Enhancing User Comfort Models for Demand Response Solutions for Domestic Water Heating Systems

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Abstract: Demand Side Management (DSM) solutions for domestic Water Heaters (WHs) can assist consumers benefit financially by optimizing their energy usage. However, users' dissatisfaction caused by negative impact of DSM on their comfort may force them to reject the provided solutions. To facilitate DSM adoption in practice, there is a need to account for user comfort and to provide users with control strategies to balance energy consumption and their comfort. Comfort models used for WHs typically account for only variability of the temperature of running water. This paper extends such typical user comfort modeling approaches by considering the tap water flow as a possible variable during water activities. The model to relate tap flow and users' comfort is the first contribution of this paper. The second contribution of this paper is the flow rate control mechanism aligned with the user comfort model by means of the multi-objective optimization. Simulations for different water activities demonstrate that the control mechanism coupled with the suggested user interface can inform the user about multiple trade-offs between electric consumption and user flow discomfort, and thus can inform about possibilities to rationally save energy for water heating. A set of suggestions on how to organize the user interface is the third contribution of the paper.

1 INTRODUCTION

Demand Response (DR) as an integral part of Demand Side Management (DSM) can be identified as a set of initiatives "designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" (Commission et al., 2006). DR is recognized by the European Commission as an important instrument to enhance energy efficiency and stability of the electrical grid (Directive, 2012).

Improving energy efficiency is impossible without considering residential users involved in the demand response. Final consumption in the residential sector accounted for 26.65% of the total energy consumption in the EU-27 in the year 2010 and continued growing as reported by Eurostat (P. Bertoldi, 2012). Therefore, reduction of energy consumption in the residential sector can significantly contribute to decrease of the Union's energy dependency and carbon-dioxide emissions (Directive, 2010).

The adoption of DR programs balances in-between how users perceive possible benefits and shortcomings. By implementing DR, small residential consumers can gain numerous benefits such as reduction of outages, more transparent and frequent billing information, participation in the electricity market via aggregators, energy and financial savings (Giordano et al., 2011). Notwithstanding, there is still a significant level of consumer resistance to participating in DR projects, mainly because consumers are afraid of losing control of devices in their own household and are sceptical about new electricity rates, (Magazine, 2014). Consumers' concerns and uncertainties create a barrier for the wide-scale uptake of DR solutions, which in turn decreases the overall profitability of DR measures (Sharon Mecum, 2002).

The need for involving consumers in sustainable consumption has been highlighted by the EC Task Force for Smart Grids "the *engagement* and *education* of the consumer is a key task in the process as there will be fundamental changes to the energy retail market" (Force, 2010). The European Communication on smart grids underlines the importance of consumer awareness by stating that "developing smart grids in a competitive retail market should encourage consumers to *change behaviour*, become more

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active and adapt to new 'smart' energy consumption patterns" (Commission, 2011).

Consumers can modify their energy consumption habits based on direct feedback about their energy usage (Directive, 2009).

To be useful, information about energy consumption and estimates for energy costs should be provided in a timely manner and in an easily understandable format (Directive, 2012). Typically, the task of informing users is handled by means of various user interfaces (UIs) integrated into automated home demand response solutions for, among others, room heating, air-conditioning, water heating systems, and other electric loads (Lu and Zhang, 2013; Giorgio and Pimpinella, 2012; Koutitas, 2012). Several off-the-shelf UI solutions are available in the market today (Nest, 2015; Honeywell, 2015).

A number of projects are now focusing on consumer engagement in DR (Jorgensen et al., 2011; to Grid Project, 2012; Project, 2011; Sæle and Grande, 2011). For example in the *EcoGrid EU* project, consumers having demand response-equipped devices and intelligent controllers can react to real-time price signals (Jorgensen et al., 2011).

The *Ewz-Studie Smart Metering* project aims to assess consumer response to different DRs through use of tools such as in-home displays, expert advice, social competition and social comparison. Other projects like *Consumer to Grid project* intend to measure the behavioral change induced by various feedback mechanisms such as monthly bills, website, smart phone APPs and ad-hoc feedback gadget (to Grid Project, 2012).

Despite of all these tools, ready-to-deploy products, and projects, the expressed European view on energy saving schemes indicates the need for further in-depth consideration of ways for improving energy utilization in individual households. Essentially, this concerns both questions about how to improve the efficiency of energy usage and how to communicate the related information with the consumer.

1.1 Modeling User Comfort for Domestic Water Heaters

This paper concentrates on the specific problem of "how to improve the efficiency of energy consumption of a domestic electric storage-tank water heater load (WH) with respect to user comfort and how to enhance consumers' awareness about their electricity expenses for water heating?". The case of domestic water heaters is particularly relevant to the residential energy consumption because they make up more than two thirds of the total household consumption together with room heaters and air conditioners in European countries (Comission, 2011). Furthermore, since tank water heating units are still present in a prevailing number of European households and because of their capability to store thermal energy, they serve as a good example of a household loads.

Previously, a number of approaches (e.g. (Belov et al., 2015a; Sepulveda et al., 2010; Du and Lu, 2011; Pedrasa et al., 2009; Dlamini and Cromieres, 2012)) have been suggested to account for user comfort with respect to WHs in order to minimize comfort disruptions and hence to increase attractivness of these DR solutions to the customers. Majority of these works deal with the thermal discomfort caused by uncomfortable tap water *temperature*. They assume that the tap flow rate is *fixed* during the entire water usage and *pre-determined* by the user.

However, additional savings can be achieved by investigating opportunities to reduce the tap flow rate. For instance, modern water efficient faucets can save water during tasks performed in running water by limiting the flow rate (Agency, 2015) or by interrupting the water flow when it is not needed (Digital, 2015; Stepon, 2015), which in turn reduces the water heater's demand and leads to energy savings.

