ECoS: Energy Control System for Smart Homes

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***Abstract*—One of the most efficient ways of reducing household energy consumption is through an online feedback system, which helps users in reducing their household energy. There are several research and commercial products available, yet over-consumption issues are still prevalent. An important factor fueling these issues is rendering too many features or information in the online feedback system, which results in a decrease in use of those applications over time. This study aims to develop a user-friendly system with a minimal set of features that would help the residential users achieve maximum savings. The energy control system (ECoS) consists of three major features, i.e., (a) visualization of energy, (b) recommendation of energy saving decision to users, (c) remote appliance control through recommendations, with thirteen sub-features. Based on an analysis of energy savings and user preferences, we identified the top seven sub-features suitable to be in ECoS to help users save energy. In addition, this article also provides recommendations to energy providers on the list of features that they should include in their online application to help their users save a significant amount of energy.**

***Index Terms*—smart homes, energy feedback, recommendations, appliance control, energy saving tips, visualization, household electricity**

I. Introduction

Household energy consumption accounts for one-third of the global energy consumption [1]. One of the primary and most prevalent ways to reduce energy consumption is through providing feedback to energy users [2]. There are various techniques and web/mobile applications to render the energy feedback to users [3]. Some of the information in the energy feedback system include visualization of total energy consumption, visualization of disaggregated energy consumption, energy saving tips, remote appliance control, etc. Even though so many features exist in these applications, over-consumption issues are still not completely resolved. Some of the reasons for the existence of these issues are (a) the applications and the related components are expensive and cannot be afforded by a large number of communities, (b) commitment to energy savings is very low due to external factors such as user motivation, their education, energy knowledge, etc., and (c) the usage of applications decreases over time either because of too many features or because of boredom using the application. This study concentrates on how to overcome the concern of having too many features on the web/mobile application leading to more energy saving [4], [5].

There are several research and commercial products focusing on building an effective solution to monitor and save the household energy through mobile phones, laptops, tablets, household energy monitor screen, etc. [6], [7], [8]. The number of features in an application increases day-by-day and is expected to save more energy. But, sometimes that leads to less, rather than more energy savings. The primary goals of this study are (a) to develop a simulation model of energy control system (ECoS) with three main features: visualization of household energy, energy saving tips/recommendations, and online remote appliance control; (b) to identify the total energy savings across all the features of the simulated system for the whole year; (c) to identify the minimal combinations of features to achieve maximum savings; (d) to identify the user preferences and their satisfaction on the minimal feature combination; and (e) to provide recommendations to the energy providers based on the complete analysis of the system.

II. Related Works

The related work targets both the research literature and the commercial products to identify the research gaps. Table I shows the analysis of various works in the research literature and the commercial solutions. The literature and the commercial solutions focus on three major features, (a) rendering energy saving recommendation, (b) visualization of energy, and (c) online remote appliance control. The recommendation feature of the energy saving system provides energy saving tips to the energy users. It may consist of (a) behaviour-based recommendation (R_B) - recommendation based on energy usage patterns, (b) constraint-based recommendation (R_C) - recommendation based on energy or cost constraints provided by the user to the system, (c) environment-based recommendation (R_E) - recommendations provided by the sensors installed in the environment, and (d) general recommendation (R_G) - recommendation that are useful to the user to save energy irrespective of energy patterns or sensors [S1 - S20].

The visualization feature of the energy saving system may consist of (a) archived visualization (V_A) - historical information of the household for the past one year, (b) comparison with peers visualization (V_C) - comparison of the energy consumption with neighbourhood or other similar peers, (c) disaggregated energy consumption (V_D) - energy consumed by each of the appliances, (d) house plan visualization (V_H) - visualization that shows the floor plan of the home with the status and location of the appliances, (e) monetary benefit visualization (V_M) - visualization of the cost of the energy consumption for this day/week/month, (f) peak energy visualization (V_P) - visualizes the time at which the maximum energy had been consumed, (g) real-time visualization (V_R)

