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CONTROL AND INFORMATICS

Testing of a price-based system for power balancing on real-life HVAC installation in real life

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Abstract. HVAC systems use a substantial part of the whole energy usage of buildings. The optimizing of their operation can greatly affect the power use of a building, making them an interesting subject when trying to save energy. However, this should not affect the comfort of the people inside. Many approaches aim to optimize the operation of the heating and cooling system; in this paper, we present an approach to steer the heat pumps to reduce energy usage while aiming to maintain a certain level of comfort. For this purpose, we employ a market-based distributed method for power-balancing. To maintain the comfort level, the market-based distributed system assigns each device a cost-curve, parametrized with the current temperature of the room. This allows the cost to reflect the urgency of the HVAC operation. This approach was tested in a real-world environment: we use 10 heat pumps responsible for temperature control in 10 comparable-sized rooms. The test was performed for 3 months in summer. We limited the total peak power, and the algorithm balanced the consumption of the heat pumps with the available supply. The experiments showed that the system successfully managed to operate within the limit (lowering peak usage), and - to a certain point – reduce the cost without significantly deteriorating the working conditions of the occupants of the rooms. This test allowed us to estimate the minimal peak power requirement for the tested set-up that will still keep the room temperatures in or close to comfortable levels. The experiments show that a fully distributed market-based approach with parametrized cost functions can be used to limit peak usage while maintaining temperatures.

Key words: distributed management; heat pump; HVAC; power management; waterloop.

1. INTRODUCTION

The power systems in Europe are challenged by the changes in technology and society, to mention a few: the overall power consumption is increasing, the increasing share of clean energy, and the general public is more aware of climate change. All of this creates a need, but also a possibility, to implement a new technological solution to save and balance power [1]. This paper describes real tests of a distributed management system that aims to lower the peak power usage of a heating, ventilation, and air conditioning (HVAC) system and limit the cost of power with a minimal change in thermal comfort. The system adopts a general market-based distributed method that can be applied for different devices in various systems.

There is a lot of research focussing on the HVAC system as they are using approximately 50% of the total building energy usage [2]. There is room for improvement because in many old buildings the systems are ineffective and very simplistically controlled without considering the energy effectiveness. Simple on/off systems can be upgraded to use more flexible managing and, what is especially promising, predictive control [2]. What is more, heating, and cooling technologies are very varied, current trends show great potential when using combined heat and power sources that can provide multiple functions to the building owners and control algorithms are implemented [3].

There are multiple management systems for HVAC systems in development with different aims and optimisation objectives, the most frequent are: energy saving, cost saving, peak load shifting capability, transient response improvement, steady-state response improvement, reduction in fluctuations from a set-point, coefficient of performance improvements, indoor air quality and thermal comfort improvement [2]. Another way to categorise the management approaches is by considering the amount of data processed: more data potentially gives better results but at the cost of long computation time and higher power usage of the control system itself. The most basic management is on/off control, mainly combined with the fixed schedule of operation; slightly more advanced systems respond to the sensor reading and react based on the defined thresholds that define the operation point of devices. The big leap in management quality is the introduction of forecasting of the conditions and the ability to pre-emptively act based on the predicted states and self-learned models of the thermal parameters. The most advanced systems use additional information from different sources or human input that can create a unique combination of parameters for the given building or space and include all types of devices, heat/cold sources, and thermal storage.

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In [2] the authors compare a simulated household with various versions of a management system and without such a system. Even considering the scenario with only switching on and off devices without further steering of their operation points, the power savings can reach up to 10% while at the same time lowering the peak usage and diminishing the carbon footprint.

The main limitation in installing advanced management systems is the cost/performance ratio and, given the high cost of installation and management of advanced control systems, the preference goes to simpler and cheaper solutions that fulfil the legal minimal requirements for the building.

At present, centralised optimisation systems that operate based on the forecast of usage and (if applicable) production [4] are fairly popular. Those systems can for example gather information from the production of solar panels and use this power to overcool the rooms a bit more than necessary, in such a way that less cooling is needed during peak power usage moments. Those systems are capable to calculate optimal behaviour for short, defined time frames (usually from 15 minutes to an hour) on a day ahead or hours ahead. Such systems, however, have some disadvantages that forced the development of different solutions. First of all, a system with central data processing must gather reliable data which requires connecting the whole system to one core installation. It might be costly and technically difficult, considering the possible renovations and changes to the building itself. Furthermore, connecting all controlled units is error-prone and hinders possibilities to easily integrate new controllable devices in the future.

