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Using Sensor Data of Widespread Smart Home Devices to Save Energy in Private Homes

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Abstract: This paper proposes an approach for using sensor data of smart home devices to optimize energy consumption in private homes. For many years, radiator thermostats have been used to keep room temperatures at given desired levels. Smart home thermostats allow the temperature to be controlled by home automation software, advanced models are connected to sensors indicating open windows or sun shining into the room. In contrast to these advances, basic optimizations of the heating system like performing hydraulic balancing or minimizing flow temperature are rarely performed by the plumbers, because the optimization process is time consuming and requires data that are not available at installation time. In this paper, we describe how data delivered by smart home devices can be used to optimize the heating system. Using our approach, hydraulic balancing and minimizing flow temperature can be easily performed by the house owner without the help of a plumber, resulting in substantial energy savings.

Keywords: Smart Home, Smart Thermostats, Hydraulic Balancing, Energy Saving, Sensor Data, Flow Temperature

1 Introduction

Devices like smart thermostats have attracted house owners' attention to increase comfort and to save energy [Re16]. They already have a wide installation basis. Smart thermostats save energy by precisely regulating room temperature and by lowering the temperature during the night or at times nobody is at home. However, the 30% potential for energy savings as promised even by market leaders [Dan17] is rarely achieved. Conventional thermostats are already very good at keeping the rooms temperature at the desired level. Nowadays, new homes are well insulated, many older homes are already brought up to new insulation standards. Hence, the effectiveness of night setback for room temperature is almost zero. The only real use case for timer based or remote setting of different temperature levels are longer absences from home (of the whole family).

However, data from smart thermostats together with data from other smart home sensors can be used to substantially optimize a heating system. For many years, hydraulic balancing is considered a very important basic optimization for each heating system. Empirical studies for different types of houses show that it typically saves energy between 10 and almost 30 percent [EvL14]. In Germany, plumbers are required to perform hydraulic balancing at installation time (VOB/C, DIN 18380). In the past, they used calculation sheets to compute the settings of the radiators balancing knobs based on parameters like room size, radiator size and valve type. Recently these sheets have been substituted by programs and smartphone apps [Dan17a]. In practice hydraulic, balancing

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is often omitted. Even with the help of modern apps, gathering all the required data and performing the necessary computations seems to be too much for the average plumber.

Unbalanced heating systems require higher flow temperatures and stronger pump pressures than necessary. This wastes energy, but remains undetected by house owners. In addition, even well balanced heating systems require re-balancing if substantial parameters change, typically when a home's insulation is improved, e.g. by installing new windows. In practice, in such cases re-balancing is almost never performed.

Physically, hydraulic balancing means adjusting a little turning knob on each radiator as shown in Fig. 1. Almost all modern radiator thermostat valves have such a knob, very old ones can be upgraded by a plumber. Adjusting the knob can easily be performed after the thermostat has been taken off, i.e., has been unscrewed by turning a large ring or bayonet catch. This is identical to the steps that are required when replacing old thermostats by smart thermostats and can be easily performed by house owners, without opening the water circulation.

Fig. 1: Red turning knob for hydraulic balancing, © Haustechnik verstehen, Martin Schlobach

Advanced smart thermostats allow the setting of a maximum for the position of their valves [ELV13]. In case such thermostats are used and the setting is available for update by the home automation software, the whole process can be fully automated for continuous optimization.

Based on live data provided by smart thermostats, we propose to perform hydraulic balancing in a completely different approach compared to the traditional computations. Our algorithm monitors the actual balance and derives adjustment values until an adequate balance is achieved. The required data is gathered from smart home devices and the algorithm can be run as part of the smart home software, e.g. as an app. Even in heterogeneous environments with smart thermostats from different vendors our approach is applicable if integrating platforms like OpenHAB [OH17] or FHEM [FHE17] are used. Reading temperature and valve position data poses no challenges to integration.

