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Finding Optimal Energy-Saving Operations in Home Network System Based on Effects between Appliances and Environment

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Abstract

We have been studying energy-saving schemes using the Home Network System (HNS), integrating multiple appliances and sensors at home. In our previous research, we defined an appliance/environment effect, with which a set of lower-energy operations were explored. However, this method did not consider the side-effects to multiple environment properties, nor optimization of the operations.

To cope with the restrictions, this paper first presents a method that analyzes the contribution of each operation to the environment properties, using the Goal-Oriented Requirement Language. We then represent the selection of energy-saving operations by a boolean vector X, and characterize each property by a polynomial $f(X)$ with coefficients of the contribution. Finally, the problem is reduced to a mathematical programming, finding an optimal solution X_o that minimizes the power consumption.

1. Introduction

Saving energy at home is now a crucial problem. Houses are furnished with a variety of electric household appliances and equipments. Several products and solutions for the energy-saving at home have come onto the market (e.g., [1] [2]). However, the existing products basically try to improve a *single* appliance at a time. A major breakthrough can be expected if multiple appliances are orchestrated together via network. Thus, the great potential of the home energy-saving lies in the next-generation *Home Network System* (HNS, for short) [3][4].

In our previous work [5], we proposed a method within the HNS that recommends a set of energy-saving appliance operations for the given user's requirement. Specifically, we defined an effect of every appliance operation to an environment property (e.g., temperature, humidity, power consumption, etc.) as appliance/environment effects (denoted by *A/E effect*). For a given user's operation p, the HNS tries to find another operation q that has a similar A/E effect to p's but consumes less energy than p. For example, suppose that a user requests "Turn on air-conditioner (say, AC.on)", while a cool breeze is blowing outside home. Since the HNS understands that AC.on has an A/E effect [decrease temperature], energy-saving operations that can [decrease temperature] more cheaply or efficiently are recommended, for example: (a) "Open window" instead of AC.on, or (b) "Turn on fan" with AC.on.

However, the previous method had two restrictions.
(Restriction R1) The A/E effect of every operation was limited to a single environment property. In fact, there exist appliances that may influence multiple properties(i.e., side-effects). For instance, AC.on decreases not only temperature but humidity. The ignorance of the side-effects may cause an unexpected result against user's requirement.
(Restriction R2) The previous method just enumerated the operations without showing which the optimal choice is. The decision was left to users, which often requires complex evaluation.

To overcome the problem, this paper presents a new framework that can derive optimal energy-saving operations. For R1, we propose a modeling method of the A/E effect using the *GRL (Goal-Oriented Requirement Language)* [6]. In the GRL, we model the environment properties and the appliance operations as goals and tasks, respectively. In the analysis, each task is regarded as a means to accomplish some goals with a degree of positive or negative contribution.

For R2, we propose a method that derives optimal energy-saving operations based on the mathematical programming. Specifically, for a set $\{O_1, O_2,.., O_n\}$ of the appliance operations, we define a Boolean vector X = (x_1, x_2,.., x_n) $\in \{1,0\}^n$ representing whether should be chosen or not. Next, based on the GRL model obtained, we quantify each environment property by the degree of contribution, represented by a polynomial formula over. Finally, the problem is reduced to an optimization problem finding a solution X_o = (x_{o_1}, x_{o_2},.., x_{o_n}) minimizing the power consumption, subject to user's requirements and environmental constraints.

To demonstlate the effectiveness, we conduct case studies in which two different requirements for "heating room" are satisfied by the proposed method.

2. Preliminaries

2.1 Home Network System(HNS)

In the next-generation smart home, house-hold appliances and sensors get smarter and can be connected to networks. These devices are integrated via networks to provide value-added services. The system comprised of such smart appliances is called *Home Network System* (HNS, for short).

The HNS makes it possible to remote-control and monitor home appliances. Also it can orchestrate multiple appliance together to provide value-added integrated services. We have so far constructed an actual HNS (CS-27HNS) in our laboratory by using various home appliances and sensors [7]. In the CS-27HNS, each networked appliance has a set of control APIs for Web services.

