Experimental implementation of a context-aware prosumer

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Abstract. This paper reports an experimental implementation of a flexible prosumer that adapts its behavior according to occupants’ objectives and system operator’s request. Model predictive control is incorporated into an existing building energy management system such that the energy management system can achieve user-defined objectives while quantifying energetic flexibility to support a stable and efficient system operation. Context-awareness is demonstrated through a series of experiments with energy efficiency, cost reduction, and carbon footprint reduction as occupants’ objectives. Besides, the flexibility of the prosumer is quantified in real-time and communicated to system operators. The results show occupants’ comfort and preference can be sufficiently guaranteed. Moreover, the flexibility quantification shows that the energy management system has considerable impacts on the levels of available flexibility.

1. Introduction

Nowadays, digitalization enables building energy management systems to operate in an occupant-centric manner [1]. Objectives such as user comfort, cost, energy efficiency, self-consumption, and flexibility can be included or combined according to the occupants’ needs [2]. At the same time, buildings have the potential to provide the much needed energetic flexibility to support the operation of the future distribution system [3]. For example, excessive photovoltaic (PV) output at the time of high solar irradiance and simultaneous Heat Pump (HP) consumption can lead to over-voltage and under-voltage issues respectively. Flexible buildings can contribute to addressing the local issues locally. The capability of achieving occupants’ customized objectives as well as reacting flexibly according system operator’s request for flexibility is defined as building context-awareness. Our previous work [3] investigates a flexibility quantification scheme in simulation to provide system operators with an overview of available flexibility. The results show that an implemented control strategy has notable impacts on the level of available flexibility. The current study complements the simulation-based study with real-world insights as all presented experiments were carried out using an occupied building. The results presented in this paper summarize and extend the project report [4]. The remainder of the paper is organized as follows: Section 2 presents the overall methodology of implementing the context-aware and flexible prosumer. Section 3 introduces the experimental setups. The experimental results related to control of Space Heating (SH) and Domestic Hot Water (DHW)
and flexibility quantification are provided in Section 4. Finally, Section 5 gives a brief summary, and areas for further research are identified.

2. Methodology

Model Predictive Control (MPC) is suitable to realize context-awareness by a weighted sum of multiple objectives. A generic compact formulation of an MPC’s Optimal Control Problem (OCP) is given by:

\[
\begin{align*}
\text{minimize} & \quad \sum_{t \in H} \sum_{i \in F} \omega_i f_i(x_t, u_t), \\
\text{subject to} & \quad g(x_t, u_t) \leq 0, \quad \forall t \in H, \\
& \quad h(x_t, u_t) = 0, \quad \forall t \in H, \\
& \quad x_t \in X, \quad \forall t \in H, \\
& \quad u_t \in U, \quad \forall t \in H,
\end{align*}
\]

where \(x_t\) denotes the states of all appliances, \(u_t\) denotes the control inputs, \(\omega_i \in \mathbb{R}_+\) is the customized weighting factor associated with the \(i\)th objective \(f_i(\cdot)\), and \(H\) is the set of time steps over the optimization horizon. Eqs. (1b) to (1e) are the operational constraints. A set of inequidistant sampling time intervals is used to reduce computational efforts [5]. Solving Eq. (1) gives the optimal state trajectory \(\{\tilde{x}_t | \forall t \in H\}\). Energy bounds are quantified by solving optimization problems with \(\{\tilde{x}_t | \forall t \in H\}\) as initial states and the operational constraints in Eqs. (1b) to (1e). The available flexible power levels and corresponding duration can be quantified following the calculation of energy bounds. Finally, the flexibility envelope can be obtained as shown in Figure 1. Interested readers are referred to [5] for a formal formulation.

Figure 1: Flexibility envelope quantification including (left) energy bounds, (middle) flexibility at one time instant and (right) flexibility envelope adapted from [3].

The implementation scheme of the context-aware prosumer is illustrated in Figure 2. The OCP formulated in Eq. (1) is solved every 15 minutes and only the decision of the next time step is implemented. At the same time, the optimal state trajectory \(\{\tilde{x}_t | \forall t \in H\}\) is utilized to quantify the flexibility envelope, which is communicated to the distribution system operator (DSO). The prosumer will be notified to provide flexibility according to system status.

