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Multi-objective demand side scheduling considering the operational safety of appliances

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HIGHLIGHTS

- Operational safety of appliances is introduced in multi-objective scheduling.
- Relationships between operational safety and other objectives are investigated.
- Adopted Pareto approach is compared with Weigh and Constraint approaches.
- Decision making of Pareto approach is proposed for final appliances' scheduling.

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ABSTRACT

The safe operation of appliances is of great concern to users. The safety risk increases when the appliances are in operation during periods when users are not at home or when they are asleep. In this paper, multi-objective demand side scheduling is investigated with consideration to the appliances' operational safety together with the electricity cost and the operational delay. The formulation of appliances' operational safety is proposed based on users' at-home status and awake status. Then the relationships between the operational safety and the other two objectives are investigated through the approach of finding the Pareto-optimal front. Moreover, this approach is compared with the Weigh and Constraint approaches. As the Pareto-optimal front consists of a set of optimal solutions, this paper proposes a method to make the final scheduling decision based on the relationships among the multiple objectives. Simulation results demonstrate that the operational safety is improved with the sacrifice of the electricity cost and the operational delay, and that the approach of finding the Pareto-optimal front is effective in presenting comprehensive optimal solutions of the multi-objective demand side scheduling.

1. Introduction

Demand side scheduling aims to schedule the energy consumption of appliances in response to varying electricity prices over time, or to incentive payments, or when system reliability is jeopardized [1–3]. Multiple objectives have been considered in the demand side scheduling, such as the minimization of the electricity cost [4–8], the reduction in the delay of the appliances' operations [6,7], the improvement of the system reliability [9], the promotion of the renewable energy [10,11], and the improvement of the users' convenience level [8]. However, to the best knowledge of the authors, improving the operational safety of appliances has not been considered in demand side scheduling, and it should be paid more attention. 1083 fires caused by washing machines and tumble driers, and 475 fires caused by dishwashers had happened in the United Kingdom in 2011/2012 [12]. 8500 fires caused by home appliances had resulted in a 265 million dollar loss in the United States in 2010 [13]. It is evident that the consequences in the cases of the appliances' faults will deteriorate if the appliances are in operation during periods when users are not at home or are asleep. As the safety risk is of great concern to users, the operational safety is worth considering in demand side scheduling to further optimize the energy usage. The relationships between the operational safety and other objectives need clarified with the operational safety taken into account as a new objective.

Multi-objective demand side scheduling (MODSS) takes into account several objectives simultaneously and is usually solved by converting multiple objectives to a single objective [4–7]. Zhao et al. [6] and Mohsenian-Rad and Leon-Garcia [7] weigh the importance of multiple objectives and sum the objectives with their corresponding importance factors as the final objective function. One objective is optimized with constraints that confine the deviations of other objectives from their corresponding optimal

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values within certain ranges as described in [4,5]. However, the approach that weighs the importance of each objective in the final objective function makes the physical meaning of the final objective unclear, and its solution largely depends on the predefined weights of multiple objectives [6,7]. The approach that sets constraints to objectives does not optimize the objectives in the constraints and it only requires them within certain ranges, and the solution of this approach depends on the predefined ranges in the constraints [4,5]. An alternative approach to those that tackle multiple objectives through the conversion and then the optimization of the final objective function, is to simultaneously optimize multiple objectives directly through finding the Pareto-optimal front. This approach does not depend on the predefined weights or ranges, and it simultaneously optimizes multiple objectives with clear physical meaning [14]. The approach of finding the Pareto-optimal front is presented in [14]. However, to the best knowledge of the authors, no previous work compares this approach with the other approaches in dealing with MODSS.

In this paper, the improvement of appliances' operational safety is proposed as a new objective of the MODSS, to further optimize the scheduling of energy consumption. The approach of finding the Pareto-optimal front is adopted to deal with the MODSS and to investigate the relationships between the operational safety and other objectives. This approach is compared with the approach that weighs the importance of multiple objectives and the approach that sets constraints to the deviations of objectives from their optimal values. For convenience, these three approaches are referred to as the Pareto approach, the Weigh approach and the Constraint approach, respectively. The operational safety is taken into account based on whether users are at home and awake to supervise the appliances' operations. Apart from the operational safety, the electricity cost and the operational delay are considered in the MODSS. Since the reduction of the electricity cost is the motivation for users to participate in demand side scheduling, it should be considered in the MODSS [1,4,5]. As the operational delay relates to the wish that the operations of the appliances are completed as soon as possible [7,15,16], the operational delay is more often given a higher weighting compared with other objectives [6,7,15,16] and is taken into account in this paper. Three situations considering the operational safety together with one or both of the electricity cost and the operational delay are considered in the comparison between the Pareto approach and the other two approaches. Furthermore, a method considering the relationships among the three objectives is proposed to make the final scheduling decision of energy consumption among solutions of the Pareto-optimal front.