As an alternative, distributed control systems are proposed, for example by defining zones that are to some level independent. The controller of a zone needs limited information about the current settings in other zones but has autonomy in its own zone. A problem appears when the controllers of the distributed system must use some common resource, for example, electricity, which can be limited for some reason. There then must be some kind of negotiation protocol or central unit that takes care of the limitations imposed. Such a problem can be solved through many different algorithmic methods, like optimisation, game theory approaches, market strategies, etc. The work [5] demonstrates that both centralized and distributed systems can be equally efficient when carefully designed algorithms are used.

In [6] an agent approach is used, but more important is the underlying market mechanism to motivate for power usage shifting. The authors show that it is an adequate approach and that many interesting market effects can be observed.

In this article, a method presented in [7] is considered; it is a distributed power management system that requires limited computation power and has a deterministic behaviour. The system has been implemented in Python as an open, general, and scalable solution. The method was integrated with the real-life environment in the KEZO Research Centre. KEZO is located in Jabłonna near Warsaw, Poland. The distributed management has been applied for a subset of heat pumps [8, 9], all being part of a waterloop installation, and the experiment has allowed us to observe the behaviour of the management system to assess its prospects while revealing possible issues that should be resolved in future work.

The next section presents details about the test setup and configuration of the equipment, it also presents short characteristics of the research centre building. Section 3 presents in more detail the algorithms used for heat pumps management and the cost functions that were implemented to manage the waterloop system. Section 4 presents the behaviour of the system under management and the obtained reduction of costs. The last section concludes the article.

2. CONFIGURATION AND SETUP

The test was conducted on real equipment in KEZO Research Centre in Jabłonna, which is an operating research facility belonging to the Institute of Fluid Flow Machinery of the Polish Academy of Sciences. It was built to be the main research laboratory for renewable energy conversion and distributed energy systems [10]. The research centre has 3 buildings: L5, B1, and B2. L5 is the administration building which has conference rooms and offices; buildings B1 and B2 are mainly laboratories. Mayekawa-HWW-2HTC, a trans critical CO_2 heat pump, is the main heat and cold source for the buildings. The waterloop is installed in buildings B1 (10 heat pumps) and B2 (13 heat pumps), building L5 is equipped only with fan coils. The heat pumps have different peak power, there are three types: 1 kW, 2 kW, and 2.2 kW, and their operation is limited to 3 states: switched off, standby, and operation during which the device is heating or cooling the room. The power usage in standby mode ranges from 80 to 150 W depending on the pump and in operation time there is a 10% change in power usage depending on the temperatures in the waterloop. The heat pumps are connected to PLC units which communicate measurements and steering commands using Modbus TCP to a computer that is used as the main steering unit. There are two air temperature sensors for each pump – one by the pump in the ceiling and another one at the lower height – both are sending data to heat pumps. The sensors are 10k Ohm thermocouples. Unfortunately, the producer does not give further information about their accuracy. The frequency of reading data is 1 minute. The schema of the individual buildings is presented in Fig. 1, the grey rooms are the ones with heat pumps installed. For the experiments a subset of the available heat pumps was used:

- 4 in building B1 (one on the sunny side of the building, and 3 on the north side of the building),
- 110 heat pumps in building B2 (6 for each of the rooms on the sunny side and 4 for each of the rooms on the north side of the building).

These rooms were chosen based on the following criteria: during the experiment no person can change the target temperature or heat pump setting in the room, the room does not contain equipment that might cause extensive heating up of the room and the room has no permanently open doors to any other room.

The baseline power usage was gathered from the 16th of April, the experiment was conducted from the 15th of May till

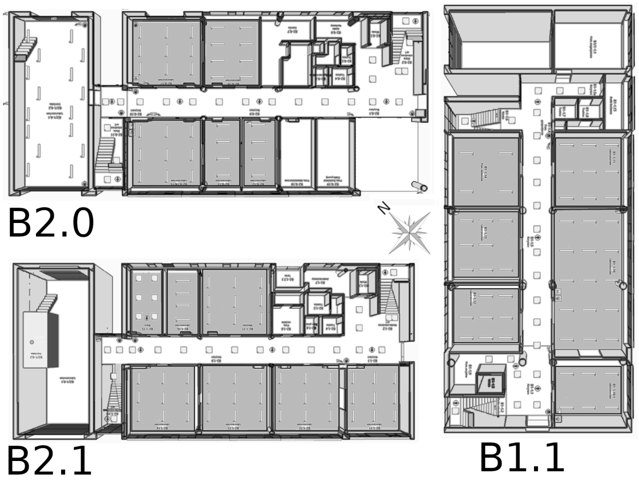

Fig. 1. Schema of the KEZO research centre with its three buildings and indicated rooms with waterloop installed

the beginning of August 2019 when there were long periods of very hot weather. As can be seen in Fig. 2, the highest outdoor temperatures were measured in June, with a couple of cooler days in July. Due to the high temperatures, none of the rooms required heating during the experiments, and hence none was provided by the heat pumps.