This paper argues that relaxing the assumption about the fixed tap flow can open up opportunities for additional electricity savings. A loosely-defined flow rate, suggested by the user and related to the user comfort model, can be a subject of sophisticated control. Additionally, by carefully examining the amount of tap hot water withdrawn, the intentions to save energy and water usage can be united. As these objectives are highly relevant for the green energy paradigm, this approach can support smoother transition towards green energy solutions.

In our view, three aspects should be considered to enable efficient utilization of both water and energy for water heating. Firstly, a model should be developed to accurately account for relations between tap water flow rate and user comfort. Secondly, a mechanism to control the WH with regard for this model should be developed. Finally, information about the control possibilities and their impact on energy consumption for water heating and user satisfaction with the tap flow rate should be represented to a user by means of a clear and understandable user interface. Together, these topics highlight multiple intricate interrelations between energy and water savings, user comfort, and possibilities for user control of flow-adjustable water events.

We build on our previous research that concerns user comfort described in (Belov et al., 2014; Belov et al., 2015a; Belov et al., 2015b). Previously, we suggested a system built around the *water activity* (WA) concept where a WA of a specific duration executed by a user has two parameters, i.e. the tap water temperature and water flow (Belov et al., 2015b). In this paper we extend the user comfort model, that has previously accounted only for a user satisfaction with water *temperature* (Belov et al., 2015a), and introduce a new flow-based discomfort metric. This paper also suggests the way to organize an interface to visualize interrelations between energy, flow rate, and user comfort to the end-user.

Therefore, this paper presents three main contributions (1) a model that can link energy savings and water usage and show their effect on one another, (2) a system incorporating this model together with the flow-rate control mechanism is proposed, and (3) a way of how the system can interact with the user.

The rest of the paper is organized as follows. Section 2 represents modeling of the water heater system, describes the scenario of hot water usage and the flow rate control. The existing approach for user flow discomfort modeling is discussed in Section 2.3 and updated later on in the paper. Initial considerations for the user interface are outlined in Section 2.5. In Section 3 we apply a multi-objective optimization to unfold an explicit relation between electricity expenses for water heating and user flow discomfort. A role of the user interface and suggestions to its implementation are also presented in Section 3. Section 4 exhibits and discusses the simulation results for the selected water activities. Some directions for the future work are outlined in Section 5 and our conclusions are summarized in Section 6.

2 MODELING HOT WATER SUPPLY

This section introduces important concepts for modeling water heater operation and user discomfort. These concepts will be used in subsequent sections of the paper.

2.1 Water Heater Operation

In this paper we consider an electric storage-tank water heater (WHs) used to heat tap water in a household. Most of such WHs operate in a cyclic manner. This means that the heating elements of a WH are continuously turned on and off to maintain the temperature inside the tank within some temperature deadband. More specifically, the WH remains on, if its internal temperature is below the upper setpoint temperature. When the upper setpoint is reached, the heating elements are shut down till the temperature in the tank drops below the lower setpoint. There is extensive literature available on modeling of WHs, see for instance (Kondoh et al., 2011; Dolan et al., 1996; Lane and Beute, 1996). In contrast, in this paper we consider a small-sized domestic WH assuming that *entire water in the tank is at the same temperature, i.e. non-stratified*. In this regard, we adopt the following thermodynamic model of the well-mixed WH described in (DOE, 2013):

$$MC\frac{dT}{dt} = P_{\mathrm{e}} + P_{\mathrm{cw}} - P_{\mathrm{hw}} - P_{\mathrm{loss}} \tag{1}$$

where M is the water mass in the tank, C is specific temperature of water, P_{e} is the thermal power supplied by the heating elements, P_{cw} and P_{hw} are cold water inflow and hot water outflow of the tank, and P_{loss} is the heat losses to the ambient.

Normally, the preferred tap water temperature and flow rate is set by using the tap mixer. The mentioned components of the model are interrelated as indicated in Figure 1.

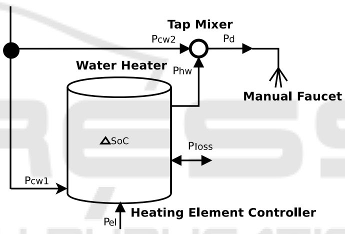


Figure 1: Considered Setup.

Energy and mass balance in the mixing device can be expressed as:

$$\begin{cases} P_{\mathrm{d}} = P_{\mathrm{hw}} + P_{\mathrm{cw2}} \\ \dot{m}_{\mathrm{d}} = \dot{m} + \dot{m}_{\mathrm{cw}} \end{cases} \tag{2}$$

where P_{d} is the tap water thermal power demanded by the user, P_{hw} is the power flow from the tank, P_{cw2} is cold water from the main controller, and $\dot{m}_{\mathrm{d}}, \dot{m}, \dot{m}_{\mathrm{cw}}$ are the demanded, hot and cold water mass flow rates, respectively.

The mixer merges hot and cold water flows in a certain proportion which basically determines how fast the temperature in the tank $T(t)$ will fall during the water activity (WA). (2) expresses that the ratio between the hot water and cold water flow rates in the mixer bind together the temperature inside the tank $T(t)$, the demanded temperature $T_{\mathrm{d}}(t)$, and the cold water temperature T_{cw} at every moment of time:

$$k = \frac{\dot{m}}{\dot{m}_{\mathrm{cw}}} = \frac{T_{\mathrm{d}}(t) - T_{\mathrm{cw}}}{T(t) - T_{\mathrm{d}}(t)} \tag{3}$$

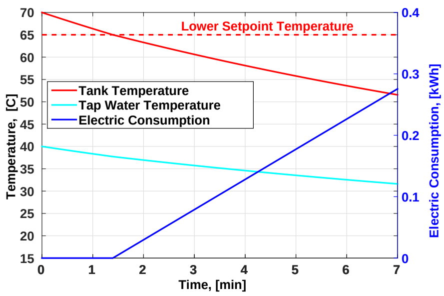


Figure 2: WH during 10-minute WA.

