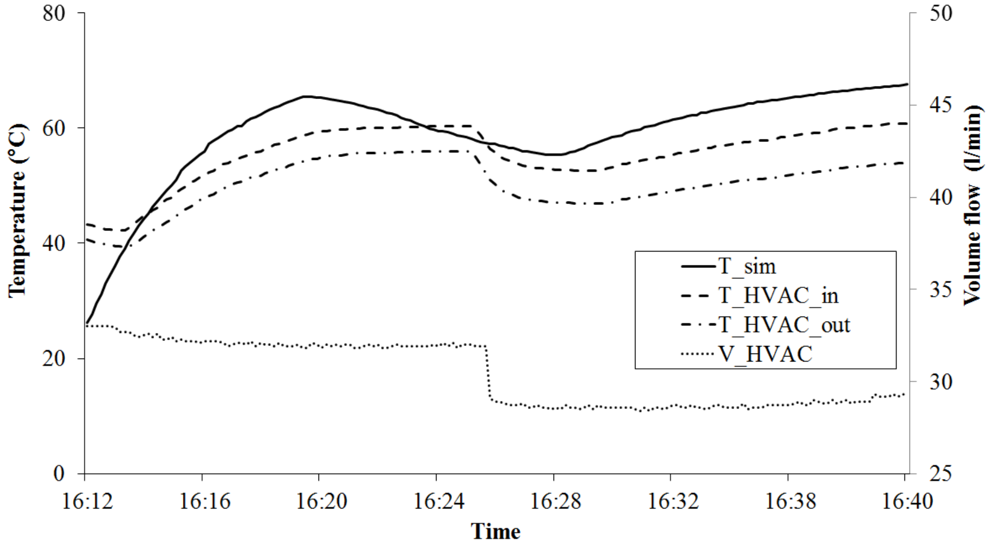


Fig. 7 Simulated and measured temperature and volume flow [12]

The plot shows, that the Hardware-In-The-Loop circuit is basically working as expected. The temperature gap between T_HVAC_in and T_sim is about 2 K at a level of 40 °C. We consider this gap as acceptable for a mere test of the negotiation process of the ABC system. Nevertheless this gap should be reduced by adapting the PID control parameters of the corresponding heating circuit.

5.2 Behavior of the agent based control system

The test of the agent based control system is initialized by a heating request of one of the test rooms. Receiving this request, the HVAC-agents gather the cost functions of the different supply agents including those from the heating circuits. The heating circuit agents for their part send a request to the supply agents of the simulated heating supply system. In this paper we show the results of the negotiation process between the agents of the heating components.

At the beginning of the measured interval (Fig. 8), the CHP unit is running at full load. The heating power of the CHP $\dot{Q}\_CHP$ is at its maximum level (150 kW). Due to temperature restriction, the CHP is switched off at 16:20. Triggered by a positive required heating power $\Delta\dot{Q}\_Req$, a negotiation process starts. The result of this process is the activation of the heat pump and a subsequent increase of the corresponding heating power $\dot{Q}\_HP$ at 16:24. After the activation of the heat pump $\Delta\dot{Q}\_Req$ is slowly decreasing as the heating demand is met by the heat pump. As the actual heat consumption of the HVAC-unit differs from the estimated value, $\Delta\dot{Q}\_Req$ does not decrease to zero.

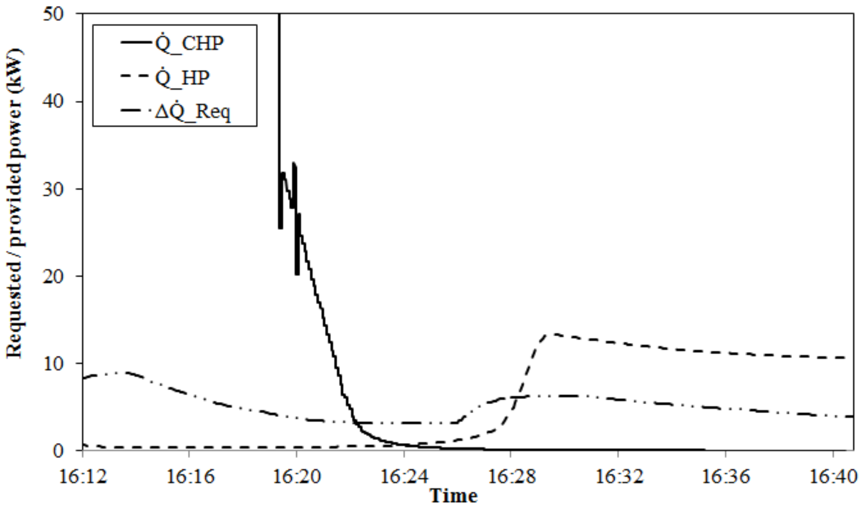


Fig. 8 Heating power of different heat suppliers of the simulated supply system

At 16:28, another negotiation process takes place since $\Delta\dot{Q}\_Req$ is still above zero. The details of this negotiation process can be seen in Fig. 9. This figure shows the cost functions of all corresponding supply agents at that point in time. It can be seen, that the heat pump agent provides the lowest costs $\Delta C\_HP\_\Delta\dot{Q}$ for a possible power adaption of up to 15 kW. Since the heat pump is already operationg with a power of 2 kW, the heat pump agent also offers a negative power adaption (for a negative price).

The costs of the CHP unit $\Delta C\_CHP\_\Delta\dot{Q}$ as well as the costs of the condensing boiler $\Delta C\_Boi\_\Delta\dot{Q}$ exceed the costs of the heat pump. Furthermore, $\Delta\dot{Q}\_Req$ is 6 kW and therefore less than the maximum power adaption range of the heat pump. Thus, only the heat pump is activated.