2.2 Energy-Saving Activities at Home

Although the electrification of house makes our life convienient and comfortable, the total energy consumptions keeps increasing. Thus, saving energy at home is now a crucial problem. Several products and solutions for the energy-saving at home have come onto the market (e.g., [1] [2]).

On the other hand, guidelines of energy saving at home is opened to the public by enterprises and various organaizations. The Energy Conservation Center in Japan (ECCJ) [8] has encouraged the energy-saving behaviors in using the house-hold appliances. For example, "if outside is brighter than inside, we should turn off the light" etc. These guidlines are published by not only enterprises but also the individuals.

2.3 Using Home Network System to Recommend Energy-Saving Operations

The HNS can monitor the home environment with sensors, and can also control multiple appliances together via network. Therefore, the HNS can provide more fine-grained controls for the house to meet the energy-saving activities.

Figure 1 shows an example of the HNS where a variety of appliances are deployed. Every appliance has a set of *appliance operations*, each of which is associated with the electricity consumption. In the figure, we suppose that the user wants to make the room warmer. For the requirement, the user may request "turn on air conditioner heating". For this, the HNS does not just follow the instruction as it is,

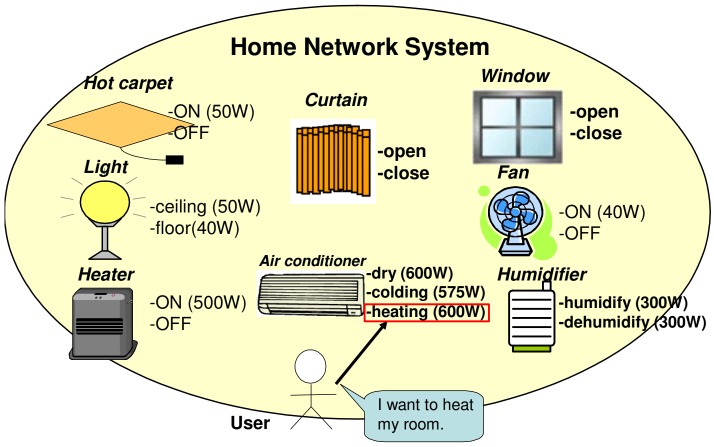

Figure 1. Recommending energy-saving appliance operations in HNS

but also can *recommend* other operations which are more energy-efficient. For instance, the HNS can recommend to use the hot carpet instead of the air conditioner, or to use the fan together with the air conditioner.

However, finding *optimal* operations is not so easy, because of the diversity of users' preferences. For instance, our preliminary experiment shows that satisfactory means to the requirement of "heating a room" vary from person to person, described as follows:

User A: I will use the electric warm carpet only. It is sufficient for me, and I care the electric usage.

User B: As long as the total electricity is below 500W, I will use the best combination of appliances.

User C: I will use air-con and heater together. I don't mind the energy saving as I hate chilling.

3. Previous Method

3.1 Appliance/Environment Effects

This section briefly review our previous method [5]. The basic ideas to save the energy within the HNS are (1) to *replace* energy-consuming operations with energy-saving ones, or (2) to use *extra* operations that increases the energy efficiency. However, each appliance has a particular set of operations. As a result, it is not easy to find which operations can be replaced or count as the extras.

To cope with the problem, we have proposed a notion of *appliance/environment effects* (A/E effects) in [5]. The A/E

Table 1. A/E effects and power consumptions of popular appliance operations in HNS

	A/E effect				
appliance method	direct effect	indirect effec	strength	precondition	power consumption(W
Airconditioner.heating(	temp+		high		575
Window.open()	temp+		low	out temp > in tem	0
Carpet.on()	temp+		low		50
Heater.on()	temp+		high		500
Airconditioner.cooler()	temp-		high		625
Window.open()	temp-		low	out temp < in tem	0
Light.on()	bright+		high		40
Curtain.open()	bright+		low	out light > in light	0
Fan.on()		temp[delta]+	high		40
Window.close()		temp[delta]+	low		0
Curtain.close()		temp[delta]+	low		0

effect is an effect of an appliance operation to an environment attribute such as temperature, light, and humidity. It is used to abstract the appliance operations by their interactions to the environment. The A/E effect is defined by the following four elements: direct A/E effects, indirect A/E effects, strength, precondition.