2.2 Hot Water Usage & Flow Control

The main focus of this paper is on improvement of energy utilization in a domestic WH by means of the WH control mechanism that treats the tap flow rate as a controllable parameter.

As it can be seen from (1), hot water demand together with heat losses to the environment contribute to the drop of thermal energy inside the water storage. Noteworthy is that heat losses to the ambient are neglectfully small compared with the heat discharge due to the hot water usage (Du and Lu, 2011). One can conclude from (1) and (2) that any outflow from the tap $\dot{m}_d > (P_e - P_{loss})/[C(T_d - T_{cw})]$ leads to the decrease of temperature inside the WH as shown in Fig. 2. As a result, the actual tap water temperature T_d will also decline over time, which can bring the user some thermal discomfort.

Unlike the above typical scenario for the flow-fixed hot water usage, this paper explores the *flow-adjustable* scenario where the user desires the fixed tap water temperature for a WA. The user request for the fixed temperature can be fulfilled by controlling the proportion of hot and cold water flows in the mixing device represented by (3). The analysis of this equation done in our previous studies (Belov et al., 2014) highlights the possibility to maintain the user request for the fixed temperature by progressively increasing the hot water flow from the tank, while gradually lowering the cold water inflow in the mixer throughout the WA.

A hot water management system can handle water flow in the tap mixer in a stepwise manner as illustrated in Fig. 3. The figure shows a case when a user is willing to obtain tap water at 45°C. However, the tap water temperature naturally goes down because (i) the cold water enters the tank and (ii) the power of electric heating elements cannot typically recover the tank temperature during the water usage. Thus, the flow controller adjusts hot and cold water flows every minute to maintain the tap water temperature at the desired level.

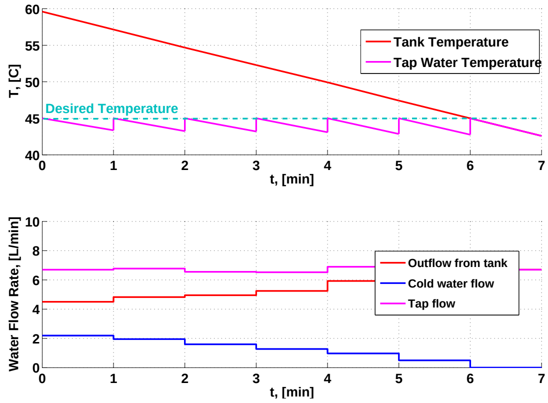


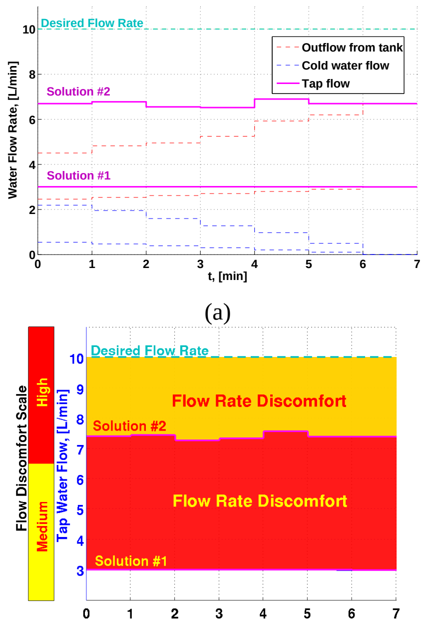
Figure 3: Flow Management in Mixing Controller.

2.3 Tap Flow Rate Discomfort

The concepts of the flow-adjustable hot water consumption and the flow control associated with it and presented in Section 2 call for a careful consideration of impacts of the flow control on user comfort.

The concept of the flow rate discomfort introduced previously in (Belov et al., 2014) can be illustrated by the following example. Let us consider a person who want to take a 7-minute shower at the fixed water temperature of 45°C. Such water service can be attained by means of the flow controller that maintains the wanted temperature by regulating the hot and cold water flows in a step-wise manner as discussed in Section 2.2. More precisely, there can be multiple solutions to this control problem, each of which resulting in a different water flow from the shower head. Two of these solutions are shown in Fig. 4(a).

As it can be seen from Fig. 4(a), both control solutions lead to the tap water flows uncomfortable for the user. In fact, the user can experience distinct dissatisfaction at every step of control which is caused by the mismatch between the currently provided flow and the flow rate desired by the user (10 [L/min]). To quantify the user inconvenience of having unsatisfactory flow rate for the entire WA, we take instantaneous flow deflections over time as illustrated in Fig. 4(b). We suppose that the time during which the user experiences the undesirable flow is significant for the WA accomplishment. This means that if the duration of discomfort is short enough, the user might still proceed with the WA. Otherwise the user might refuse to continue. Moreover, flow variation considered over time can indicate the amount of overused/undelivered liters of water. This can be crucial in some scenarios, for example, in filling a bath. To this end, we accumulate all instantaneous deviations of the supplied water flow over the entire duration of a WA. The total flow rate discomfort can be then described by:



(a)

(b)

Figure 4: Flow Rate Discomfort.

$$A_{\dot{m}_d} = \sum_{i=1}^{N} |\dot{m}_{\exp,\,i} - \dot{m}_{d,\,i}|\Delta t, \tag{4}$$

where N is the number of control steps, $\dot{m}_{\exp,\,i}$ is the desired flow rate at i-th step, $\dot{m}_{d,\,i}$ is the tap water flow provided at step i, and Δt is the size of the control step.

2.4 Effect on Thermal Discomfort

Apart from the flow rate discomfort, the user can also experience a drop of tap water temperature within every step of the flow control as illustrated for a single step in Fig. 5. Noticeably, different people typically have different tolerance to cold and hot water due to individual skin sensitivity (Robertson et al., 2006). To estimate the levels of thermal discomfort the user can experience during the flow control, we employ the thermal discomfort model presented earlier in (Belov et al., 2015a). The model takes into account that different people can tolerate the tap water temperature deflections differently by incorporating personal temperature discontent functions.