To the best of our knowledge, performing hydraulic balancing based on live data from smart thermostats is a novel approach, as the heating systems vendors' apps, e.g. [Dan17a], use the traditional computation approach.

This paper is organized as follows. In chapter 2, we show how sensor data of smart home devices can be used to derive the correct balancing values for the radiators in a home. We provide an algorithm that can be implemented in a small app, showing the optimized settings for each radiator or performing the settings automatically. Chapter 3 discusses how the flow temperature can be minimized based on the now optimal hydraulic balance. Chapter 4 describes ideas for further optimizations.

2 Optimizing Hydraulic Balance

Hydraulic balancing means optimizing the flow of hot water through all radiators such that each radiator can heat its room up to the desired temperature. The optimization goal is to achieve this with a minimal flow temperature. A radiator that takes more than its share of hot water "steals" water from other radiators. This is a typical situation if distances between radiators and the boiler vary or the radiators are installed on different floors. See Figure 2. Unbalanced systems require higher flow temperatures than necessary, i.e. the burner consumes more energy compared to a balanced situation [Kö14]. Hydraulic balancing achieves an optimal balance between all radiators. It is not a process of optimizing a single radiator and can therefore not be achieved by smart thermostats alone, unless they communicate via some optimization software as derived in this paper.

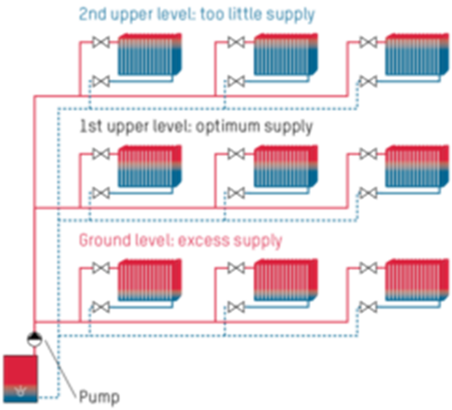

Fig. 2: Unbalanced heating system, © Taconova

Hydraulic balancing can save substantial amounts of energy. Fig. 3 shows estimates of savings based on studies of the technical University of Dresden and case studies of several (large) buildings. The savings are in the same range as savings achieved by replacing unregulated radiator valves by simple thermostat valves, an optimization almost every home owner has already implemented because of the high savings that are achieved.

Because of this potential, German plumbers are required to perform hydraulic balancing at installation time of a new heating system. However, Fig. 4 shows that this is rarely performed in practice, indicated by the low percentages of houses that have hydraulic balancing.

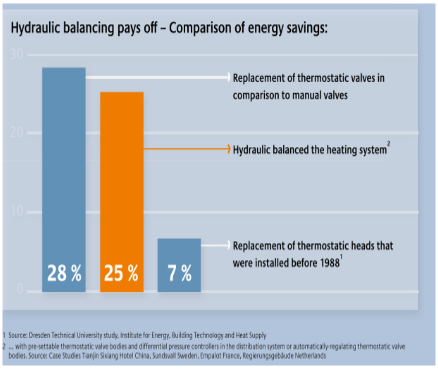

Fig 3: Hydraulic Balancing: Savings

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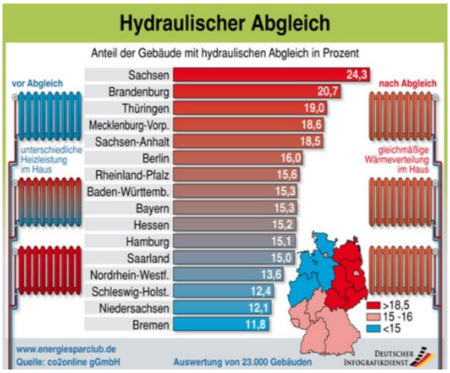

Fig. 4: Buildings with hydraulic balancing

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Hence, a hydraulic balancing process that can be performed by the house owner or which is even fully automated can substantially contribute to energy savings.