If a given appliance operation m has a direct impact to an environment attribute p, we define a *direct A/E effect* from m to p. For example, "turn on air-conditoner cooling" has a direct A/E effect to temperature, while "turn on light" has a direct A/E effect to brightness. Each effect has a direction of impact, where the positive (or negative) impact is specified by "$+$" (or "$-$", respectively).

Some operations don't influence for the environment attributes directly, but may have *indirect* impacts with respect to the efficiency of changes. For example, "turn on fan" does not change the temperature itself, but increase the heat efficiency by circulating the air flow. For such an operation, we associate an *indirect A/E effect*. Thus, "turn on fan" has an indirect A/E effect to temperature, which can be efficiently used together with "air-conditioner heating". Each indirect effect also has a direction of impact, where the positive (or negative) impact is denoted by "$\triangle+$" (or "$\triangle-$").

Even if two appliance operations have the same A/E effects, degree of intensity might be different. For example, both "turn on air-conditioner cooling" and "open the window." have the same direct A/E effect "temperature +". But degree of influence for temperature is obviously different. So, we characterize the difference as *strength*. Also, the direction and the strength of the A/E effects are sometimes *conditional*, depending on the time and/or surrounding context. So, we define *pre-condition* to specify the context where the effect is actually caused.

Table 1 summarizes the A/E effects, and power consumptions of popular appliance operations in HNS.

3.2 Recommendation Algorithm for Energy-Saving Operation

Using the A/E effects, we proposed a recommendation algorithm of energy-saving operations. For a given input x of appliance operation, the algorithm finds other operations y's that have the same direct A/E effects but consume less energy than x, and recommends y's as *alternative operations* of x. Simultaneously, the algorithm looks up operations z's that have indirect A/E effects supporting the direct A/E effect of x, and recommends z's as *supporting operations* of x.

For example, suppose the configuration in Table 1 where the inside room is colder than outside. If a user request "Air-conditioner.heating()", the HNS interprets its A/E effect [temperature+], and searches less-energy operations that have [temperature+]. So, "Carpet.on()" and "Heater.on()" are recommended as the alternative choices. Also, the HNS recommends "Fan.on()", "Window.close()" and "Curtain.close()" as supporting operations for "Air-conditioner.heating()".

3.3 Limitations of Previous Method

The previous method had two major restrictions.

(Restriction R1) The A/E effect of every operation was limited to a *single* environment attribute. In fact, there exist appliances that may influence multiple properties(i.e., side-effects). For instance, Air-conditioner.on decreases temperature as well as humidity. The ignorance of the side-effects may cause an unexpected result against user's requirement.

(Restriction R2) The previous method just enumerated the operations without showing which is the optimal choice. Since the requirements for energy-saving vary from user to user, it is impossible for the HNS (even for the users) to determine the best appliances operations without the explicit requirement.

4. Proposed Method

4.1 Key Idea

To overcome the restrictions, we propose a new method based on the following key ideas.

(Key Idea 1) Modeling A/E effects with GRL

We analyze interactions between the environment properties and the appliance operations for considering side-effects. For this, we propose a modeling method using the Goal-oriented Requirement Language(GRL).

(Key Idea 2) Finding optimal energy-saving operations by mathematical programming

Based on the GRL model, we obtain the contribution of each operation to the environment, and use this to represent the user's requirement. We then formulate a optimizing problem minimizing the power consumption where the requirements are the satisfied. The optimal energy-saving operations are finally calculated as a solution of the mathematical programming.

4.2 Analyzing A/E Effects with Side Effect

4.2.1 Goal-oriented Requirement Language(GRL)

To consider the side-effects of each appliance operation, we need to represent n-to-n relationships between the appliance operations and the environment attributes. For this, we propose to use the Goal-oriented Requirement Language (GRL) [6]. The GRL is a schematic language that supports the goal-oriented requirement modeling.