2.5 Hot Water Management System (HWMS) and User Interface

In addition to the flow rate control mechanism that concerns user comfort, this paper also presents a novel approach for developing a clear and understandable user interface (UI). The suggested UI is part of a bigger hot water management system (HWMS) that consists of a smart tap and main controller for the WH (Belov et al., 2015b). The diagram that gives a general idea on how a user can interact with the system and its major components are shown in Fig. 6.

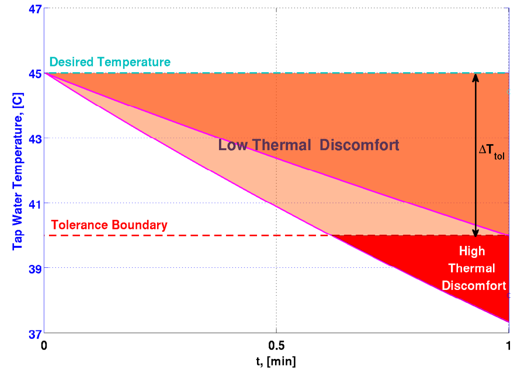


Figure 5: Motivation Example to Consider Thermal Discomfort During Flow Control.

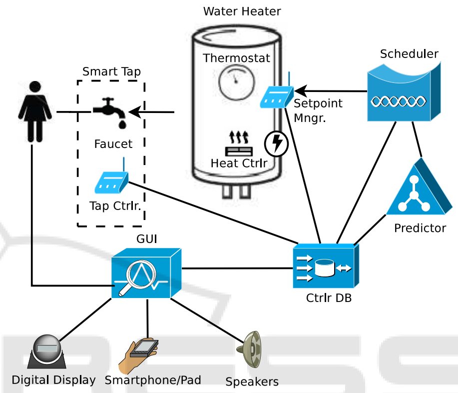


Figure 6: System's Functionality (no arrows show bi-directional links).

Figure 6 illustrates that the main controller includes GUI, database controller 'Ctrlr. DB' that stores all user preferences and optimization results, prediction module that builds a daily timetable of the expected WAs and the Scheduler that calculates the outcomes of the flow control and executes it. The user can communicate with the HWMS through GUI that can be realized on diverse user gadgets and digital display. GUI serves three main purposes (a) to collect the needed for the Scheduler comfort related information from the user, (b) to represent control options found by the Scheduler, and (c) to obtain user feedback about the offered options. Once the user has estimated and chosen the desired control outcome, the steering signals from the Scheduler are fed to the setpoint control manager to change the thermostat current setpoint temperature setting and start/stop heating as well as to the Smart Tap to adjust the flow ratio specified in (3).

All in all, at every step of the flow control, the system withdraws a small portion of hot water from the tank and mixes it with cold water to achieve the wanted tap water temperature. Obviously the stronger is the hot flow rate at every step, the (potentially) higher is the tap water temperature. However, a strong step-increase of the hot flow can lead to a rapid WH discharge and thereby to the thermal discomfort. The flow control seeks optimal combinations of $\{T_i, \dot{m}_i, \dot{m}_{\mathrm{cw},i}\}, \forall i \in N$, where T_i is the tank temperature at the beginning of step i and N is the total number of control steps. Consequently, (4) also implies an *implicit* link between the flow rate discomfort and electric consumption for preheating. Having such relationship in *explicit* form before the WA the user can estimate the consequences of current comfort settings on energy consumption with respect to the heat currently available in the tank.

3 LINKING ENERGY CONSUMPTION TO FLOW RATE DISCOMFORT

Since the flow control outlined in Section 2.2 should be executed with respect to the user acceptable level of the flow rate discomfort as discussed in Section 2.3, the flow control algorithm should be coupled with the user flow comfort model. In order to explicitly incorporate the comfort model into the flow control scheme the relationship between the user flow discomfort and electricity expenses should be found.

3.1 Pre-heating Procedure

To maintain the tap water temperature at the requested level and to ensure the accepted level of the flow rate discomfort, there might be a need to pre-store additional heat in the WH, taking into account the constraint for the maximum tank water temperature dictated by safety reasons (InterNACHI, 2015). If the SoC of the WH at the beginning of water usage is insufficient to suit the user comfort choice, the main controller of the system initiates a *pre-heating* procedure.

The HWMS reminds the user about the expected WA by sending him a notification message. The message contains different options to provide the hot water service to the user. Once the user has acknowledged one of the offered alternatives, the system estimates the required SoC at the start-up of the WA and finds the optimal time to start the pre-heating procedure. The user might end up with a higher energy consumption than usual, if the requested comfort level was high as demonstrated in Fig. 7. Here we make an assumption that no other WAs can occur in the interval in which the user approves one of the offered solutions and the WA starts.

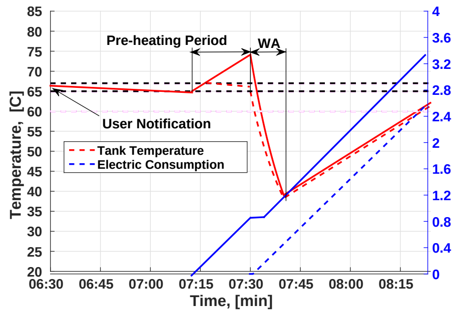


Figure 7: Pre-heating Procedure (dashed lines - WH regular operation, solid lines - WH pre-heating).

3.2 Multi-objective Optimization & Pareto Front

In order to *explicitly* link the electric consumption for water pre-heating with the user flow rate discomfort, we apply a multi-objective optimization approach. We consider minimizing energy consumption and minimizing flow rate discomfort as two conflicting objectives. In general, multi-objective optimization allows to manage multiple goals to be achieved simultaneously subject to a set of constraints. If achievement of one goal has a negative impact on attaining another goal, two goals are said to be conflicting. From mathematical point of view, minimization (or maximization) of conflicting objective functions leads to a number of optimal solutions that make up Pareto front (Caramia and Dell'Olmo, 2008). Pareto front is characterized in the way that switching from one solution to another on the front improves one of the conflicting objectives and degrades the value of another. The approach to align two goals by means of the multi-objective optimization and the resulting flow control mechanism is the *first contribution* of this paper.

