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Household Appliance Commitment with Appliance Dependency Modelling

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***Abstract*—Smart home energy management is one of the main topics in demand side management. In the literature, many Home Energy Management Systems (HEMSs) are designed to optimally schedule the operation of household appliances. However, most of existing work ignores the lifestyle related requirements of the user on the appliances' operational dependencies. In this paper, we propose a new household appliance commitment model that integrates both the operational constraints of individual appliances and the dependency constraints among them. In this sense, the proposed HEMS can more accurately reflect the end user's lifestyle requirements. Several simulation scenarios are designed to validate the proposed HEMS.**

***Index Terms*—Smart building, smart home, demand response, demand side management, smart grid**

I. INTRODUCTION

Thanks to the prevalence of wireless communication technology, ubiquitous sensors, and building automation facilities, modern buildings are increasing the evel of automation specified for their day-to-day functioning. In the context of important building automation systems, the Home Energy Management System (HEMS) [1] takes the role of managing operation of building energy resources to serve the residential user while respond to demand side management signals from the utility.

The home energy resources managed by HEMSs usually include distributed renewable energy sources, Battery Energy Storage Systems (BESSs), Plug-in Electric Vehicles (PEVs), and controllable appliances. The commitment of home energy resources under a dynamic electricity tariff penetrated environment is actively studied in recent years, with some representative works introduced in the following. [2] proposes a HEMS that optimally schedules the operation of household appliances under a real-time pricing scheme. [3] optimally schedules a Residential Battery Energy Storage System (RBESS) and multiple controllable household appliances to accommodate a rooftop solar power source. In [4], a HEMS is developed to harness the back-up power supply capability of PEV. In [5], a HEMS is designed, which dynamically schedule appliances in each dwelling unit based on which the power demand of the whole community is forecasted and reported to the utility. In [6], a commitment scheme for electric water heaters is proposed to minimize the electricity cost while consider the user's thermal comfort settings. In [7], a mix-inter linear programming model is proposed for controlling air conditioner loads, so as to better accommodate the rooftop photovoltaic solar power source. In [8], a multi-objective home energy management scheme is proposed and it optimizes the electricity bill and appliance usage convenience respectively for the user. In [9], a multi-stage home energy management system is developed, that performs day-ahead scheduling and real-time correction on home energy resources. [10] models the user's dissatisfactions that is used to design a household appliance scheduling model.

As for the controllable appliances, the existing works consider the operational constraints of individual appliances e.g. [2-10]). These constraints include the permitted operation time range constraint, power consumption constraint, minimum online time constraint and thermal comfort constraint. The operational dependency requirements among the appliances are not considered, which are commonly observed in people's daily lives. For example, a user may require to run the induction cooker and smoke exhaust fan simultaneously in the cooking time. Another example is that the user might not run the pool pump and clothes dryer at the same time due to the large noise produced by the appliances. Based on the above considerations, this paper proposes a new HEMS that performs optimal appliance scheduling by integrating both operational constraints of the individual appliances and the dependency constraints among the appliances. The schematic of the HEMS is illustrated in Fig. 1. The proposed model can therefore better take the user's lifestyle requirements into account. We present our work as follows: In Section II, the generic appliance dependency modes are presented; in Section III, the proposed HEMS model is formulated; in Section IV, the solving approach is presented; the case studies are discussed in Section V; finally, Section V

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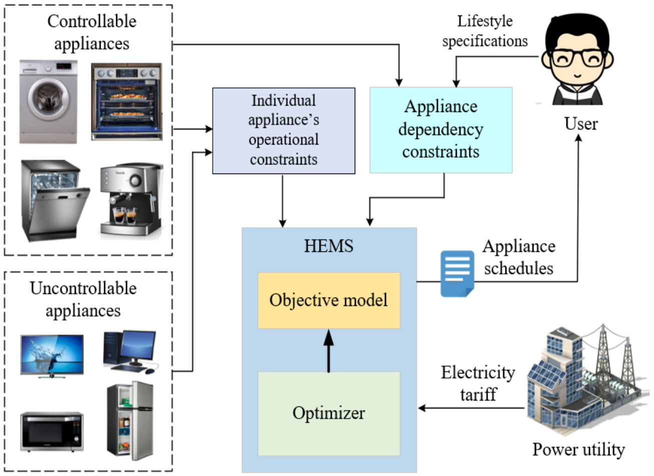

Fig. 1. Schematic of the HEMS

provides the concluding remarks.