All the heat pumps had the same target temperature (20°C) and hysteresis (2°C). The heat pumps have three states: on, standby, and off. In the on-state, the heat pump supplies cool air to the room, in the standby state the pump circulates the air in the room but does not supply cool air. In the off state, the heat pump is completely off. The internal heat pump management system only allows it to switch between on and standby. This internal management system follows a simple logic: the heat pump starts cooling down the room when the temperature sensor senses a room temperature higher than 22°C (target temperature plus hysteresis). In the on-state, the temperature of the air exiting the heat pump varies between 10 and 15°C, depending on various factors that are not controlled in the experiment (e.g. temperatures in the waterloop). When the target temperature is reached, the heat pump switches to standby and continues to mix the air in the room. From the outside, the heat pump only appears to have the states on/standby (it decides by itself if cooling is needed) or off; we have no other means to control the temperatures. This in turn means that we can always force the heat pump not to use power (and thus limit overall power usage), but we cannot force it to cool down the room if temperatures are already in the comfort range. That restricts the possibility to regulate the power usage only in one direction – limiting the usage.

The implementation and testing of the system were divided into 3 main stages:

- First, the operation of the waterloop was validated without any external interference during two weeks in April. The aim was to observe how the setting of hysteresis influences the operation of the heat pump.
- Next, the power management with a simple polyline cost function that allows the cost to increase with the difference between the current and the target temperature.
- Finally, the system was tested with a modified cost function in order to check if a smooth cost function provides any benefits.

The problem with performing the test is the changeability of weather conditions, in particular temperature and irradiance. In order to mitigate this, the system was only run on alternating days: every other day, the power management system was active, thus every day alternating with the standard behaviour in which the pumps decide independently for themselves between on and standby. In July, the system used the polyline cost function, whereas in August the smooth cost function was tested. Hence, the other days can be used as a reference to quantify the performance improvements by the proposed control methodology.

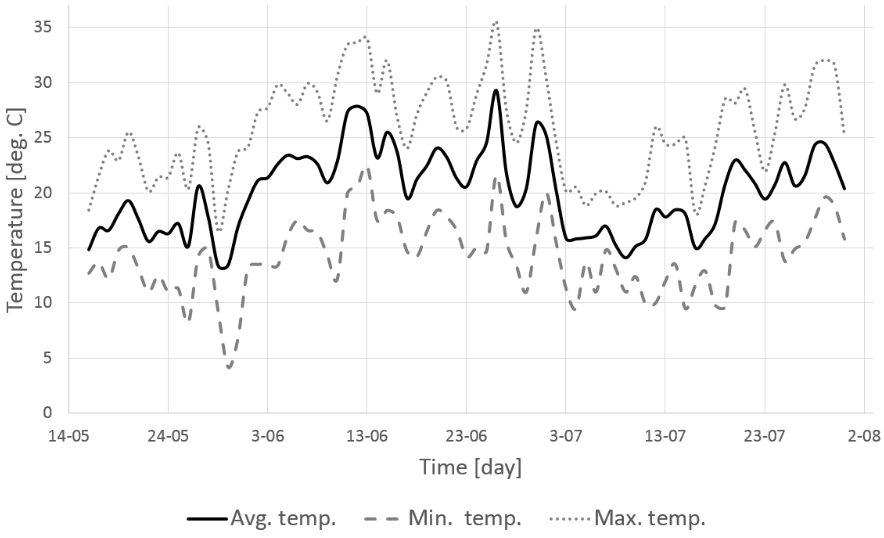

Fig. 2. Daily average, minimal and maximal temperatures during the experiment from 15th of May to 1st of August

3. ALGORITHM AND COST FUNCTIONS

The research aims to find a suitable method to manage the operation of the heat pumps in order to minimize energy usage without impacting the comfort of the users of the building. The requirements are that the algorithm cannot have big requirements for the computational power, it should be fast and scalable so it can be applied in e.g. households. Considering the existing requirements and equipment, the auction method and algorithm described in [7] are implemented.