The rest of the paper is organized as follows. The system model is presented in Section 2. Section 3 introduces the multi-objective demand side scheduling and the three approaches dealing with multiple objectives are presented in Section 4. Section 5 introduces the method of decision making based on the Pareto approach and simulations are presented in Section 6. Finally, conclusions are presented in Section 7.

2. System model

The structure of the energy management system is shown in Fig. 1. Based on the day-ahead real-time electricity price, the users' demands for the appliances' operations and the users' at-home and awake status, the energy management controller (EMC) will automatically control the energy consumption of shiftable (time adjustable) appliances.

The EMC is the main part of the energy management system. The electricity price is transmitted to the EMC a day ahead with the real-time price for next day from the utility company [8,17,18]. The users' demands for the appliances' operations and their at-home and awake status are defined and input to the EMC by users as users have different demands for appliances' operations and their at-home status and awake status are different as well. Based on the day-ahead real-time electricity price, users' demands and status, the EMC works out the energy consumption schedules for home appliances based on the proposed method that will be introduced in the following sections. Then the appliances will be controlled automatically by the EMC according to the energy consumption schedules through the home area network [6,7]. The home appliances are categorized into shiftable appliances and manually operated appliances. The energy consumption of shiftable appliances, such as water heaters and washing machines, is flexible and they can be scheduled in advance [18–20], and are assumed to be non-interruptible [5]. The manually operated appliances whose energy consumption is fixed and manually controlled based on users' real-time demands, such as TV and lights, are not included in the energy management system [21].

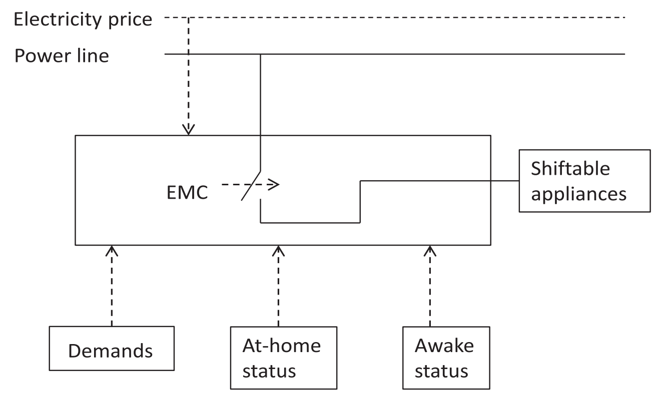

Fig. 1. Energy management system.

The users' demands for appliances' operations include the length of operation time (LOT) and the operation time interval (OTI), which are represented by γ_a and $[\alpha_a, \beta_a]$ for appliance a, respectively [6], where α_a indicates the earliest start time of the operation and β_a indicates the deadline for finishing the operation. Considering the general operation time of appliances, 1 h is divided into 5 time slots [6] and the LOT is mapped to time slots with one time slot representing 12 min. For example, the LOT is 2, i.e., $\gamma = 2$, for an appliance whose operation length is 24 min. The LOT is approximated to be the greater and nearest integer when the operation length is not an integer multiple of 12 min [6]. One day is mapped to 120 time slots and the OTI is also mapped to the corresponding time slot. For instance, the OTI is from 1 to 60, i.e., $\alpha = 1,\ \beta = 60$, for an appliance whose operation is predefined between 12 midnight and 12 noon.

3. Multi-objective demand side scheduling

The multiple objectives including the minimizations of the appliances' operational unsafety (i.e., the maximization of the appliances' operational safety), the electricity cost and the appliances' operational delay are considered in MODSS, and their formulations are presented as follows.

3.1. Multiple objectives

- Objective 1: Minimization of appliances' operational unsafety

  The operational unsafety of appliances is taken into account based on whether users are at home and awake to supervise the appliances' operations. The situation that the energy consump-