In the GRL, a primary objective is called *goal*, and is described by a rounded rectangle. Any means to achieve the goal is called *task* described by a hexagon. If a task has a positive effect to a goal (called *positive contribution*), an arrow from the task to the goal labeling a positive integer is drawn. Similarly, if a task has a negative effect to a goal (called *negative contribution*), we draw an arrow with a negative integer.

4.2.2 Modeling A/E Effects Using GRL

Using the GRL, we model the A/E effects taking the side-effects into account. Specifically, we describe every environment attribute as a goal, and represent every appliance operation as a task. If there exists any effect from an operation to an environment attribute, we define the positive/ negative contribution from the task to the goal, and draw an arrow. Moreover, for each contribution we specify the degree of intensity (we call *coefficient*) by analyzing how much effect each task gives to the goal.

Values of the coefficients may depend on many factors including the current environmental status, the floor plan, the layout of the appliances. So, it is generally difficult for the end-users to determine the precise values. Therefore, we assume that all the coefficients are determined by service vendors and/or environmental specialists, and that the values are given beforehand. We also suppose that for every arrow (i.e., effect) a coefficient is specified by an integer. If the effect is an indirect A/E effect, we represent the coefficient with $\triangle$.

4.2.3 Example

Figure 2 shows a example of the GRL diagram modeling the A/E effects within the HNS. For the simplification, we describe only four environment attributes (temperature, humidity, brightness and power consumption) in the figure. Twelve tasks are specified as tasks, each of which affect some environment attributes. The coefficients are specified as variables $(a, b, c, ...)$ supposing that their values are not yet determined.

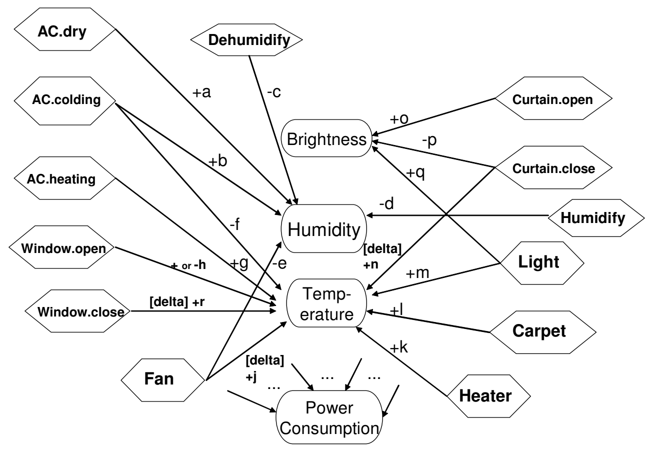

Figure 2. sample of modeling A/E effects using GRL

4.3 Finding Optimal Energy-Saving Operations

4.3.1 Reducing to Mathematical Programing

For a given user's requirement of the energy-saving, finding an optimal set of appliance operations is not so easy. For this, we propose a method that derives optimal energy-saving operations based on the *mathematical programming*.

For a set $O = \{o_1, o_2, ..., o_n\}$ of all appliance operations in the HNS, we introduce a Boolean vector $X = (x_1, x_2, ..., x_n)$, where x_i represents whether o_i should be chosen (x_i = 1) or not (x_i = 0). We call such a vector X *operation selection vector*. Then, we try to characterize every environment attribute e as a polynomial function $e(X)$, which is used to specify the user's requirement R. Finally, the problem is reduced to be a mathematical programming finding a optimal solution X_o satisfying R. That is, X_o represents the optimal selection of the energy-saving operations meeting the user's requirement.

4.3.2 Characterizing Environments by A/E Effects

To formulate the mathematical programming, we here characterize every environment attribute using the operation selection vector and the A/E effects analyzed by the GRL.

Let $O = \{o_1, ..., o_n\}$ be a given set of appliance operations, and let $X = (x_1, ..., x_n)$ be a operation selection vector. Also, let $E = \{e_1, ..., e_m\}$ be a set of all environment attributes. Suppose now that a GRL with respect to O and E is given, and that there exists a direct A/E effect from $o_i \in O$ to $e_j \in E$ whose coefficient is specified by d_{ij}.