TABLE I
ANALYSIS OF RELATED WORKS - RESEARCH LITERATURE AND COMMERCIAL SOLUTIONS

Study Source	**Study ID/System Features** (Study ID [S#] are mentioned in [9])									
Research Literature (2012 - 2017)	[S1]	[S2]	[S3]	[S4]	[S5]	[S6]	[S7]	[S8]	[S9]	[S10]
	$V_{A,D,R}$	$V_{M,R,S}$, $C_{S,T}$	$R_{B,C,G}$, $V_{A,M,P,R}$,	R_C, $V_{A,C,M,P,R}$	$R_{B,E}$, $V_{H,S}$, C_T	R_C, $V_{A,C,D,R}$	R_C,$V_{A,C,D,R}$	$R_{B,C,G}$, $V_{A,D,R}$	$V_{A,D,M,R}$	R_C, $V_{A,D,R}$,
	[S11]	[S12]	[S13]	[S14]	[S15]	[S16]	[S17]	[S18]	[S19]	[S20]
	$V_{A,C,D,R}$	R_G, $V_{A,C,D,R,S}$	$V_{A,C,D,M,R}$	R_G, $V_{A,D,M,R}$	$V_{A,C,M,R}$	$R_{C,G}$, $V_{A,C,D,M}$	$R_{B,C}$,$V_{A,C,R}$	$V_{A,D,H,R}$	$V_{A,C,D,R,M}$, C_T	R_G,$V_{A,C,D,R}$
Commercial Solutions	[S21]	[S22]	[S23]	[S24]	[S25]	[S26]	[S27]	[S28]	[S29]	[S30]
	R_G,$C_{S,T}$, $V_{A,C,M,R,S}$	$V_{M,R}$	$V_{A,D,R}$	R_E,V_R, $C_{S,T}$	$R_{C,G}$,$C_{P,T}$, $V_{A,M,P,R}$	$V_{A,M,R}$, $C_{S,T}$	$R_{C,G}$,$V_{A,C,R}$	R_C, C_T, $V_{A,M,R,S}$	R_C,$V_{D,M,R}$	R_C, C_T,$V_{A,C,M,R}$
	[S31]	[S32]	[S33]	[S34]	[S35]	[S36]	[S37]	[S38]	[S39]	[S40]
	R_C, C_T, $V_{A,C,D,M,R}$	$R_{B,E,G}$,$C_{S,T}$, $V_{A,D,M,R}$	$V_{A,M,R}$	$V_{A,M,R}$	$R_{B,C}$,$V_{A,C}$	R_B,$V_{D,S}$, C_T	R_E,$V_{D,R,S}$, C_T	R_C,$C_{P,T}$, $V_{A,M,R,S}$	R_B, $V_{A,C,M,R}$	$V_{A,D,M,R,S}$, C_T

Legend

Recommendation (R)
R_B - behaviour-based recommendation
R_C - constraint-based recommendation
R_E - environment-based recommendation
R_G - general recommendation
Visualization (V)
V_A - archived energy visualization
V_C - comparison with peers visualization
V_D - disaggregated energy visualization
V_H - house plan visualization
V_M - monetary benefit visualization
V_P - peak energy visualization
V_R - real-time visualization
V_S - appliance status visualization
Control (C)
C_P - postpone appliance operation
C_S - set temperature control
C_T - turn on/off control

- visualizes the current power consumed at home, and (h) appliance status visualization (V_S) - visualizes the current status of the appliance [S1 - S20].

The control feature of the energy saving system controls the appliances based on the recommendation or visualization. It may consist of (a) postpone appliance operation (C_P) - postpone or schedule the appliance operation to overcome peak pricing, (b) set the temperature of the appliance (C_S) - set/change the temperature of the heat pump, air conditioner, freezer, etc., and (c) turn on/off the appliance (C_T) - turn on/off the household appliance based on recommendation or visualization [S1 - S20].

A. Research Literature & Commercial Solutions

Table I shows the analysis of 20 related works in research literature (ranging from year 2012 - 2017) and 20 related works in commercial solutions, which are represented by S#s. The features are colour coded in Table I as red for visualization, green for recommendation, and blue for control.

B. Research Gaps

After analyzing both the research literature and the commercial solutions in Table I, there are few research gaps that needs to be addressed in the simulation of the system. They are as follows: (a) There is a lack of research focus on recommendation/energy saving tips for energy conservation. Existing literature provides recommendations or context-aware data (using various sensors). Some of the studies also include general recommendations (R_G). However, no research has focused in detail on developing a recommendation engine based on usage patterns (R_B), context-aware data (R_E), and user constraints (R_C). Also, the focus on the recommendation algorithm and its analysis are still in infant stage; (b) Current research on control engine does not include controlling the appliances based on the recommendations and the user preferences such as timing constraints, targeted energy consumption, and peak pricing; (c) Current research on visualization energy consumption, near-real-time power data, and energy prediction, but lacks presenting end-users the information about where exactly at home (e.g., kitchen, living room, etc.) the energy is being consumed; and (d) There exists no single system that integrates effective and useful features of these three aspects (visualization, recommendation, control) for energy conservation.