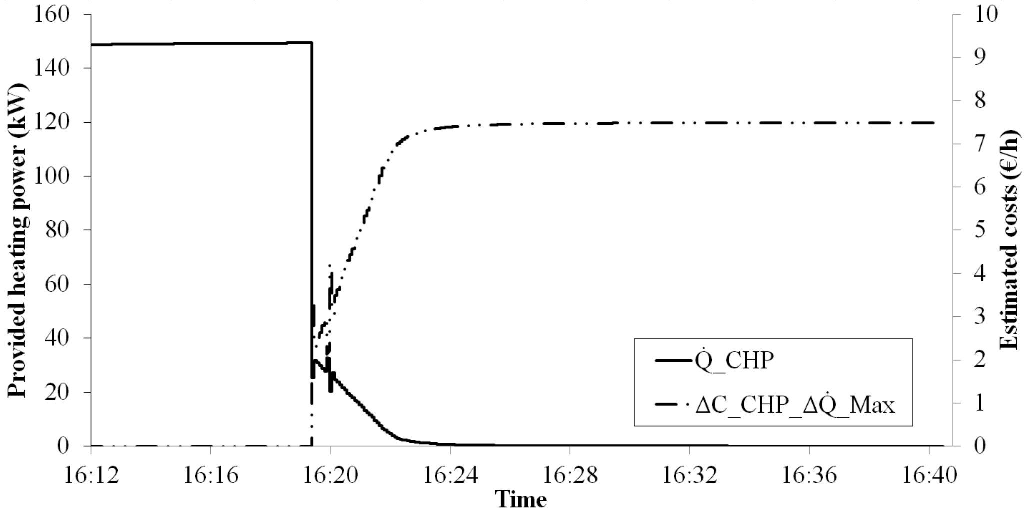


Fig. 9 Cost functions for different heat sources at 16:28

In addition to the cost functions of the active components, the corresponding function of the supply agent of the hot water $\Delta C\_TSto\_\Delta\dot{Q}$ can be seen. Since no energy is stored, the storage can only work as a heat sink at this time. Thus it can provide a negative power adaption. Thereby, the cost function reveals a negative price level with an amount smaller than the amount of the cheapest supply unit. Thus the storage agent does not influence the system.

5.3 Cost function of supply agents

The cost functions are crucial to the ABC system. Since no other control mechanisms are implemented, all control mechanisms of the system have to be achieved by the configuration of the MAS ontology and the design of the agents' cost functions.

The cost functions therefore describe the current estimation of additional costs of an agent's entity for adapting the power output. Fig. 10 shows the costs of the CHP unit for supplying its maximum heating power $\Delta C\_CHP\_\Delta\dot{Q}\_Max$ during the test run. At the beginning of the test, the CHP is already running at maximum power ($\dot{Q}\_CHP$ = 150 kW). The additional costs to reach the maximum heating power are therefore 0 €/h. While the heating power of the CHP is decreasing, the maximum power adaption of the CHP and thereby the estimated costs for achieving the maximum power is increasing.

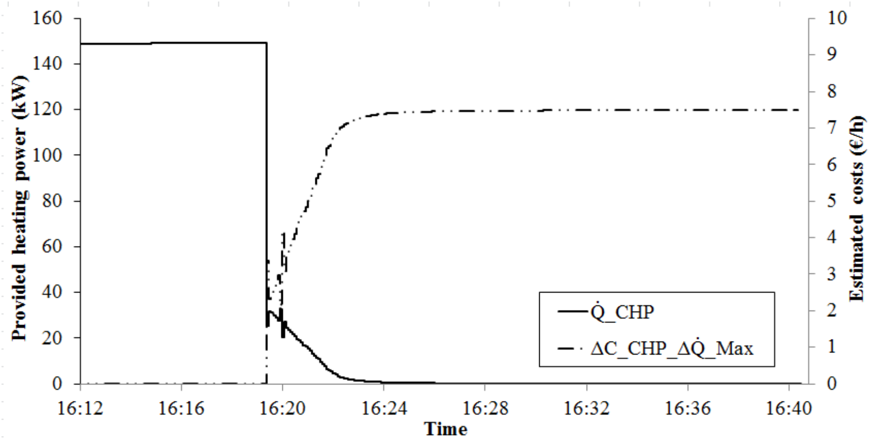


Fig. 10 Cost function as subject to heating power [12]

The plot shows how the current operating point of a component influences the corresponding cost function. As a result, the control decisions of the operating consumers also depend on the current operating conditions of the system.

6. Conclusions

The test results show that the basic setup of the agent based control system is working. The use of cost functions as a basis for the negotiation process allows the agents to detect the most efficient component at any time.

The test bench and the virtual extension using a simulated heat supply system are interacting well. The interface between these two tools ensures the interoperability. Thus the agent based control system can be tested in both surroundings simultaneously.

Future research will have to improve the cost functions in order to approximate the real system costs.

Another big challenge is the assignment of agents to the components. The agents have to know, which component or entity they are responsible for and which other agents are assigned to the corresponding supply components. In our test, this information has been implemented into the agents' database. In future systems, the agents should be able to acquire this information autonomously.

Nomenclature

Letter symbols

ΔC	cost adaption (€/h)
$\Delta\dot{Q}$	power adaption (kW)
$\dot{Q}$	heating power (kW)
T	temperature (°C)
V	volume flow (l/min)

Subscripts and superscripts

Boi	boiler
comp	component
CHP	combined heat and power unit
HP	heat pump
HVAC	heating, ventilation, and air conditioning
In	inlet
main	maintenance
Out	outlet
TSto	thermal storage
sup	supply
Req	required
startup	start up

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