Then, for every environment attribute $e_j \in E$, we characterize the absolute intensity of e_j by the *total contribution* of the direct A/E effect, which is represented by:

$$D_{e_j}(X) = d_{1j} * x_1 + d_{2j} * x_2 + ... + d_{nj} * x_n$$

Note that $D_{e_j}(X)$ is a function over $X \in \{0, 1\}^n$. That is, if an operation o_i is chosen (i.e., $x_i = 1$), the coefficient d_{ij} is accumulated as the contribution to e_j.

Next, we consider the indirect A/E effect. Suppose that there exists an indirect A/E effect from $o_i \in O$ to $e_j \in E$ whose coefficient is specified by g_{ij}. Then, we define the impact of the indirect A/E effect on e_j as follows:

$$G_{e_j}(X) = 1 + g_{1j} * x_1 + g_{2j} * x_2 + ... + g_{nj} * x_n$$

Note that $G_{e_j}(X) = 1$ when $g_{ij} = 0$ for all $i(1 \leq i \leq n)$. The indirect A/E effects increase the efficiency of the direct A/E effects. Therefore, we adjust the absolute contribution $D_{e_j}(X)$ derived from the direct effects by multiplying G_{e_j} obtained by the indirect effects. Thus, we define the adjusted contribution of e_j as a product of $D_{e_j}(X)$ and $G_{e_j}(X)$:

$$C_{e_j}(X) = D_{e_j}(X) * G_{e_j}(X)$$

Note that the total contribution equals to $D_{e_j}(X)$ if there is no contributions from the indirect A/E effects.

4.3.3 Solving Optimization Problem

Now, for every environment attribute $e_j \in E$, we can represent the contribution of appliance operations to e_j as a polynomial function $C_{e_j}(X)$. The function can be used to specify the user's requirements as well as the the environmental constraints. For example, the requirement "I want the contribution to the temperature to be greater than 15" can be formalized as [$C_{temp}(X) \geq 15$]. Or "the total power consumption must be below 620W" might be encoded to [$C_{power}(X) \leq 620$]. Thus, the problem is to find the optimal solution X_o satisfying the all requirements and constraints. More specifically, we define the following optimization problem.

MAXIMIZE (or MINIMIZE) $C_{e_k}(X)$
SUBJECT TO
[$C_{e_{j1}}(X)$ *cmp* a_1] AND ... AND [$C_{e_{js}}(X)$ *cmp* a_s]

The first line defines the *object function* to be maximized or minimized, which should be specified by a contribution function $C_{e_k}(X)$. Following lines define a *constraint condition*. It is supposed to be given by a conjunction of conditions over $C_{e_{jl}}(X)$, where *cmp* represents a comparative operator and a_l is a constant.

The object function has to be determined based on the user's primary goal on the energy saving. Whereas, the constraint condition is supposed to be given by user's requirements and environmental constraints. We assume that these are given from users in some way.

5. Case Study

5.1 Overview

To demonstrate the effectiveness, we conduct a case study assuming a practical setting with the CS27-HNS[7].

First, from all appliances in the CS27-HNS, we extract operations that influence the environmental attributes and analyze their A/E effects. Table 2 shows concrete values of coefficients which was variables in Figure2. The raw "Boolean vector" defines a mapping between fourteen appliance operations and the elements $x_1, ..., x_{14}$ of the operation selection vector. Each of the following rows defines the coefficient of each operation to a environment attribute within the direct or indirect A/E effects. As a result, we obtain the total contribution for the environment attributes shown in Figure 3 (a).

In this case study, we consider two slightly different requirements for "warming the room". Although their goal is similar, two requirements would yield different combinations of appliance operations.

Requirement R_A: Heat and moisturize the room a bit with as little power consumption as possible.

Requirement R_B: Heat the room as effectively as possible with the power less than 620W.

5.2 Case A

First, we encode Requirement R_A using the total contributions to the environment attributes. In this case, we specify a constraint condition [$C_{temp}(X) \geq 15$] (the total contribution to temperature is more than 15) AND [$C_{humid}(X) \geq 5$] (the contribution to humidity is more than 5). Under this constraint, we determine the object function as [MINIMIZE $C_{power}(X)$] (minimize the power consumption). Thus, the problem can be formulated as shown in Figure 3(b). By solving this problem, we get the optimal solutions $X_o = [0, 0, 0, 1, 0, 1, 1, 0, 0, 0, 0, 0, 1, 0, 1]$, which suggests to use the ceiling light, the floor light, the fan, and the carpet to satisfy Requirement R_A.