3.3 Objective Function I - Minimum Energy Consumption

To formulate the first objective function, we assume that the water heater can be initially at any allowed temperature depending on the previous history of water usage. By solving the differential equation (1) electric consumption for pre-heating E_e in the period Δt_{pre} can be expressed as:

$$E_e(\Delta t_{pre}) = P_e \Delta t_{pre} = \alpha P_e log[\beta f(SoC(0), SoC(\Delta t_{pre}))] \quad (5)$$

, where α and β are coefficients dependent on engineering parameters of the WH; $SoC(0)$ and $SoC(\Delta t_{pre})$ are the SoC of the WH in the beginning and at the end of the preheating period respectively.

Aiming at minimum electric energy consumption, we set the objective $F_1 = min[E_e(\Delta t_{pre})]$ as the first objective function for our multi-objective optimization.

3.4 Objective Function II - Maximum User Flow Rate Comfort

To account for variations in user perceptions of the water flow, we extend the discomfort metric $A_{\dot{m}_d}(t)$ represented earlier in Section 2.3 by incorporating the individual discontent function $F_{\dot{m}_d}$. The discontent function $F_{\dot{m}_d}$ reflects how deviations of the tap water flow are important to a person in a specific scenario of water usage. Thus this extension adds flexibility to the original comfort model and enables to differentiate between discomfort levels of multiple users. We assume that the individual discontent function establishes a linear relationship between user dissatisfaction and tap water flow deflections at any time step i:

$$F_{\dot{m}_d,i} = \begin{cases} 0 & \text{, if } \dot{m}_{d,\,i} \in \Delta\dot{m}_{d,\,comf}; \\ \alpha_1 \dot{m}_{d,\,i} + \beta_1 & \text{, if } \dot{m}_{d,\,i} \in \Delta^-_{tol}; \\ \alpha_2 \dot{m}_{d,\,i} + \beta_2 & \text{, if } \dot{m}_{d,\,i} \in \Delta^+_{tol}; \\ 1 & \text{, otherwise;} \end{cases} \quad (6)$$

where $\dot{m}_{d,\,i}$ is the tap water flow rate at step i; $\Delta\dot{m}_{d,\,comf}$ is the range of flows comfortable for the user; $\alpha_1 < 0, \alpha_2 > 0, \beta_1, \beta_2$ are some coefficients; Δ^-_{tol} and Δ^+_{tol} are lower and upper flow tolerance zones as illustrated in Fig. 8:

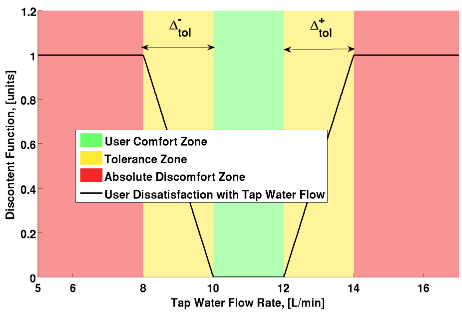


Figure 8: Discontent Function.

Then the updated user flow rate discomfort model can be formalized as:

$$D_{\dot{m}_d} = \sum_{i=1}^{N} F_{\dot{m}_d,i} A_{\dot{m}_d,i} \quad (7)$$

where $F_{\dot{m}_d,i}$ is the user discontent level reached at step i; $A_{\dot{m}_d,i}$ specifies the area resulted from the flow $\dot{m}_{d,\,i}$ deviation from the comfort zone $\Delta\dot{m}_{d,\,comf}$ during step i.

The second objective function can be formalized as $F_2 = min[D_{\dot{m}_d}]$.

The designed user flow rate comfort model is the *second contribution* of this paper.

3.5 User Interface

The necessity of attaining Pareto fronts in our case is mainly dictated by two reasons: (a) its convenience of representing an extensive information about multi-objective optimization results in a compact form that is abstract enough to hide unnecessary details from the user; (b) its capability to plainly illustrate a wide range (possibly infinite) of alternative solutions that the user can accept while pursuing either of the above goals. This means that the user can observe not only a single solution that satisfies his current choice but also a variety of other options that might also influence his actual decision. All in all, it can be assumed that the user supported with multiple trade-offs can make more conscious and justified choices when balancing energy consumption/costs and personal comfort.

In principal, the system starts operating with checking the available comfort models for the planned activities. If the system starts up freshly or if some of the user comfort parameters from the previous runs are missing, the Scheduler requests 'Ctrlr. DB' to derive the needed inputs from the user via GUI as shown in Fig. 9. The needed input parameters consist of (a) user comfort preferences for the planned WAs, and (b) updated WAs schedules. The former inputs can be entered in the form of user comfort model parameters, though some of them can be automatically set within the system *calibration phase*.

As it can be concluded from Fig. 9, the important role of the GUI is to check the user feedback about the quality of hot water service provided. The user feedback feature of the GUI is essential for correct provision of hot service with respect to the user's comfort choice and the amount of money (s)he is ready to pay for it. In *calibration phase*, the GUI can initiate a test program that tends to automatically tune the tap flow rate during the selected WAs, check the user response, and re-adjust some of the comfort model parameters.