II. MODELLING OF HOUSEHOLD APPLIANCE AND APPLIANCE DEPENDENCY

In the literature, the appliances managed by HEMSs can be generally categorized into two classes: thermostatically controlled appliances (TCAs, such as air conditioner and water heater) and non-thermostatically controlled appliances (NTCAs, such as washing machine and clothes dryer). In this paper, we only consider NTCAs. However, the proposed appliance dependency models can be applied on both TCAs and NTCAs, and the proposed HEMS can be further extended to incorporate TCA models.

A. Models of Controllable Appliances

The controllable appliances considered in this paper are categorized into two classes: interruptible appliances and non-interruptible appliances that are described as follows:

(1) Ω^{NIA} : Set of non-interruptible appliances, which operate at the nominal power and have a prescribed energy consumption that must be completed between a specific time range. The operation of the HERs cannot be interrupted until its completion. Typical HERs in this class include appliances like toaster and rice cooker;

(2) Ω^{IA} : Set of appliances operating at the nominal power and having a prescribed energy consumption that must be completed between a specific time range. The operation of the applications can be interrupted and resumed later. Typical appliances in this category include appliances like washing machineand dish washer.

B. Modelling of Appliance Dependencies

Various kinds of operational dependencies can be created on appliances. In this study, we model following six fundamental modes of appliance operational dependencies, where t_a^{start} and t_a^{end} represent starting and completion time of appliance a's operation; t_{xy}^{*2} and t_{xy}^{*1} are constants and there is $t_{xy}^{*2} \ge t_{xy}^{*1} \ge 0$.

1) Dependency mode 1: The task of one appliance (denoted as x) must be started after the completion of the other appliance (denoted as y) plus a time shift:

$$t_y^{end}+t_{xy}^{*1} \le t_x^{start} \le t_y^{end}+t_{xy}^{*2} \tag{1}$$

2) Dependency mode 2: The task of appliance x must be started after the start of appliance y plus a time shift. This dependency can be formulated as:

$$t_y^{start}+t_{xy}^{*1} \le t_x^{start} \le t_y^{start}+t_{xy}^{*2} \tag{2}$$

3) Dependency mode 3: The task of appliance x must be completed after the completion of appliance y plus a time shift.

$$t_y^{end}+t_{xy}^{*1} \le t_x^{end} \le t_y^{end}+t_{xy}^{*2} \tag{3}$$

4) Dependency mode 4: The task of appliance x must be completed after the start of appliance y plus a time shift:

$$t_y^{start}+t_{xy}^{*1} \le t_x^{end} \le t_y^{start}+t_{xy}^{*2} \tag{4}$$

5) Dependency mode 5: The overlapped running time of appliances x and y cannot be larger than a threshold γ :

$$\left|\{t|P_{x,t}>0, t=1:T\}\right| \cap \left|\{t|P_{y,t}>0, t=1:T\}\right| \le \gamma \tag{5}$$

6) Dependency mode 6: The overlapped running time of appliances x and y cannot be smaller than a threshold γ :

$$\left|\{t|P_{x,t}>0, t=1:T\}\right| \cap \left|\{t|P_{y,t}>0, t=1:T\}\right| \ge \gamma \tag{6}$$

It is noticeable that above dependency modes can be considered as atomic modes. More complex appliance dependencies can be created by compositing the above atomic modes. For example, to specify a dependency mode that K appliances must be operated sequentially, mode (1) can be repeatedly applied K times for the appliances.