III. ECoS Overview

The primary objective of the ECoS is to develop a system model that will enable simulation of the behaviour of an average energy saving smart home with the applicability of all three major features to the real system without modifications. The features of ECoS are shown in Table II.

A. ECoS Inputs

Figure 1 provides an overview of the Energy Control System (ECoS), and this subsection explains the inputs to ECoS. The ECoS has (A) modelled appliances and sensors information - this study uses the simulated electricity information for which the behaviour of the household appliances and the sensors are modelled, (B) current and historical electricity data – these are simulated by the modelled appliances and sensors and are used to generate the recommendations, e.g., May 2016 energy consumption is 12% less than May 2015, (C) appliance status – represents whether the appliance is on/off. This is updated based on the user inputs, automatic control or manual control of the system, (D) recommendation templates – the customized templates are generated, and the standardized recommendations are from US-DoE and NZ-EECA websites, (E) appliance profile – referred to the energy usage pattern of each appliance, (F) peak pricing information

TABLE II
FEATURES OF ECoS

Recommendation	Visualization	Control
$R_{B,C,E,G}$	$V_{A,D,H,M,R,S}$	$C_{P,S,T}$

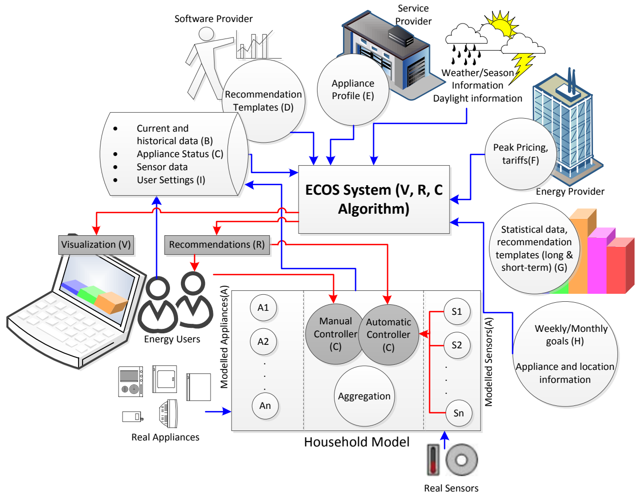

Fig. 1. ECOS - Overview

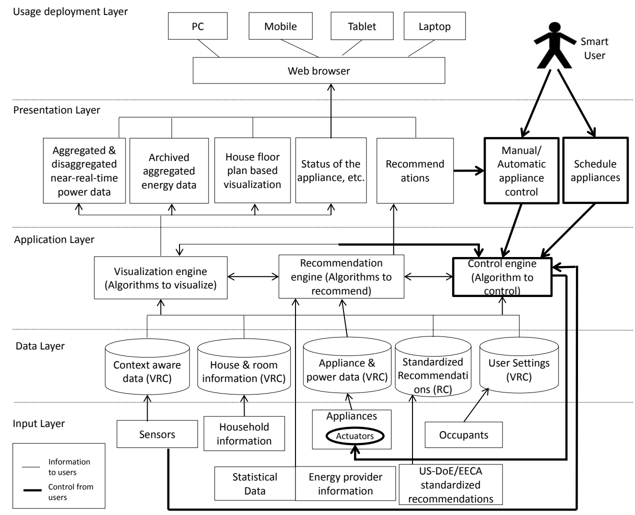

Fig. 2. ECOS Architecture

– this information is helpful in scheduling the appliances such as washing machine or dishwashing to optimize the energy consumption, (G) statistical information – this information is useful to make the recommendation to the users by comparing the energy with the statistical data, (H) user goals – users can set their weekly/monthly energy goals either in kWh or $, and (I) user settings – users can change the settings such as automatic/manual mode, preferred recommendations, etc. The inputs to ECoS are represented using blue arrow in Fig. 1.