The HWMS and the flow rate control mechanism that it implements delegate to the user the responsi-

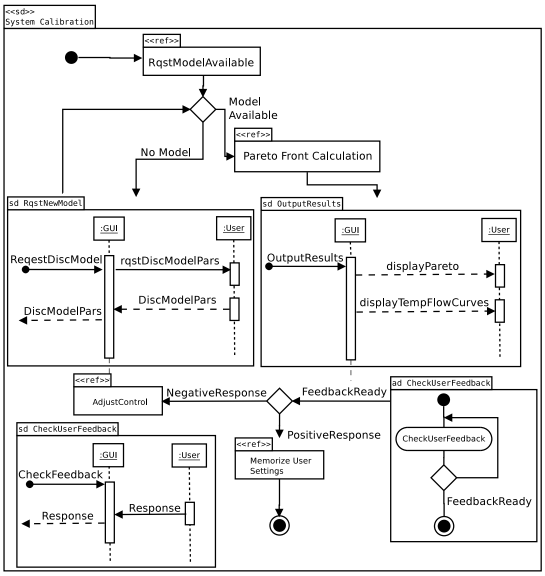


Figure 9: System Calibration.

bility for making a decision concerning how realistic and comfortable is the current user flow comfort model and how much money to pay. Therefore, at this stage the system is fully user-centric and governed by the user's choice. It does not take decisions about how much comfort to provide and at what expense instead of the user, but it rather works out control actions based on the information from the user and offers different control alternatives to the user, assisting him in making a rational comfort-energy choice.

4 PERFORMANCE EVALUATION AND VALIDATION

In the system calibration phase the controller utilizes available user comfort model to provide the user with the feedback about the upcoming WA by calling the Pareto Front Calculation Block (PFCB) as shown in Fig. 9. In PFCB the Scheduler component of the system solves the the multi-objective optimization problem, simultaneously resolving the objectives F_1 and F_2.

We present how the PFCPB retrieves solutions (Pareto front) for several WAs regularly performed at home to demonstrate the existing connection and to find an explicit relationship between the above two goals. The chosen WAs are listed together with their estimated flow rates and volume values (Widén et al., 2009; Kaye, 2009; EngineeringToolbox,) in Table 1.

We first build Pareto fronts for the selected WAs with varied duration aiming to estimate the maximum and minimum values of the shifted electric consumption and the resulting flow rate discomfort. The values used in these simulations are listed in Table 2.

Table 1: WAs Selected For Simulations.

WA	Volume, [L]	Estimated Flow Rate, [L/min]	Flow Range, [L/min]
Wash Hands[a]	0.7 ... 7.5	6	2 ... 9
Dishwashing[b]	38 ... 75	9	6 ... 25
Shower[c]	32 ... 225	15	8 ... 25

[a] Bath tap, running water.
[b] Kitchen tap, running water.
[c] Mains fed.
Note: There is little statistical data on hot water usage per activity available. Some of the missing data per activity is replaced by data per water source location.

Table 2: Simulations of WAs with Different Duration.

Duration, [min]	Comf. Flow Range, [L/min, L/min]	Flow Tolerance, [L/min, L/min]	Temp. Tolerance, [°C,°C]
0.5	[10,12]	[8,12]	[40,45]
7			
15			

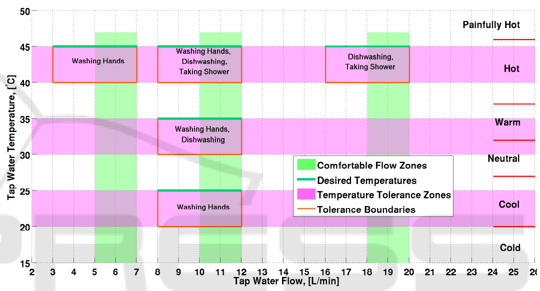


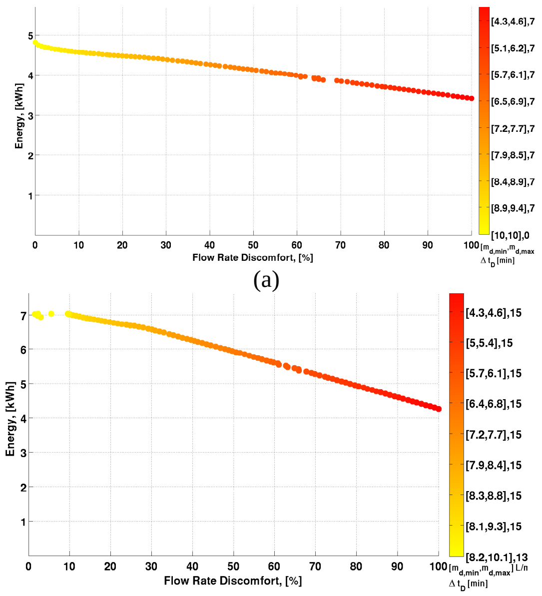
Figure 10: WAs & Parameters Used for Simulations.

We further carry out simulations for 7-minute WAs in distinct ranges of tap water temperatures and flow rates desired by the user while setting the fixed lower boundaries for the flow tolerance zones Δ^{-}_{tol} and Δ^{+}_{tol} as well as the thermal tolerance zones ΔT_{tol} as shown in Fig. 10.

Since the flow rate discomfort $D_{\dot{m}_d}$ depends on the size of the control step (via term $A_{\dot{m}_d,i}$ in (7), we also estimate the effect of altering the step size on $E_{\text{e}}(\Delta t_{\text{pre}})$ and $D_{\dot{m}_d}$. In addition, we show how $D_{\dot{m}_d}$ affects the thermal discomfort D_{T} following the discussion in Section 2.4.