In detail, an unbalanced system causes two kinds of problems:

1. In an unbalanced system, remote radiators do not get hot enough. Of course, in this situation the user complains and the plumber will increase the flow temperature. Modern heating systems even perform this increase automatically if the remote radiator is in the so-called reference room monitored by the heating system (where the remote control of the heating system is installed). Plumbers frequently make remote rooms the reference room to avoid user complaints, thereby wasting energy. Hence, many heating systems operate with higher flow temperatures than necessary. This results in distribution losses.

2. In an unbalanced system, the flow speed through different radiators varies substantially. A high flow speed results in high return flow temperatures. The overall return flow temperature at the burner gets higher in case there are radiators with high return flow temperatures in the system. This causes not only high distribution losses, but also decreases the efficiency of the burner. Modern low-temperature burner use the energy in the hot exhaust to additionally heat the water, but this only works in presence of low return temperatures. In addition, the switching frequency of the burner increases, as the returning hot water is quickly heated up again, causing the Burner to switch off and on frequently.

Unfortunately, many heating systems run poorly balanced, for two reasons:

1. The house owner is unable to detect the poor balance unless the heating system is so extremely unbalanced that the maximum flow temperature of the burner is not sufficient to heat remote radiators. Given the safety margin in the plumber's calculations, this is rarely the case.
2. Plumbers do the hydraulic balancing by performing simple calculations that disregard many important factors. A precise balancing can only be achieved by measuring the pressure of the feed line of each radiator and adjusting the balance until all pressures are equal. In practice, this is never performed as it requires installing pressure gauges into the heating system.

In an ideal situation, all valves of all radiators in all rooms are constantly fully open, and the burner produces only enough energy needed to keep all rooms at their desired temperatures. Thermostats need to close a radiators valve only if there is additional energy injected into the room, e.g. because the sun shines through a window. Radiator sizes are calculated by the plumber based on this setting, plus a safety margin. For a given maximum flow temperature and the lowest possible (assumed) outside temperature, the size of a radiator must be sufficient to heat the room with the valve fully open.

With all valves fully open, radiators close to the burner get too hot, radiators far away get too cold. To balance temperatures of the radiators, radiators close to the burner need additional flow resistors. Adjustable resistors are already built into modern radiator valves as shown in Fig. 1. Adjusting them achieves the desired hydraulic balance.

Using time series of temperature and valve position data, we can easily detect imbalances as follows: Given the typical situation that hydraulic balancing has never been performed, all balancing valves of all radiators are fully open. Thermostats regulate a rooms temperature by opening and closing their valve. The valve of a radiator close to the burner will be almost fully closed to not overheat the room. Valves of radiators far away from the burner will be constantly wide open. By comparing the mean values of the thermostats valve positions, we can detect the hydraulic imbalance.

Our algorithm works as follows: We compute the mean values *AvgPos(i)* of all valve positions *valve(i)* of all rooms R_i over a period of n days every m Minutes (e.g. $n = 5$ and $m = 10$), and the overall mean *TotalAvg* over all *AvgPos(i)*. A zero valve position means the valve is fully closed. If the mean value of the valve positions of a radiator is more than a threshold Δ_v of about 10% away from the overall mean, the user is asked to open or close the balancing valve *hydPos(i)* of this radiator by a tick. If a smart thermostats max. open position *MaxValvePos(i)* can be controlled by software, user action is not required and the process of balancing occurs automatically. Note that increasing *hydPos(i)* means closing the balancing valve, which is equivalent to decreasing the max. open position *MaxValvePos(i)*. This process is repeated until hydraulic balance is achieved, i.e., all means are within the given range Δ_v. Deriving adequate values for Δ_v is subject of further research and should be based on field studies. If Δ_v is chosen too high, optimization potential remains unexploited. If Δ_v is too low, the algorithm doesn't terminate. In case balancing is achieved by setting the maximum valve position by software, termination is not required. In this case, the algorithm constantly optimizes the balance.

```
Repeat
  //Array of sets of valve positions of i rooms
  ValvePositions[i] := {}
  Over n days, perform every m minutes:
    for each room Ri
      if (sun(i) < smin) and (|setpoint(i) - act(i)| < Δt)
        add valve(i) to ValvePositions[i]
  After n days:
  AvgPos(i) = avg(ValvePositions[i])
  totalAvg = avg(AvgPos(i))
  for each room Ri:
    If (|totalAvg - AvgPos(i)| > Δv)
      If (totalAvg > AvgPos(i))
        Manually by User: Increase hydPos(i) by one Tick
        Automatic: MaxValvePos(i)--
      else
        Manually by User: Decrease hydPos(i) by one Tick
        Automatic: MaxValvePos(i)++
Until for all rooms Ri: |totalAvg - AvgPos(i)| <= Δv
```