B. ECoS Outputs

The outputs of the ECoS are the recommendations for energy users to save energy (*recommendation engine*), visualization of household energy (*visualization engine*), and manual and automatic control of appliances (*control engine*). These are rendered to the energy users to be viewed on a web application. The outputs from the ECoS are represented using red arrow in 1. The requirements of the ECoS were collected through the systematic literature review [10] and the survey.

IV. ECOS Architecture

ECoS architecture is described in the Fig. 2. ECoS has five different layers. They are (a) input layer, (b) data layer, (c) application layer, (d) presentation layer, and (e) client layer.

Input layer: The information that is present in the input layer are sensors (i.e., light intensity sensors, temperature sensors, human presence sensors), household information (i.e., information about the households such as floor plan, placement of appliances, etc.), appliances (i.e., number and type of appliances along with its energy rating), occupants (i.e., information on the number of residents and the age group and the amount of time they spent at home to improve the energy information), statistical data (i.e., NZ statistical data to compare the users' consumption with the average consumption in the city/state/country), energy provider information (i.e., information such as energy tariff and peak pricing), and standardized recommendations from US-DoE and EECA (NZ).

Data layer: The data layer includes the following information to be used by the three major features of ECoS. They are (a) context aware data (i.e., data that are received from the sensors such as temperature, human presence, etc.), (b) house and room information (i.e., appliance in each room, number of rooms, etc.), (c) appliance and power data (i.e., information regarding the appliances such as energy rating, appliance id, appliance name, etc.), (d) standardized recommendation (i.e., recommendations that are retrieved from the US-DoE websites and NZ-EECA websites), and (e) user preferences (i.e., preference specified by the user. For instance, the user can specify that the lights in any room can be automatically controlled based on human presence). The above-specified information is specified along with either 'VRC' or 'RC' in brackets, which means that the data is either fed into 'visualization-recommendation-control engine' or 'recommendation-control engine' respectively.

Application layer: The application layer involves the three major features of ECoS. The application layer utilizes the information from the data layer and uses the algorithm present in the application layer to output several information in the presentation layer.

Presentation layer: The presentation layer outputs the features such as V_A, V_R, V_H, V_S, R_E, R_G, R_B, C_T, C_S, etc.

Usage deployment layer: The household user can view their ECoS application in various kinds of devices such as PC, laptop, tablet, mobile, smart phones, etc. through their web browsers. The users, in turn, can control or schedule devices using the interface.

V. Implementation of ECoS using SystemJ

The ECoS was developed using a programming language named SystemJ. The primary reason to use SystemJ for modelling and simulation of the energy consumption of a home is that it is easy to replace the simulation with the real appliances and sensors with practically no changes to the existing prototype [11]. Also, SystemJ employs GALS (Globally Asynchronous and Locally Synchronous) model of computation that helps in modelling of a household test bench

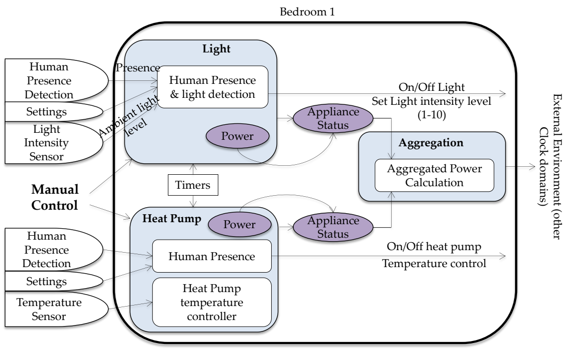

Fig. 3. Partial graphical representation of ECoS SystemJ sub-system (bedroom1)

through *clock domains* (asynchronous processes) and *reactions* (synchronous behaviours) in SystemJ, which is explained in Section V-B.

The first input to ECoS is the household model with eight rooms and 26 appliances, assuming four people staying in the home. The second input is the energy usage patterns of the appliances differentiated by time (weekdays/weekends), season, number of people at home, etc. As developing a novel user modelling was not within our research scope, we adopted the algorithm from [12], which models HVAC in correlation with user preferences. All other appliances usage patterns were derived with reference to the user behaviour modelling with activity graphs for four resident household as specified in [13].