4.1 Simulation Results

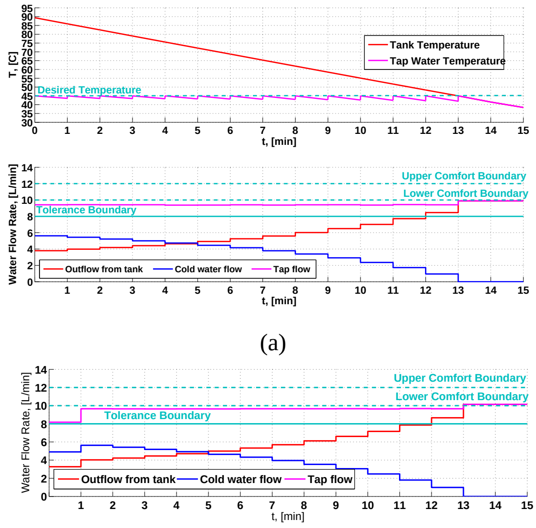
Pareto optimal solutions for WAs with different duration can be found in Fig. 11. The graphs represent the electric energy consumed for water preheating $E_{\text{e}}(\Delta t_{\text{pre}})$ as a function from the flow rate discomfort $D_{\dot{m}_d}$. The discomfort is shown in percentage as a share of the maximum $D_{\dot{m}_d}$ for the current parameters of water usage. The color of each solution on Pareto



(a)

(b)

Figure 11: Varied Duration ((a) 7-minute WA, (b) 15-minute WA).



(a)

(b)

Figure 12: 15-minute WA & Fully Charged Tank ((a) $D_{\dot{m}_d} = 10\%$, (b) $D_{\dot{m}_d} = 3\%$.

front refers to the certain range of tap water flows and the time during which the user experiences $D_{\dot{m}_d}$. The bar exhibits these values in the following format $[\dot{m}_{\text{d, min}}, \dot{m}_{\text{d, max}}], \Delta t_D$, which is the minimum and the maximum flows reached during the WA and the duration of $D_{\dot{m}_d}$. The two sequential solutions from Fig. 11(b) that have different $D_{\dot{m}_d}$ and equal $E_\text{e}(\Delta t_\text{pre})$ are plotted in Fig. 12.

The influence of the control step size on the flow discomfort $D_{\dot{m}_d}$ is demonstrated in Fig. 13. The thermal discomfort D_T has been calculated for every solution on Pareto front of the considered WAs. The connection between two different types of discomfort, D_T and $D_{\dot{m}_d}$, is represented for the 7-minute WA in Fig. 14(a). Colorful curve illustrates a number of Pareto optimal solutions where each color refers to a certain tap water temperature range $[T_\text{max}, T_\text{min}]$ and discomfort duration ΔT_DISC specified in the bar. We also show how the relation between D_T and $D_{\dot{m}_d}$ depends on the control step size in Fig. 14.

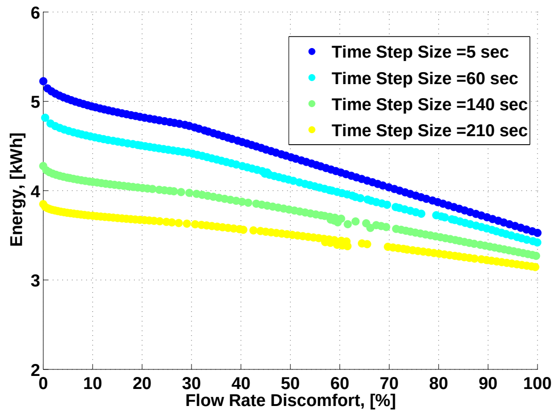
4.2 Discussion of Results

According to the set of Pareto optimal solutions shown in Fig. 11, the user can reduce $D_{\dot{m}_d}$ at the cost of the increased $E_\text{e}(\Delta t_\text{pre})$ and vice versa, indicating that a non-linear negative correlation between these functions.

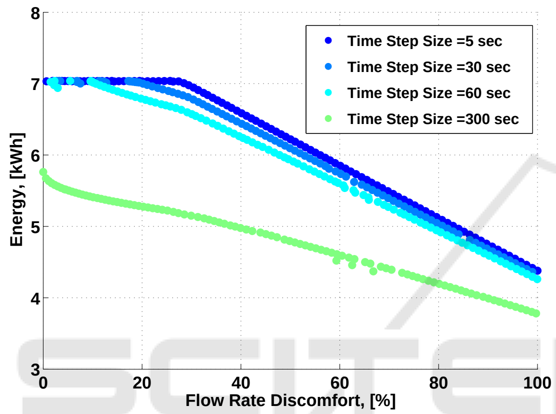
It is noteworthy that in case of intensive water usage the flow controller cannot handle the user request for the fixed temperature during the entire WA. For example, the tap water temperature inevitably drops within the last 2 minutes of the 15-minute WA as represented in Fig. 12(a). It can be explained by the limited capacity of the tank. Although the WH is preheated to the maximum temperature defined by safety reasons (90°C in our case), the thermal energy accumulated in the tank is insufficient to provide the user with tap water of the preferred 45°C along the whole WA.

As it can be seen from Fig. 11(b) minimization of $D_{\dot{m}_d}$ for long lasting WAs can be achieved without maximizing electric consumption. This situation takes place because the WH is fully charged and cannot be further heated. More rigorous examining of the neighbor solutions on Pareto front points out that such decrease of $D_{\dot{m}_d}$ results in a steep jump of the resulting tap water flow rate $\dot{m}_\text{d}$ as depicted in Fig. 12. Such sudden acceleration of the water flow can bring extra inconvenience to the user and thus should be also taken into account during the flow control.

As it follows from the simulation results illustrated in Fig. 13, long time lags between the flow control actions allow to minimize $D_{\dot{m}_d}$ spending less electricity than in the case of the frequent flow regulation. While the extension of control steps has a positive effect on $D_{\dot{m}_d}$ and $E_\text{e}(\Delta t_\text{pre})$, it has an negative effect on the thermal discomfort D_T as shown in Fig. 14. The longer steps permit the water in the tank cool down to the lower temperature which results in the increase of D_T. Considering the contrary effects of the step size on the two types of discomfort and $E_\text{e}(\Delta t_\text{pre})$ a compromise between $D_{\dot{m}_d}$ and D_T can be achieved by incorporating D_T as the third objective function for



(a)



(b)

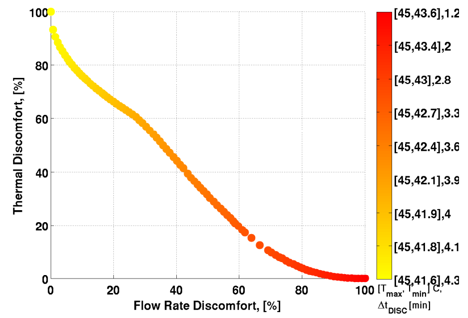
Figure 13: Varied Size of Timesteps ((a) 7-minute WA, (b) 15-minute WA).