The method is based on the double-side auction in which the aim is to fairly balance energy available on the market. The participants on the market are the device agents, which construct a cost function, and a controller (auctioneer) that gathers their bids from the devices. Based on the current supply and demand of power, the auctioneer establishes the market-clearing price. The clearing price is sent to all agents and subsequently changes the operation mode of the devices to satisfy the promised power usage for the given price. The auctioneer is an element that centralizes the calculations and must be placed on a secure server with access to all agents. The general, simplified schema of the algorithm is presented in Fig. 3. Cost functions define the priorities of devices in each operating point – Fig. 4 presents an example of 3 abstract devices with their cost functions: device 1 can gradually decrease its power usage depending on the given price; device 2 has 3 main states, in which it can use different amounts of power; device 3 is a simple switch on/off the device. In this example, if a supply of 110 W is assumed, the demand function maps this to a virtual price of approximately 0. At this price point, device 1 will operate a set-point close to 10 kW, device 2 will be on (100 W) and device 3 will be switched off.

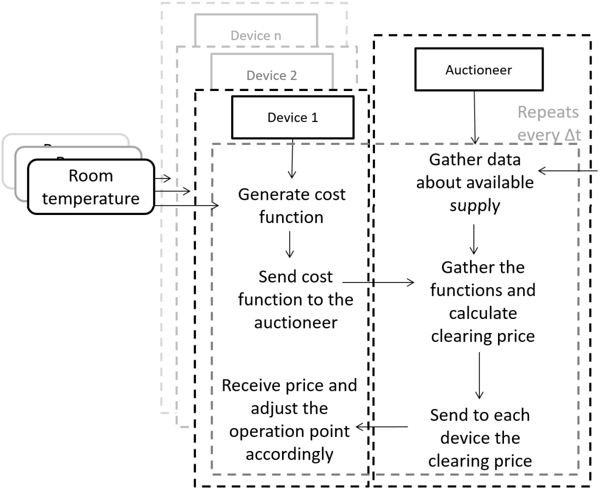

Fig. 3. The general schema of the algorithm

In the original algorithm described in [7], the cost functions were defined for each device before the start of the system and fixed during the operation. In our case of steering the heat pumps, the shape of a cost function is dependent on both room temperature and target temperature. The first function that was defined for the heat pumps is a very simple monotonic linear function given by (1), where T_r is the temperature of the room in °C, T_s is the required set temperature and h is hysteresis. Its parameters were chosen to distinguish between the comfort zone temperatures between 20–24°C (the shape of the function is presented in Fig. 5)

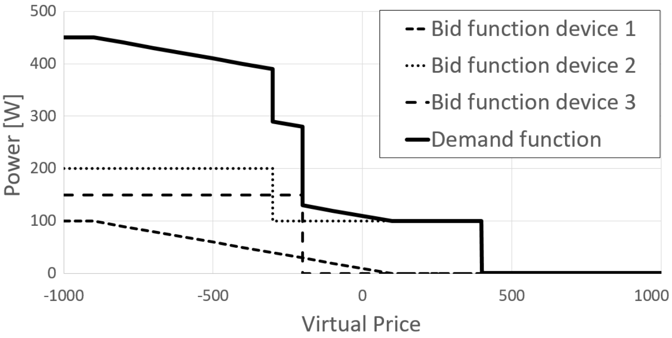

Fig. 4. Bid functions of devices and the overall demand function for the defined set of devices

$$X_1 = -1000 + 1999\left(\frac{T_r - T_s}{2h}\right). \tag{1}$$

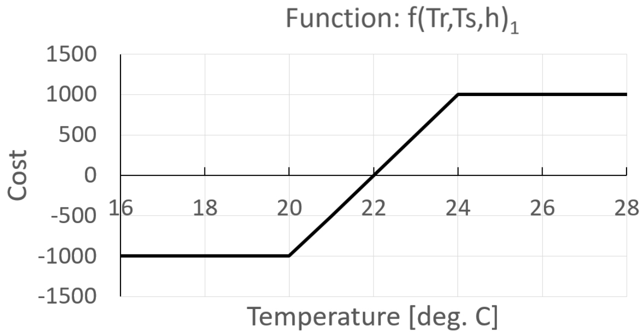

Fig. 5. Polyline cost function for heat pumps dependent from the room temperature and the settings of the pump. On the X-axis the temperature of the room is presented, Y-axis represents the cost

The second cost function used in the experiments is a smoothed version of function (1): a sigmoid function described by (2) (the shape of the function is presented in Fig. 6).