A. SystemJ

A SystemJ program consists of a fixed number of mutually asynchronous processes called *clock domains* (CD), which encapsulate one or more synchronous concurrent behaviours called *reactions*. In ECoS, all the rooms in the home were represented as *clock domains* and the appliances in the rooms and several other features were coded as *reactions*. For communication between reactions two types of abstract objects called, *signals* and *channels*, were used. The *signals* were also used for communication with the external environment and the *channels* were used for communication between reactions in different *clock domains*. In ECoS, the communication of features (*reactions*) with the user (external environment) was through the *signals,* and the communication between the appliances and features were through the *channels*.

B. ECoS SystemJ Example

Fig. 3 is a partial graphical representation of ECoS SystemJ program. There are three *reactions*, light, heat pump and aggregation, which is encapsulated inside the *clock domain* called as bedroom1. There are several concurrent *behaviours* inside each *reaction,* and the communication between *reactions* takes place through the *channels*, 'power' and 'appliance status'. Communication with the external environment is through *signals*, 'ambient light level' and 'human presence'. This figure implements the decision making and generates the control actions through the actuators and schedules of activities. For instance, once the human presence sensor and light intensity sensor provide value to the system, ECoS

TABLE III
KWH/YEAR ANALYSIS FOR ECOS

Description	Energy Consumption (in kWh/year)			
	Test case 1 (High)	Test case 2 (Medium)	Test case 3 (Low)	Average
Without ECoS	8257.35	7892.07	7599.5	7916.31
With ECoS	6429.11	6134.34	6053.24	6205.56
Savings	1828.24	1757.73	1546.26	1710.74
% Savings/year	22.14%	22.27%	20.34%	21.58%

decides whether to turn on/off the light and also makes a decision to set the intensity of the light based on daylight. Similarly, various other modules were designed in SystemJ.

The energy usage pattern has been generated for the whole household (8 rooms, 26 appliances) assuming four users by modelling the appliances and sensors. Each appliance generates the recommendations (R_E, R_G, R_B, R_C) based on the several external factors (mentioned in Fig. 1) and was shown in the visualization (V_H, V_S) for the users and the reaction can either be turn on/off (C_T), schedule (C_S) or postpone (C_P) the appliance operation. ECoS calculates the energy savings based on C_T, C_S and C_P, i.e., energy consumption with and without C_T, C_S and C_P.

TABLE IV
EVALUATION OF ECOS USING ENERGY USAGE PATTERNS FROM THREE COUNTRIES (FOR ONE YEAR)

Country	Energy Consumption (kWh/year)		Savings/ year	% Savings
	Without ECoS	With ECoS		
Australia	6742.15	5442.25	1299.99	19.28%
USA	8492.45	6945.24	1547.21	18.22%
Finland	6478.23	5147.55	1330.68	20.54%

VI. RESULTS & DISCUSSION

A. Total Energy Savings

Table III depicts several test cases, which were different test conditions of the household energy simulation and calculated total energy consumption (in kWh) per year with and without ECoS. The input to the test cases were the usage pattern of each appliance for one year. The average total energy consumption (without ECoS) across the three test cases (high, medium, low energy usage - these three testcases were chosen out of 10 different testcase trials) was 7916.31 kWh/year (SD: 188.02, 2.38%), which was close to the average energy consumption in New Zealand for 100m^2 home (9373 kWh/year [14]). After using ECoS, the average total energy consumption was reduced to 6205.56 kWh/year, which achieved an average energy savings of 21.58%. Also, all the features were tested against energy usage patterns from three other countries (Australia, USA and Finland) and those results are shown in Table IV. A reason for Finland having the highest savings was that its usage pattern had more energy consumption from space heating as ECoS had more recommendations for the heater.

B. User preference on Online Feedback

A survey was conducted using *eSurv* online tool to understand the effectiveness of energy feedback. The primary purpose of the survey was to understand the user preferences