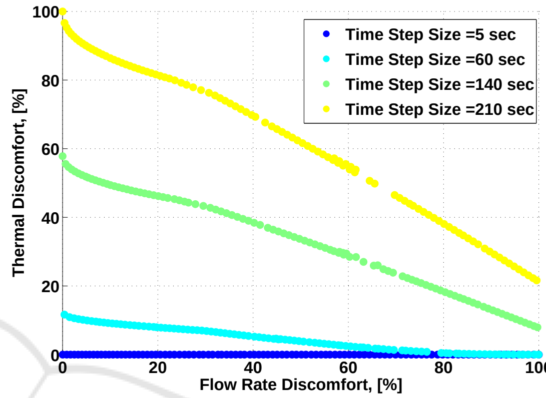
the multi-objective optimization problem and finding the optimal timing for the flow control actions.

The obtained Pareto fronts in Fig. 11 represent a simple, yet efficient way to visualize the detailed information about multiple solutions for flow rate control and their effect on energy consumption and user comfort. By picking any of the suggested solutions on Pareto front via the GUI the user can further demand the information of any level of complexity about the expected water usage such as the resulting tap and tank water temperature values, water flow rates in the whole hot water supply system and duration of $D_{\dot{m}_d}$ at every moment of the expected WA, for example, as shown in Fig. 11(a) and Fig. 12.

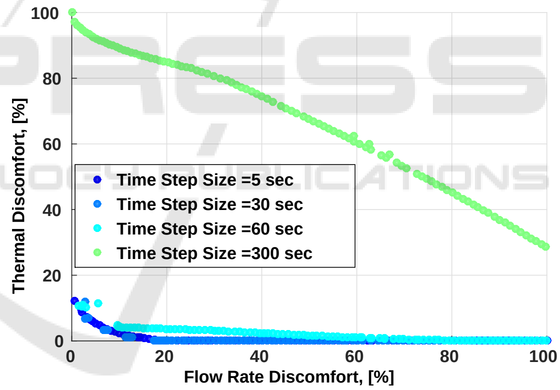
5 FUTURE WORK

The normal operation of the WH implies that the hot water outflow from the tank induces the equal inflow of cold water, which creates the needed pressure to deliver hot water to the tap and causes the insider WH temperature to drop. One might think of the ways to cut the cold water inflow in the WH so that the insider temperature remains fixed during WAs and there is sufficient pressure in the hot water pipe.





(a)



(b)

Figure 14: Effect on Thermal Discomfort ((a) 7-minute WA, (b) 15-minute WA).

In our studies we applied a linear relationship to model the user dissatisfaction with the aberrant tap water flow. The future work can concentrate on obtaining the realistic shapes of individual discontent functions.

Some extra work on UI improvement and real-world testing can be also suggested. Comparative feedback through the UI may lead to a sense of competition, whereas social comparison and social pressure may be especially effective when relevant others are used as a reference group (Abrahamse et al., 2005; Team, 2011). On the other hand, it is essential to provide a feedback about individual's influence on aggregated energy consumption (e.g., neighborhood), because having an insight about personal contribution to a global energy use/CO2 reduction problem a householder can estimate his input as valuable and continue to actively save energy (Abrahamse and Steg, 2011). Applying these phsycological principles to electric energy conservation domain means that the HWMS should provide a networking interface to connect an individual household into a 'green energy' network.

Learning such Pareto 'curves' in a broad range of scenarios of water usage and organizing them in a knowledge base by different users' preferences and diverse water usage scenarios could make it possible to forsee water individual usage habits over a day and in the future to set the right trade-offs in an automated way without interrogating the user and only based on the obtained knowledge.

The scenario considered in this paper can be also adapted to ToU double-rate tariffs in the future. For example, if the night price is lower than the day time electricity rate (e.g., Economy 7 in UK), then controller can preheat all the water in the period of lower energy cost.

The future work can be also done on the new type of user discomfort originating from the tap water flow acceleration. One can derive a new metric that quantifies user inconvenience from sudden variation of the water flow. To diminish this discomfort this metric could be, for example, translated into constraints for the flow control algorithm.

6 CONCLUSION

In this paper we pointed out a new possibility to improve the efficiency of energy consumption for water heating by means of the tap water flow rate control mechanism implemented in conformity with the user comfort demand. It can be expected that based on the information about impacts of the offered flow control solutions for a domestic electric tank water heater on energy consumption and personal comfort the end-user can consciously limit the tap flow rate in certain scenarios of the hot water usage and thereby can gain energy/money savings.

We introduced a metric that quantifies user dissatisfaction with the tap flow rate, the flow discomfort model, and extends the thermal discomfort model presented previously in our works. The flow discomfort model has been explicitly utilized in the flow rate control scheme by means of the multi-objective optimization and its performance has been demonstrated for the specific scenario of water usage where the user requests the fixed tap flow rate.

The paper has a special focus on the way the proposed flow control mechanism can be communicated with the user. By simulating several home WAs we illustrated a powerful potential of Pareto fronts to meaningfully group and cross-relate multiplicity of different individual solutions. Visualized in the user interface Pareto fronts enable to make focused trade-offs between the desire to save energy for water heating and to get the preferred quality of water service.

In addition, the analysis points out that the flow control step-size has opposite effects on the user flow rate discomfort and thermal discomfort respectively. To have a control over the both types of discomfort the size of the flow control steps should be optimally chosen.

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