3. Experimental setup

In a series of experiments, a fully equipped prosumer was considered [4], including HPs for SH and DHW, a stationary battery, an electric vehicle (EV), and a rooftop PV installation. Loads such as lighting and cooking stove were included in the experiments, although they were not controlled. The experiments were carried out at the NEST demonstrator of Empa in Dübendorf [6]. An occupied three-room flat was used and each room was treated as one zone.
Figure 2: Overall implementation scheme adapted from [3] and [6].

The whole flat is heated with water-based ceiling panels. While DHW is equipped with a water tank of 590 litre, there is no dedicated thermal storage for SH. SH and DHW require two inlet temperature levels and are supplied by different HPs. The temperature limits were set to [22 °C, 23 °C] and relaxed to [21 °C, 25 °C] between 8 am and 8 pm, when the occupants are likely not present. In principle this could also depend on occupants’ inputs. The DHW tank temperature limits were set to [45 °C, 60 °C] to ensure a sufficient amount of hot water inside the tank. Meanwhile, the tank temperature needs to be boosted to [59 °C, 60 °C] at least once a week to avoid Legionella contamination [7]. In the experiments, Sunday morning between 4 am and 6 am was chosen to implement such changes. Two control objectives were defined. Once a cost-aware operation with a local two-tier electricity tariff (0.13 CHF/kWh and 0.18 CHF/kWh) [3] and a fixed feed-in-tariff of 0.05 CHF/kWh. A second emission-aware operation optimized energy consumption according to the electricity emission intensity profile provided by our industrial partner [4]. The profile is calculated using data from ENTSO-E Transparency Platform [8]. Comprehensive test specifications, experiment plans, and full details of the facility can be found in [9].

4. Experimental results

In this section, closed-loop control experimental results of SH and DHW are discussed. The time resolution of all of the measurements is 15 minutes by re-sampling the data collected every 1 minute. Device models were obtained by using data from 2019. Note that the experiments are not of the same duration. A more detailed analysis of the experiments can be found in [4,5]. The experimental results of SH are summarized in Figure 3, which shows the temperature measurements of each room and the pre-defined temperature limits. The top plot shows the results of an experiment in October 2020 with energy efficiency as the main optimization objective. The temperatures of the two bedrooms (room 272 and room 274) were kept close to the lower limits most of the time. Additionally, large temperature deviations over upper limits can be observed in room 273 that has large window area and the deviations were mainly driven by high solar irradiance. Moreover, a drop of temperature in room 273 can be observed (marked by the grey period ①) because the window was opened for a sustained period. The bottom plot
shows the experimental results in November 2020 when emission-aware operation was the main objective. We can observe that temperature of all three rooms were close to the upper limits. This is because the controller tried to heat the room during the day when the electricity carbon intensity was low. High solar irradiance during the day also contributed to the temperature increase. Dramatic drops of temperatures can also be observed (marked by the grey periods 2 to 6) because the window was opened for a sustained period. Nonetheless, we can conclude that comfort was maintained as temperatures were mostly kept within the limits.

Figure 3: Experimental results of SH with energy efficient (top) and emission-aware (bottom) control.

The experimental results of DHW are shown in Figure 4, which shows the average tank temperature measurements, the pre-defined temperature limits and the hot water usage. The top plot shows the results of an experiment in October 2020 with cost reduction as the main optimization objective considering both the cost of electricity import and the revenue of export to the grid. The bottom plot shows the results of an experiment with emission-awareness as the main objective. In fact, it is the same experiment that leads to the results presented in the bottom plot of Figure 3. We can observe that the tank temperatures were kept close to the lower limits most of the time in both plots. When the temperature boost appeared in the horizon of the controller, the tank temperatures were gradually increased such that the tank temperature can comply with the pre-defined hygienic criteria. In contrast, a conventional controller normally utilizes hysteresis control strategy with a comfort zone of $[55\degree C, 60\degree C]$, which would result in higher average tank temperature. In all the experiments, flexibility envelopes were quantified, with which we can obtain the available flexibility levels that the existing DSO could utilize. More specifically, the duration that the SH/DHW power could be switched off without compromising comfort is a key indicator to use in the existing infrastructure, similar to how ripple control has been used to directly control large domestic appliances such as HPs [10]. The switch-off duration in different cases is summarized in Figure 5. We can observe that the SH HP cannot be switched off for more than 2 hours most of the experiment time. This is because the energy-efficient operation kept the room temperatures close to the lower limits as shown in Figure 5(a).
Figure 4: Experimental results of DHW with cost- (top) and emission-aware (bottom) control.