TABLE V
ENERGY FEEDBACK OPTIMIZATION

Energy Feedback	$R_E V_H C_T$	$R_E V_S C_T$	$R_E V_H C_S$	$R_E V_S C_S$	$R_B V_D C_T$	$R_B V_R C_T$	$R_G V_H C_T$	$R_G V_H C_P$	$R_G V_H C_S$
Energy Savings with ECoS (kWh/year)	384.9	240.1	232.56	208.32	161.13	160.26	147.24	142.93	80.29
Monetary Benefits	$115.47	$72.03	$69.77	$62.5	$48.34	$48.08	$44.17	$42.88	$24.09
% Savings	21.89%	13.66%	13.23%	11.85%	9.17%	9.12%	8.38%	8.13%	4.57%

for some of the top recommendations in ECoS. There were three important parts in the survey, (a) how likely were users to accept or act on the recommendations when they can control appliances physically, (b) how likely were users to accept or act on the recommendations when they can control appliances from a software application, and (c) how likely were users to accept or act on the recommendations when they can control appliances from a software application knowing the frequency of recommendation. There were totally 15 respondents, and they preferred software application over physical action by 20.25%. Also, they preferred the software application more by 5.17% when they know the frequency of occurrence of those recommendations. The online feedback also showed that the people preferred R_E (refer Legend in Table I) over all other types of recommendation.

C. Energy Feedback Combination and Savings

The combinations of features from visualization, recommendation and control were identified from Table II which have the ability to achieve higher energy savings. Fig. 4 identifies all the possible combinations of recommendation with visualization and control features. For instance, $R_E V_H$ C_T represents that the environment-based recommendation (R_E - e.g., *Turn off the light as the light intensity is very high*) can be viewed in house plan based visualization (V_H) and the action is to turn off the light (C_T) to save energy. Similarly, $R_G V_H C_P$ represents that the general recommendation (R_G - e.g., *postpone the washing after 2.5 hours due to peak pricing*) pops up in house plan based visualization (V_H) and the action is to postpone the appliance operation (C_P). There were several other combinations of features possible such as $R_B V_A$, $R_C V_M$, etc. but these can only achieve energy savings in longer run based on several factors pertaining to the users. Since, ECoS has the ability to track only the immediate savings based on the control feature, the long term savings cannot be tracked.

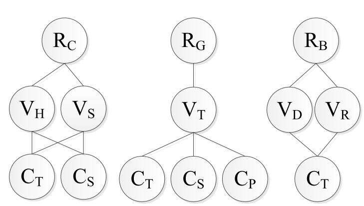

Fig. 4. Possible feature combinations of visualization, recommendation and control in ECoS

The energy savings were calculated for each combination using ECoS simulation model and is depicted in Table V for the medium test case (shown in Table III). Table V also shows the monetary benefits along with the percentage savings. The '% savings' depicts the percentage of savings for a given combination out of the total overall savings (1757.73 kWh/year - 21.58%). Table V shows that the top 4 feature combinations saved upto 60.63% of the total energy savings from ECoS and it includes only 5 features across visualization, recommendation and control (V_H, R_E, C_T, V_S, C_S).

D. Analysis of online feedback

For the final analysis, we combined three factors: (a) amount of energy savings, (b) user preferences, and (c) frequency of the energy feedback, as the previous section analyzed only against the energy savings. Fig. 5 represents a bubble chart where the size of the bubble shows the energy savings (larger bubble signifies more savings) and the graph co-ordinates represent the user preferences and frequency of the feedback. The frequency of the feedback is obtained from the ECoS simulation whereas the user preference values are obtained from the online survey (Subsection VI-B) where participants where asked to specify their likeliness of using certain types of feedback. The top six combinations of features from the total nine depicted in Fig. 5 are $R_E V_H C_T$, $R_E V_S C_T$, $R_E V_H C_S$, $R_E V_S C_S$, $R_G V_H C_P$, $R_G V_H C_T$. Although the combinations $R_B V_R C_T$and $R_B V_D C_T$ achieved more savings than $R_G V_H C_P$, they are not in the top six because very few users preferred that feature.