5.3 Case B

For Requirement R_B, we simply specify the constraint condition that [$C_{power}(X) \leq 620$] (the total power consumption is less than 620W). Under this constraint condition, we determine the object function as [MAXIMIZE

Table 2. Parameter settings for CS27-HNS

		Airconditioner			Humidifier		Light		Curtain		Window		Fan	Heater	Carpet
		heating	colding	dry	humidify	dehumidify	ceiling	floor	open	close	open	close	on	on	on
	operation selection vector	*x1*	*x2*	*x3*	*x4*	*x5*	*x6*	*x7*	*x8*	*x9*	*x10*	*x11*	*x12*	*x13*	*x14*
direct A/E effect	Temperature	10	-10	0	3	0	1	1.5	0	0	-3	3	0	6	4
	Humidity	3	-4	-6	7	-7	0	0	0	0	-2	0	0	0	0
	Brightness	0	0	0	0	0	7	6	5	-5	0	0	0	0	0
	P.Consumption	575	625	650	300	300	50	40	0	0	0	0	60	500	50
indirect A/E efffect	[delta]temp	0	0	0	0	0	0	0	0	0.1	0	0.2	0.4	0	0
	[delta]humid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	[delta]bright	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	[delta]P.C	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Temprature $C_{temp}(x) = (10x_1 - 10x_2 + 3x_4 + 1x_6 + 1.5x_7 - 3x_{10} + 3x_{11} + 6x_{13} + 4x_{14}) * (1 + 0.1x_9 + 0.2x_{11} + 0.4x_{12})$

Humidity $C_{humid}(x) = (3x_1 - 4x_2 - 6x_3 + 7x_4 - 7x_5 - 2x_{10}) * (1)$

Brightness $C_{bright}(x) = (7x_6 + 6x_7 + 5x_8 - 5x_9) * (1)$

Epower $C_{power}(x) = (575x_1 + 625x_2 + 650x_3 + 300x_4 + 300x_5 + 50x_6 + 40x_7 + 60x_{12} + 500x_{13} + 50x_{14}) * (1)$

(a) the total contributions for the environment attributes

R_A: Heat and moisturize the room a bit with as little power consumption as possible.

MINIMIZE: $C_{power}(x)$

SUBJECT TO:
$C_{temp}(x) >= 15$
$C_{humid}(x) >= 5$

SOLUTION
$X_o = (0,0,0,1,0,1,1,0,0,0,0,1,0,1)$
$C_{power}(X_o) = 500$

Recommend:
Humidifier, ceiling light, floor light, fan, carpet

(b) Case A

R_B: Heat the room as effectively as possible with the power less than 620W.

MAXIMIZE: $C_{temp}(x)$

SUBJECT TO:
$C_{power}(x) <= 620$

SOLUTION
$X_o = (0,0,0,0,0,0,0,0,1,0,1,1,1,1)$
$C_{temp}(X_o) = 17$

Recommend:
curtain(close), window(close), Fan, heater, carpet

(c) Case B

Figure 3. Case study

$C_{temp}(X)$] (maximize the contribution to the temperature). Thus, the problem can be be formulated as shown in Figure3(c). By solving this problem, we obtain the optimal solutions $X_o = [0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 1, 1, 1, 1]$, suggesting to use the curtain(close), the window(close), the fan, the heater, the carpet.

6. Conclusion

In this paper, we proposed a method of finding the optimal energy-saving operations using the modeling with the GRL and the mathematical programming. We also conducted a case study to demonstrate how the optimal operations are derived from different requirements.

To apply the proposed method to the practical use, it is important to determine the coefficients precisely, in accordance with individual environments. In the future work, we will investigate a method that can be used for the setting and tuning of the coefficients. Moreover, we plan to conduct feasibility studies with more practical requirements.

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