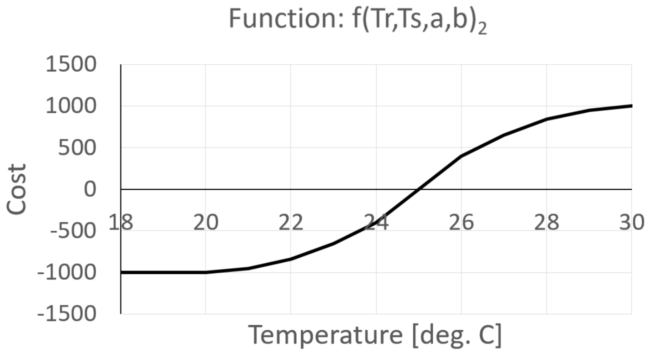

Fig. 6. Diagram of the sigmoid bid function, where on X-axis the temperature of the room is presented and the Y-axis

$a = 0.1$ and $b = 10$ are parameters defining the shape of the sigmoid function

$$X_2 = \begin{cases} 0, & T_r \le a, \\ 2\left(\dfrac{T_r - a}{b - a}\right)^2, & a \le T_r \le \dfrac{a+b}{2}, \\ 1 - 2\left(\dfrac{T_r - b}{b - a}\right)^2, & \dfrac{a+b}{2} \le T_r \le b, \\ 1, & T_r \ge b. \end{cases} \tag{2}$$

Making the cost function dependent on the temperature in the room is a mechanism to curtail the overall power consumption by all pumps. The system intends to balance the operation of the heat pumps under limited power. It is quite artificial in the research centre to impose a power limit, so it was opted to consider the real pricing tariff of power for the institute, and artificially limit the power available to the heat pumps at times when energy is more expensive. This also provided us with the possibility to compare the realistic cost-benefit of the system.

The research centre has a 3-zone tariff with the highest tariff between 16:00 and 20:00, a high tariff between 7:00 and 12:00, and a lower tariff the rest of the day. The system is defined such that it will not switch on the pumps during the high peak, whereas the total power available to the pumps in a lower peak is 50% of their total power; for the rest of the day, it is not limited. This means that at most half of the pumps will be able to switch on between 7:00 and 12:00. This configuration prevents the operation of pumps in the high peak and limits what they can take in the low peak. In Fig. 7 the prices, as well as the imposed power limit to the heat pumps, are illustrated.

For the experiments each pump had its own agent; the controller and agents were operating on the same computer connected to the devices using the TCP/IP Modbus protocol. The method and software allow for distributing the agents among different processing units, but due to the small scale of the example it was not necessary; neither hardware nor communication channels were a bottleneck. The heat pumps in the off-state use only minimal amounts of power necessary. The heat pumps in on mode use a couple of tens of Watts when in standby mode (not cooling) when the temperature sensor triggered the requirement to switch on the pump, they were using from 1 kW to 2.2 kW depending on the type of the pump (there were 3 types of heat pumps installed in the centre). The Modbus command to switch on the pump allowed it to work but this did not necessarily mean that the pump would switch on immediately and start cooling.

4. EXPERIMENTAL RESULTS

The aim of the work was, first, to check how the heat pumps would react to management with the distributed system, and then to evaluate the possibilities and methods to manage the operation of heat pumps to decrease the cost of the system operation.

Regarding the first goal, the implementation of the algorithm was successful, the time of response of the pump was around 5 seconds, which is probably connected with the frequency of reading signals via Modbus by the heat pumps. The time between switching on the pump and the pump starting to cool the room (if the conditions required that) took around 1 minute. Generally, it should be assumed that the minimal time between sending any signal to the heat pump should be 2 minutes. There were very few communication problems observed and the agents were operating correctly during the whole testing period.

There was no observable difference between the two proposed cost functions (multiline and sigmoid) for the operation of the heat pumps. It became clear that the relative difference between the functions is much more important than their shape.