III. HOME ENERGY MANAGEMENT SYSTEM WITH TIME-OF-USE AND DEMAND CHARGE TARIFFS

In this section, the formulation of the HEMS is formulated.

Objective:

The HEMS aims to minimize the one-day electricity cost for the home:

$$\min F = \sum_{t=1}^{T} \lambda_t P_t \Delta t \tag{7}$$

where T is the total number of scheduling time intervals; λ_t is the electricity price at time t (\$/kWh); Δt is time duration of one time interval (hour); denote $\mathbf{P}=[P_1, P_2, ..., P_T]$ is the power consumption vector of the unit, where P_t is the power consumption of the unit at time t (kW), calculated as:

$$P_t = P_t^{mr} + \sum_{n=1}^{N} s_{n,t} P_n^{rate} \tag{8}$$

where N is the total number of controllable appliances, i.e. $N = \left|\Omega^{NIA}\right| + \left|\Omega^{IA}\right|$; $s_{n,t}$ is the decision variable of the model. It is a binary variable, representing the status of the nth appliance at time t: 1-ON, 0-OFF; P_n^{rate} is the rated power of the nth appliance (kW); P_t^{mr} is the must-run power consumption of the unit at time t (kW);

Mandatory Constraints:

Model (7) is subjected to following constraints, which are mandatory applied to individual appliances:

(a) Energy consumption requirement constraint of controllable appliances:

$$\sum_{t=1}^{T} P_n^{rate} s_{n,t} \Delta t = D_n^{req} \quad \forall n = 1:N \tag{9}$$

where D_n^{req} is the task duration of the nth controllable appliance to complete its task (hour);

(b) Allowable operation time range constraint of controllable appliances:

$$s_{n,t} = 0 \qquad \forall t < t_n^{pmt1} \ and \ t > t_n^{pmt2}, n = 1:N \tag{10}$$

where [t_a^{pmt1}, t_a^{pmt2}] is the permitted operation time range of the nth appliance, specified by the user.

(c) Non-interruptible constraint for non-interruptible appliances:

$$\sum_{t=t_n^*}^{t_n^* + D_n^{req}/\Delta t} P_{n,t} = P_n^{rate} \qquad \forall n \in \Omega^{NIA} \tag{11}$$

where t_n^* represents the time interval index when the appliance n is first time to be turned on.

(d) Minimum online time constraint of interruptible appliances, which is applied to protect the mechanical device of the interruptible appliances:

$$\tau_{n,t}^{on} \geq \tau_n^{on,\min} \qquad \forall n \in \Omega^{IA} \tag{12}$$

where $\tau_{n,t}^{on}$ is the current online time duration of appliance n at time t (hour); $\tau_n^{on,\min}$ is the minimum online time requirement of appliance n (hour).

Optional Constraints:

Besides the mandatory constraints (9)-(12), model (7) could also be subjected to zero or multiple optional constraints from Eq. (1)-(6), which models the user's lifestyle related appliance operational dependencies.

IV. SOLVING APPROACH

The proposed model is a combinatorial optimization problem with integer variables and non-linear constraints. Therefore, it is hardly to use commercial solvers to solve it. In this study, we use a metaheuristic optimization algorithm previously proposed by the authors – Natural Aggregation Algorithm (NAA) [11, 12], to solve the model. The NAA algorithms has been applied in solving several power system optimization problems, such as [13, 14].

Each individual in NAA represents a potential HEMS solution, encoded as a vector with dimension of $\left|\Omega^{ICA}\right| + \sum_{a \in \Omega^{NICA}} (t_a^{pmt2} - t_a^{pmt1} + 1)$. The first $\left|\Omega^{ICA}\right|$ dimensions are integer variables, representing the starting time interval of the appliances in Ω^{ICA}. The task completion time can be correspondingly calculated based on the starting time and the appliance's operation cycle. The last $\sum_{a \in \Omega^{NICA}} (t_a^{pmt2} - t_a^{pmt1} + 1)$ dimensions are binary variables, representing the ON/OFF status of appliances in Ω^{NICA}; each consequentially $t_a^{pmt2} - t_a^{pmt1} + 1$ dimensions represent the ON/OFF status of the ith appliance within its permitted operation time range.