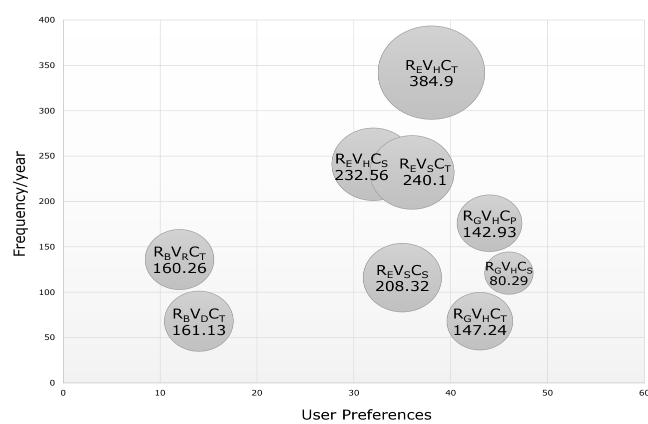

Fig. 5. Analysis to identify useful and effective combinations of features

E. Implications for energy providers

There are four major points that might help the energy providers while designing an application for their customers to save household electricity. They are as follows: (a) most of the recommendations concerning major consuming appliances such as heat pump, air conditioning, water heater, etc. should be applied automatically with minimal human intervention as users tend to prefer software application more than the physical action; (b) user preference is one of the primary factors which needs to be considered while designing the features. Some of the highly preferred features from the survey that may be considered for the online system are R_E, R_G, V_S, V_H, C_S, C_P and C_T; (c) visualization, recommendation and control features in ECoS play a significant role in energy savings. The combinations of features are presented in Table V and the energy provider may prefer to have the top four combinations ($R_EV_HC_T$, $R_EV_HC_S$, $R_EV_SC_T$, $R_EV_SC_S$) to achieve significant energy savings, as the top four sum upto approximately 60% of the total savings; (d) Fig. 5 depicts an analysis on energy savings by taking into account all three factors: energy savings, user preferences and frequency of recommendations and shows that the following combinations save more energy with high user preference and medium-high number of frequency per year: $R_EV_HC_T$, $R_EV_SC_T$, $R_EV_HC_S$, $R_EV_SC_S$, $R_GV_HC_P$, $R_GV_HC_T$.

From the above analysis, the authors would recommend the following features to be used in the energy saving software system: R_E, R_G, V_H, V_S, C_T, C_S, C_P with all the combinations covered from the grid analysis in Fig. 5. These seven features can account for upto 17.18% savings using the most preferred features. The primary advantages of this analysis are (a) significant amount of time can be reduced in application development, testing and maintenance, (b) the energy users are exposed to fewer features leading to less decision making and possible frustration, and (c) with fewer features, all the features are just a click away with a few navigation in dashboard.

F. *ECoS with minimal set of features*

Before applying user preferences, ECoS had 13 features spread across a very long dashboard with five menus. As per the recommendations shown in Subsection VI-E, the ECoS system was minimized to top four combinations of features, which includes only the seven features: R_E, R_G, V_H, V_S, C_T, C_S, C_P and is shown in Fig. 6.

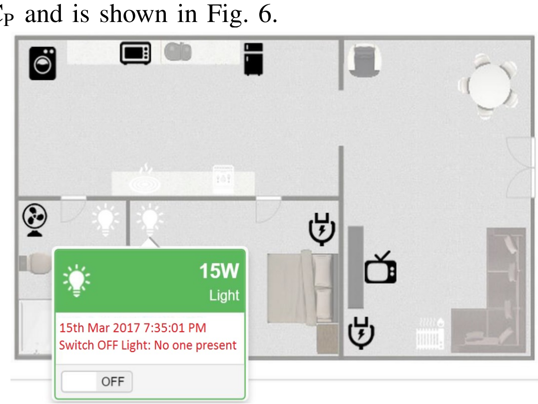

Fig. 6. ECoS with minimal set of features

VII. Conclusion & Future Work

The primary intention of this study was to develop an user-friendly online feedback system to reduce household energy consumption. An energy control system (ECoS) was simulated using a programming language, SystemJ with 13 features (six visualization features, four recommendation features, three control features) after identifying the research gaps from the existing literature and commercial solutions. The energy savings with and without ECoS was calculated, and the ECoS achieved a total of 21.58% savings.

One of the primary problems with the current day systems are visualizing too many features which results in more screen interaction time for users, which is when the energy conservation fails. For ECoS, the initial full set of 13 features was saving 21.58% but almost half of those features (six) were identified as low in user preference, risking the overall abandoning of the system by users. Hence, to improve the user-friendly characteristics of the system, an analysis was carried out to identify the best minimal combinations of features, which achieve maximum energy savings. This was achieved by applying a combination of three factors: energy savings, user preferences and frequency of recommendation. Our three-factor analysis resulted in the identification of top four combinations of features using individual seven features. These features account for 17.18% overall energy savings with seven features that were highly preferred by users and hence more likely to be used to derive actual energy savings. A future work would be to extend the model to include long-term energy savings in addition to immediate savings as captured by ECoS currently.

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