During very hot days, the rooms were heating up very fast. Due to limited available power during the lower peak (between 7:00 and 12:00), the management system caused the heat pumps to switch on and off very frequently (the off signal was sent even 10 minutes after the switch-on signal). While this had the effect of balancing the operation of the pumps in the rooms, such frequent changes can reduce the lifetime of the devices or even contribute to their malfunctions. The reason for this behaviour was very frequent priority changes due to quickly raising temperatures in the rooms. During peak hours only half of the heat pumps are allowed to work to curtail the power usage, but if the temperature is very high all the heat pumps need to work, and all have a quite high value of their switching on price. The cost function is made in such a way that with a decrease of temperature the cost at which the pump stays on is falling rapidly. That allowed the pump to decrease the room temper-

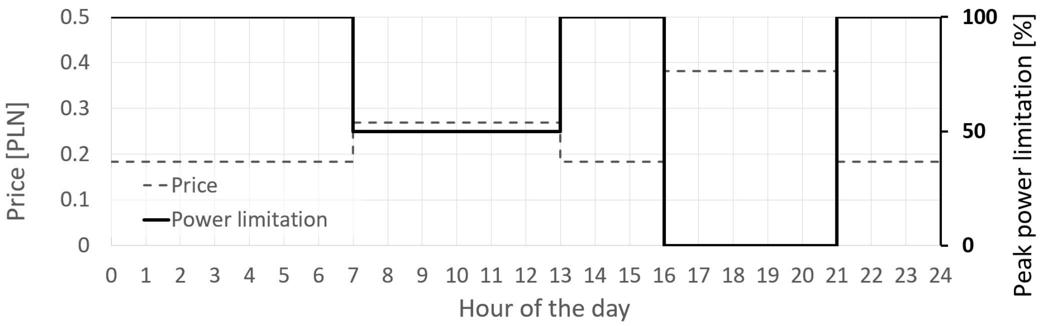

Fig. 7. The supply curve, which depends on the price of the energyduring a day

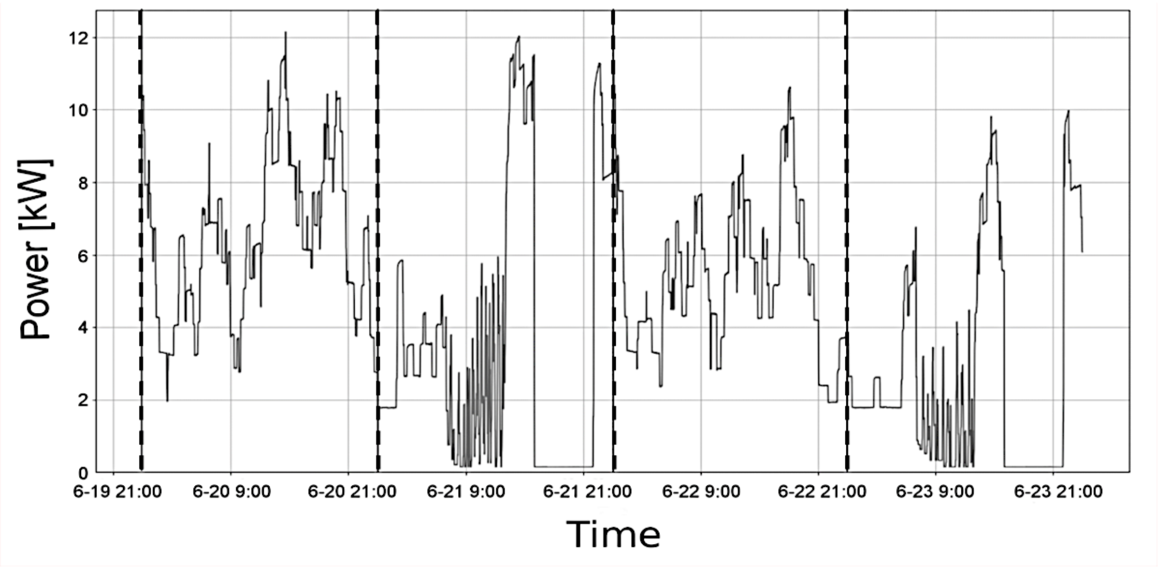

Fig. 8. The sum of power usage of all tested heat pumps in the waterloop

ature by just a few degrees before its operation cost become lower than that of the other (inactive) heat pumps. In Fig. 8, the behaviour of one heat pump is plotted; the behaviour is visible, the measurements were taken from the 19th of June when the outside temperature reached 30°C. The framed areas are days when the control system was in operation. During the morning peak the heat pump has a very short operation time and during the main peak, it is completely off.