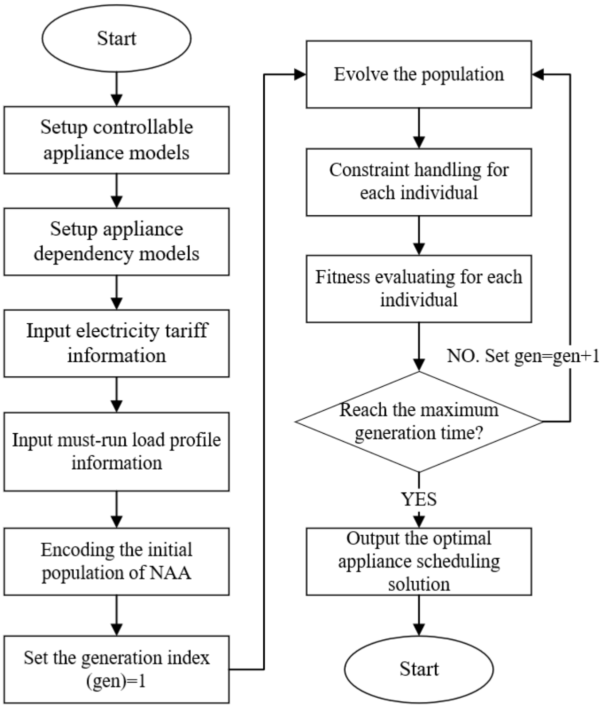

Fig. 2. Workflow of the NAA based solving procedures

The NAA-based home energy management optimization procedures are illustrated in Fig. 2.

V. SIMULATION STUDY

In this section, numerical simulations are conducted to validate the proposed appliance scheduling model.

A. Scenario Setup

A home environment is simulated, which consists of 12 controllable appliances with the setting shown in table I. A one-day must-run, uncontrollable load profile of the home is generated from the Australian "Smart Grid, Smart City" dataset [15]. The settings in table I are consistent with the life experience of a British household. A Real-Time Tariff (RTP) is considered. The scheduling horizon is set as 24 hours, starting from 8am. The duration of each control time interval is set to be 10 minutes.

We further consider two lifestyles of the user, which is partially reflected in two sets of appliance dependency relationships, shown in tables II and III, respectively. These two sets include five and two dependency constraints, respectively. We denote these two scenarios as Case 1 and 2, respectively.

TABLE I
CONFIGURATIONS OF CONTROLLABLE HOUSEHOLD APPLIANCES

Name	Task duration	Permitted time	P_a^{ca}	Interruptible	$\tau_n^{on,\min}$
Dish washer (DW)	1hr	[8pm, 8am]	1.8kW	YES	20mins
Washing machine (WM)	1hr	[8am, 7pm]	0.8kW	NO	N/A
Clothes dryer (CD)	80mins	8am, 7pm]	2.5kW	YES	20mins
Oven (OV)	1hr	[4-7pm]	1.3kW	NO	N/A
Induction cooker (IC)	80mins	[10:50am, 1:30pm]	2kW	NO	N/A
Vacuum Cleaner Charger (VCC)	2hrs	[12-7pm]	1.1kW	YES	20mins
Coffee maker (CM)	20mins	[8:00-9:10am]	0.3kW	NO	N/A
Toaster (TS)	20mins	[8:00-9:10am]	0.4kW	NO	N/A
Smoke exhaust fan (SEF)	80mins	[10:50am, 1:30pm]	0.3kW	NO	N/A
Dehumidifier (or humidifier) (DH)	30mins	[8pm, 7pm]	0.3kW	NO	N/A