Under certain circumstances, valve measurements should not be considered for computing the mean value:

1. Additional energy is injected into the room, for example the sun shines through a window. In this case the valve closes, but the closing should not affect the computing of the hydraulic balance. This situation can be detected by sun sensors delivering a measure for the light intensity *sun(i)*. Many rooms already have such sensors for automated blinds. A value of *sun(i)* above threshold s_{min} indicates that the sun shines into the room.

2. The user has just altered the desired room temperature *stepoint(i)*, and the thermostat is now wide open or almost fully closed to adjust the room temperature from its actual value *act(i)*. This valve setting must not impact the setting of the hydraulic balance. We detect such a situation by comparing the difference between actual and desired temperature against a threshold Δ_t of about 1 degree.

3 Optimizing Flow Temperature

Modern heating systems adjust the flow temperature automatically by measuring and regulating the temperature of a reference room. The controller of the heating system must be installed in this room, and he thermostat of the reference room must be kept fully open. The flow temperature is then adjusted such that the temperature of the reference room is kept at its desired level. Of course, the reference room must not be subject to additional energy injection such as sunshine.

Many installations don't have a room that qualifies as a reference room, or the controller is installed in the living room for user convenience. In these cases, our algorithm can be used to optimize flow temperature without a reference room

If at the end of the hydraulic balancing process, the overall mean *totalAvg* of valve positions is lower than say 80% open, the flow temperature should be lowered. In this case, the algorithm of chapter 2 can also be used. Lowering the flow temperature does not change the hydraulic balance. Therefore, no adjustments of hydraulic balancing valves by the user are necessary. Instead, only *totalAvg* of valve positions as computed by the algorithm is used. Adjusting the flow temperature should be done in small decrements of 1-2 degrees until *totalAvg* is above 80%. Waiting a few days between adjustments should be sufficient for the system to stabilize. In heating systems where the flow temperature can be controlled by software, this process can be fully automated.

In case the flow temperature is adjusted manually, the optimization for a low flow temperature should be repeated for different ranges of outside temperatures. This way, optimal settings for the flow temperature depending on the outside temperature can be determined. Typical heating systems only allow (almost) linear dependencies between outside temperature and flow temperature, which may result in too high flow temperatures over longer periods of time.

All these optimizations should be repeated whenever substantial parameters of the building are changed, for example by installing new windows in some rooms or better isolating the whole building.

4 Further optimizations using sensor data

Modern highly insulated homes require controlled ventilation to avoid mildew. Unless ventilation is controlled by a dedicated ventilation system, airing rooms manually by opening windows is required. Sensor data can aid users in doing this. To warn users when they forget to close windows, the smart home can send messages to a user's smartphone. In addition, messages can also be sent when the thermostat's humidity sensor detects a too high humidity for a longer period, indicating it's time for airing the room.

5 Summary

In this paper, we have shown how time series of sensor data collected by smart home devices can be used to optimize a home's heating system to save energy. The basic principle for the optimization process is well known for years, and plumbers are even required to perform this optimization at installation time. However, studies show that this is rarely performed. We have presented an algorithm for deriving the optimization parameters form sensor data and have shown how house owners can simply perform the optimizations by themselves. With advanced thermostats, as already on the market, the optimizations can even be done automatically without user intervention.

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