Generally, if the overall power consumption is considered, the system managed to largely decrease the power usage during peak hours. Fig. 9 shows the power usage by all the managed pumps for four consecutive days: the first and third day without the control system, and the second and fourth with the control system. During the latter two days, the impact of the control system on the peak times is visible: during the low peak, there are frequent fluctuations in power but with a limit of the maximum power. The limit is expected as this is imposed by the system, frequent fluctuations are caused by the delays of switching on and off the pumps. Once the first peak period ends, more pumps are switching on as there is a big increase in power usage: this shows that they were starved for power and that the system successfully limited their usage. The second peak time is very visible as no power is used by the heat pumps, as imposed by the system.

The power usage was compared between days with and without the system, and the results are presented in Table 1 – depending on the location of the heat pump the power usage when the system was present decreased from 12 to 19% compared to days without the system.

Table 1
The energy used by the heat pumps during the tested period

Heat pump	With control system [Wh]	Without control system [Wh]	Difference [Wh]	%
B1_1_10.1	38260	46460	8200	17.65
B1_1_12	59890	69730	9840	14.11
B1_1_14	58500	67390	8890	13.19
B2_0_12	40940	46950	6010	12.80
B2_0_13	14810	17500	2690	15.37
B2_0_14	21280	26350	5070	19.24
B2_0_16	32010	36930	4920	13.32
B2_0_17	36000	42070	6070	14.43
B2_1_11	31360	37540	6180	16.46
B2_1_13	43230	48720	5490	11.27
B2_1_14	24340	30180	5840	19.35
B2_1_16	35340	42340	7000	16.53
B2_1_17	80570	98320	17750	18.05
Sum	**516530**	**610480**	**93950**	**15.39**

The system was operating according to tariffs, so we expected that the system would also decrease the cost of cooling the buildings. The cost of the waterloop operation was calculated, and the change in the cost for each heat pump is presented in Table 2. The experiment was done in a real environment, on real heat pumps. Energy saving for the whole building is a bit less than 94 kWh. Because the heat pumps worked less in the high peak times (when the tariff is the highest) and limited their operation in low peak time, the overall monetary cost of operation of the heat pumps is reduced. According to expectations, the overall cost has fallen by an average of 34%, which is a significant amount for such a small modification. The research centre that is used in the experiment has a large PV production that exceeds the usage during sunny days. The real cost of the research centre was different due to the high production