TABLE II
LIFESTYLE SETTING 1

Index	Appliance Dependency	Explanation
1	$t_{CM}^{start}+0 \le t_{BM}^{start} \le t_{CM}^{start}+0$	Make coffee and bread simultaneously in the morning
2	$\left\|\{t\|P_{WM,t}>0, t=1:T\}\right\| \cap$ $\left\|\{t\|P_{CD,t}>0, t=1:T\}\right\| = 0$	The washing machine cannot be operated simultaneously with clothes dryer due to the large noise
3	$t_{WM}^{end}+0 \le t_{DH}^{start}$ $t_{CD}^{end}+0 \le t_{DH}^{start}$	The dehumidifier in the laundry cannot start to work until both washing machine and clothes dryer finish their tasks
4	$t_{IC}^{start}+0 \le t_{SEF}^{start} \le t_{IC}^{start}+0$	Run the induction cooker and smoke exhaust fan simultaneously

*Note: notations t_x^{start} and t_x^{end} representing the starting and completion time interval of the appliance '*x*', where *x* is an abbreviation in table II.

TABLE III
LIFESTYLE SETTING 2

Index	Appliance Dependency	Explanation
1	$t_{IC}^{start}+0 \le t_{SEF}^{start} \le t_{IC}^{start}+0$	Run the induction cooker and smoke exhaust fan simultaneously
2	$t_{WM}^{end}+0 \le t_{CD}^{end} \le t_{WM}^{end}+6$	The completion of clothes drying cannot be one hour later than that of the clothes washing

B. Simulation Results

By solving the optimization model, the appliance schedules of both cases are determined, as shown in Figs. 3 and 4. It can be seen that in both cases, all appliances are properly scheduled so that all the mandatory operational constraints (Eqs. (7)-(12)) are satisfied. Meanwhile, the lifestyle-related appliance dependency constraints for each case are satisfied as well. For example, in Fig. 4 shows that in Case 1, the HEMS ensures that the running time of washing machine and clothes dryer do not overlap with each other to minimize the noise produced at night, while both appliances are scheduled to finish their tasks before the specified deadline (7pm). As required by the user, the dehumidifier starts its work after the completion of both clothes washing and drying. For both cases, the smoke exhaust fan is scheduled to work with the induction cooker to create a clean and comfortable cooking environment.

The total home load profiles of both cases are shown in Figs. 5 and 6, respectively. The RTP tariff used in this simulation is also plotted. The figures clearly show that the HEMS well schedules the appliances to avoid the peak electricity prices, while ensuring the appliance operational constraints. Therefore, the HEMS can help the user to optimize the home energy consumption and reduce the electricity bill.

To further quantify the home electricity cost, we compare Case 1 and Case 2 with two more benchmark cases denoted as Case 3 and 4, respectively:

(1) Case 3: Model (7) is solved, and mandatory constraints (8)-(12) are considered. No appliance dependency constraints (i.e. Eqs. (1)-(6)) are considered;

(2) Case 4: No appliance scheduling is considered. That is, each appliance starts to work at time t_a^{pmt1}, and keeps running until completion of the task.

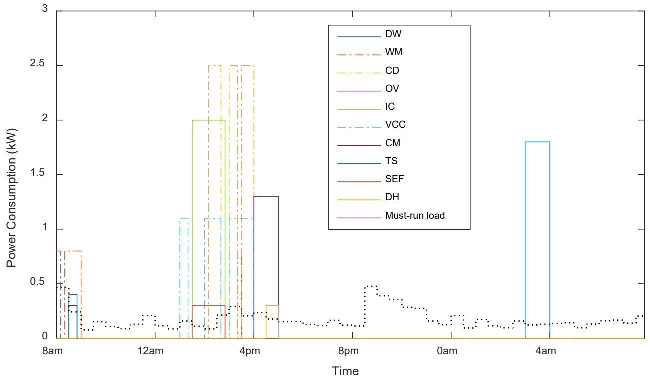

Fig. 3. Appliance scheduling results of lifestyle 1 (Case 1)