As a result, there is not much flexibility left for the existing ripple control infrastructure. In contrast, the results in Figure 5(c) show that the SH HP can be switched off for around 1 hour most of the time and up to 6 hours when the controller is emission-aware. Additionally, measurements show that average ambient temperatures were 8.8 °C and 5.5 °C for Figure 5(a) and Figure 5(c) respectively. In other words, SH HP can be switched off for longer duration even though the ambient temperature is lower, showing the impacts of the control strategy. As for DHW, results in Figure 5(b) and Figure 5(d) show that the DHW HP can be switched off for up to 24 hours. In comparison with the results of SH, DHW can be switched off for longer and provide more flexibility due to its storage. Comparing Figure 5(b) with Figure 5(d), we can observe that Figure 5(d) has more flexibility as power can be switched off for a longer period of time. Additionally, although the average water draw was 0.09 L/min and 0.18 L/min for Figure 5(b) and Figure 5(d) respectively, more flexibility is available in Figure 5(d). From the analysis above, we can conclude that the control strategy has notable impacts on the level of available flexibility. If a sufficiently large number of prosumers operate with unknown control strategies, DSOs may no longer use the ripple control infrastructure at least with the existing flexibility estimation method. Self-reported flexibility can be a solution to address the issue by providing an updated overview of flexibility without revealing extensive details of individual devices. Interested readers are referred to [5] for an example of flexibility provision.

5. Conclusion

With the advancement of information and communication infrastructure and advanced control strategies, buildings can both achieve user-defined objectives and provide flexibility to a system operator, and such capability we define as context-awareness. In this study, a fully equipped context-aware prosumer is demonstrated in a series of experiments with various objectives using a real occupied building. The results show that the control strategy has notable impacts on the level of available flexibility. The current work will be extended to account for modeling and forecast errors. Additionally, the interactions between the flexible prosumer and the system operator will be investigated.
Figure 5: Estimated probability density of switch-off duration for the SH HP ((a) and (c)) and the DHW HP ((b) and (d)).

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References
[1] J. Y. Park, M. M. Ouf, B. Gunay, Y. Peng, W. O’Brien, M. B. Kjærgaard, and Z. Nagy, “A critical review of field implementations of occupant-centric building controls,” Building and Environment, vol. 165, p. 106351, 2019.
[2] J. Drigoña, J. Arroyo, I. C. Figueroa, D. Blum, K. Arendt, D. Kim, E. P. Ollé, J. Oravec, M. Wetter, D. L. Vrabie, et al., “All you need to know about model predictive control for buildings,” Annual Reviews in Control, 2020.
[3] J. Gasser, H. Cai, S. Karagianopoulos, P. Heer, and G. Hug, “Predictive energy management of residential buildings while self-reporting flexibility envelope,” Applied Energy, vol. 288, p. 116653, 2021.
[4] Swiss Federal Office of Energy, “aliunid - versorgung neu: Feldtest 1.1.2019 – 30.6.2020.” https://www.aramis.admin.ch/Beteiligte/?ProjectID=43459. accessed: 19.04.2021.
[5] H. Cai and P. Heer, “Experimental implementation of an emission-aware prosumer with online flexibility quantification and provision,” Applied Energy, submitted.
[6] P. Richner, P. Heer, R. Largo, E. Marchesi, and M. Zimmermann, “Nest–una plataforma para acelerar la innovación en edificios,” Informes de la Construcción, vol. 69, no. 548, p. 222, 2018.
[7] H. Cai, S. You, J. Wang, H. W. Bindner, and S. Klyapovskiy, “Technical assessment of electric heat boosters in low-temperature district heating based on combined heat and power analysis,” Energy, vol. 150, pp. 938–949, may 2018.
[8] ENTSO-E, “ENTSO-E Transparency Platform.” https://transparency.entsoe.eu/, 2021.
[9] H. Cai, “Test specifications and experiment plans.” https://info.nestcollaboration.ch/wikipeapublic/research/currentprojects/aliunid/, 2020. accessed: 17.06.2021.
[10] N. Boogen, S. Datta, and M. Filippini, “Demand-side management by electric utilities in switzerland: Analyzing its impact on residential electricity demand,” Energy Economics, vol. 64, pp. 402–414, 2017.