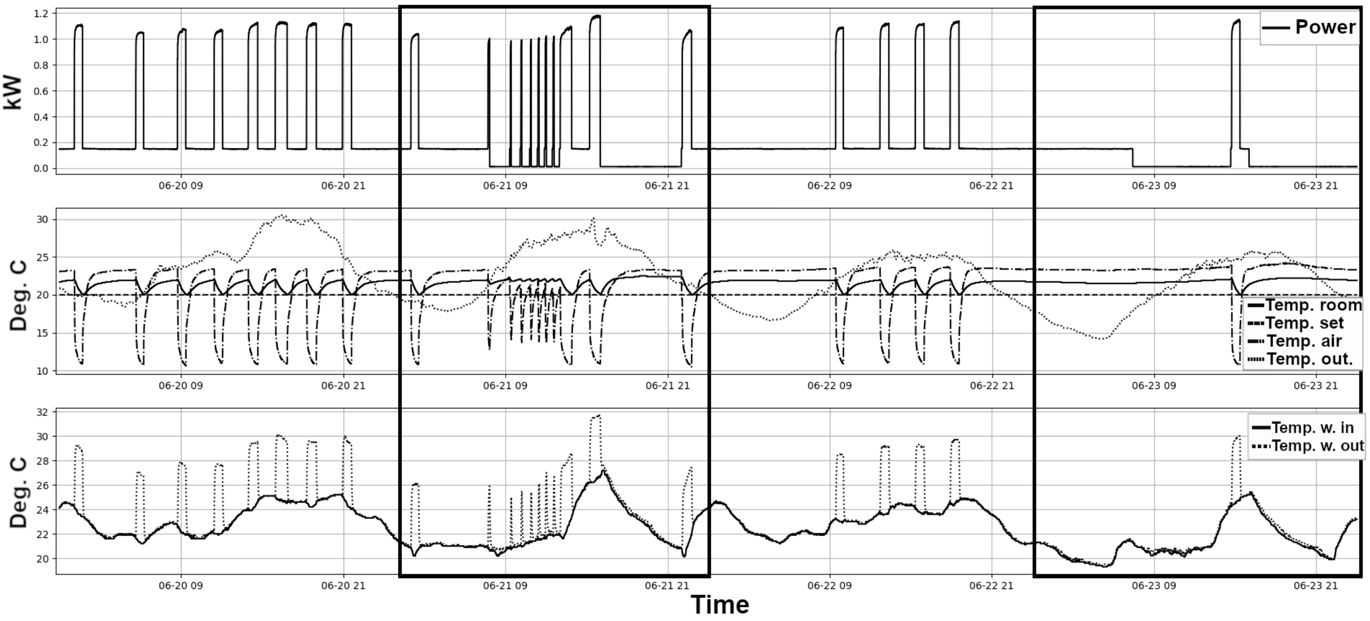

Fig. 9. The operation of heat pumps on a hot day

of the PV modules – the real gain was in sending more energy to the external grid. Using a simple calculation (assuming the saved energy was never produced elsewhere) the estimated CO_2 equivalent is 0.067 metric tons.

Table 2

Change in cost of operation with the system and without

Pump	Savings [%]
B1_1_10.1	37.25239
B1_1_12	35.77174
B1_1_13	37.35748
B1_1_14	36.6158
B2_0_12	33.10669
B2_0_13	26.41705
B2_0_14/15	31.30132
B2_0_16	14.97703
B2_0_17	36.39259
B2_1_11	36.83083
B2_1_13	34.95802
B2_1_14	34.09951
B2_1_16	42.79891
B2_1_17	39.35469

Last but not least, there was a small change in human comfort observed, but the temperature in the room has not increased so significantly that it was not possible to work. The test was performed in office conditions where people work between 8:00 and 16:00, which means that switching the cooling-off after 16:00 had a minor influence on their comfort. As also observed in the power usage graph (Fig. 9), the system was cooling down significantly between the peaks, which means between 12:00 and 16:00.

5. CONCLUSIONS AND FUTURE WORK

This article presents a real-life implementation of the management system based on market-based control with price function and finding the equilibrium price that defines the operating point of the devices. For the experiments, the heat pumps in a waterloop were chosen as they were controllable, and their operation could be postponed or stopped without immediate disruption of research centre operation.

The system worked very well during normal summer days, allowing the rooms to be cooled undisturbed during off-peak hours and limiting the operation of the waterloop during peak hours. One of the main observed issues was the frequency of switching pumps on and off – in the ideal situation pumps should work for a period of half an hour or more (even under-cooling the room) to limit the amount of switching off and on during the day. This requirement clearly shows that the optimal operation of the cooling and HVAC systems requires planning ahead and forecasting the conditions within and outside of the building.

The problem was caused by the dynamic of temperature change in rooms located on the south side. Unless the constraints are weakened, the pumps will be switching on and off too frequently. To counter this, one option is to have the algorithm dynamically adjust the desired temperature, as this will have the effect that the pumps will not change state for longer periods. The downside is that this will worsen the feeling temperature of the inhabitants of the rooms and further research about their temperature comfort should be done to estimate how far the system can deviate from the predefined settings.

The system could not change dynamically the power used by the heat pumps – the devices had no such possibility foreseen. For testing this type of scenario, other types of devices will have to be considered.

A second important observation is a peak in power usage that occurs immediately after managed intervals (the tariff peak times). They are a result of the fact that there is no smooth transition between the managed time intervals and the non-managed time intervals (peak vs non-peak tariff). However, it may be desirable to avoid such sudden peaks in power usage, which can be achieved by managing the entire day and making the cost function not only temperature but also time dependent.

A great improvement to the performance of the management system would be including occupancy detection, for example using the movement sensors in some parts of the building or other known methods, like the ones described in [11], and also incorporating them in the cost function. This would allow us to increase the priority of cooling for the rooms that are occupied.

The next step in the current setup is to combine the power availability not with the tariffs, but with the real balance of the research centre, which is equipped with photovoltaic panels. Because the irradiance is at the same time heating the rooms and allowing photovoltaic to produce power there is space for further decrease in the cost of cooling by combining those technologies. What is more, increasing the controllability of the usage provides opportunities for dynamic electricity contracting, which might push down the costs even further [12].

The presented method of steering controllable units is not limited to heat pumps, but we chose those types of devices because they are manageable, use significant amounts of energy and there is time to delay them without direct danger to the operation of the building and its function. The general implementability of the presented management system in other buildings is limited due to the requirement of having a set of devices that can be managed. At present most of the HVAC systems are optimised towards user comfort and maintaining air quality within parameters – there is often no possibility to intervene with the external system. Adding to standard HVAC installation the power saving options is a next step that is slowly being considered in new buildings.

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