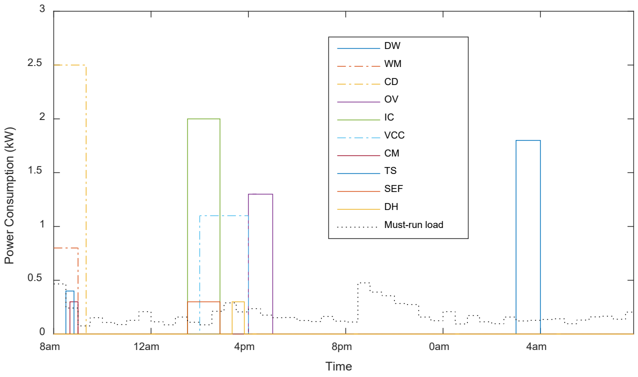

Fig. 4. Appliance scheduling results of lifestyle 2 (Case 2)

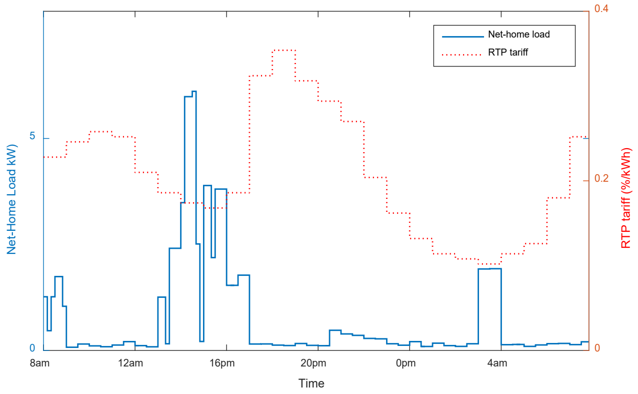

Fig. 5. Net-home load profile of Case 1

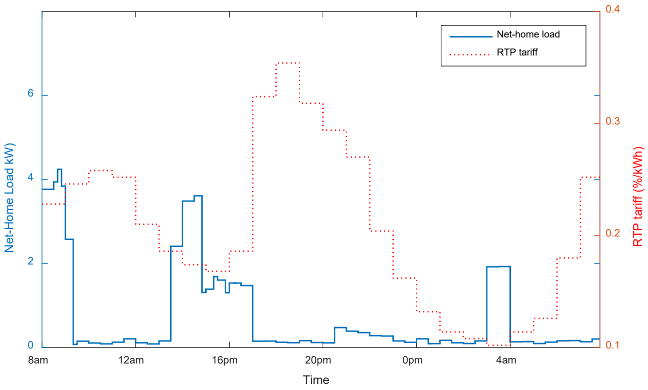

Fig. 6. Net-home load profile of Case 2

TABLE IV
ELECTRICITY COST COMPARISON OF FOUR CASES

	Case 1	Case 2	Case 3	Case 4
Cost	\$3.02	\$3.28	\$2.64	\$3.91

Comparison results on electricity cost of the four cases are reported in table IV. The results show that with different lifestyle settings, electricity costs under Case 1 and Case 2 are similar. When no appliance dependency considered (Case 3), since constraint number is reduced, there is more appliance scheduling flexibility. As a result, Case 3 has least electricity cost (\$2.64). However, in this case, the lifestyle requirements of the user are not satisfied and this solution would not be preferred by the user. When there is no HEMS (Case 4), the home electricity cost significantly increases. These results highlight the effectiveness of the proposed HEMS.

VI. CONCLUSION

The paper proposes a new home energy management system that incorporates the lifestyle requirements of the user. The requirements are interpreted as a set of appliance dependency constraints. Our simulation results show that the proposed HEMS is effective in ensuring the user's life convenience and in optimizing the home energy consumption.

The approach presented in this paper relies on the fact that, residential energy management, dependency constraints mong appliances should be considered together with operational constraints of individual appliances to achieve a satisfactory solution for the user. We envisage that more demand side management applications can be constructed in future based on the modelling framework presented in this paper.

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