An Agent Based Approach to Find High Energy Consuming Activities

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Abstract— *Inhabitants' behaviour in buildings has a strong impact on the energy consumption patterns resulting in energy waste. The existing multi agent and centralized energy management approaches are focused on consumption optimization and load predictions without taking into account the inhabitants' behaviour. We argue that the consumption optimization without waste reduction is difficult. In this article we focus on the energy waste reduction associated with the inhabitants' behaviour. As an example a physical model for the fridge to predict the energy waste component and an agent based co-simulation methodology to identify high energy consuming activities, are developed. The proposed methodology demonstrates that based on the co-simulation results a library of high energy consuming activities can be built to support energy waste reduction efforts in Smart homes. It shall result in a shift from an energy manager towards an energy wizard to provide agents with the information on their consumption behaviour and alternatives to ensure the energy waste reduction.*

Keywords: Multi agent simulation, behaviour, energy consumption, human behaviour modelling

1. Introduction

Buildings account for 30-40% of the total primary energy use globally [1]. The inhabitants' behaviour has a significant impact on energy consumption and is an important factor for energy waste reduction [2]. We argue that the appliance consumption patterns are strongly influenced by the inhabitants' behaviour. Existing models that are used for the usage prediction of appliances are mostly based on presence/absence profiles [3]. Such profiles could be helpful for the appliances where energy is consumed only when they are turned on, e.g. lighting systems (active appliances). However, such profiles are insufficient for the appliances having continuous energy consumption e.g. fridge, freezers (cold appliances). Widén and his colleagues proposed a scheme to predict energy demand against different activities on both active and cold appliances, however the cold appliances operation was assumed unrelated to the activity patterns [4]. We argue that these appliances offer a great challenge to model them based on human behaviour due to the diversity of different possible actions on them and their resulting consumption. It will be interesting to see that how the energy waste component resulting from actions on cold appliances impacts the energy consumption optimization efforts in the Smart homes. In this article we have focused on the inhabitants' behaviour to identify high energy consuming activities with the support of proposed physical model for our example cold appliance « fridge ». This is done in a co-simulation platform using Brahms (agent modeling language) and simulink. The purpose of this co-simulation methodology is to assess the sensitivity of inhabitants' behaviour to the energy waste component and identify the high energy consuming activities to be transformed into a library for further use in the Smart homes. It will help in developing true smart environments as well as testing the design of new appliances models. It will also help to design the smart energy advisors suggesting human agents with the alternatives that minimize the energy waste component. This article is divided in 5 sections. Section 2 presents the literature review, on existing agent based approaches for energy management and the importance of inhabitants' actions on energy consumption. The modeling of household behaviour with an agent based approach is presented in section 3. The proposed physical model for the refrigeration cycles and the co-simulation methodology are detailed in section 4 and 5. Conclusion and future perspectives are discussed in the section 6.

2. Background

The literature review is divided in 3 sub sections: (i) agent based approaches for energy management, (ii) importance of inhabitants' actions on the energy consumption and (iii) human behaviour representation.

2.1 Agent based energy management

Multi agent system approaches have been used in the domain of energy management within buildings. Davidsson and Boman proposed and implemented a multi agent system based decentralized system to monitor and control the HVAC system (Heating, Ventilation and Air Conditioning) and lighting in office buildings [5]. Abras and his colleagues proposed a home automation system made up of software

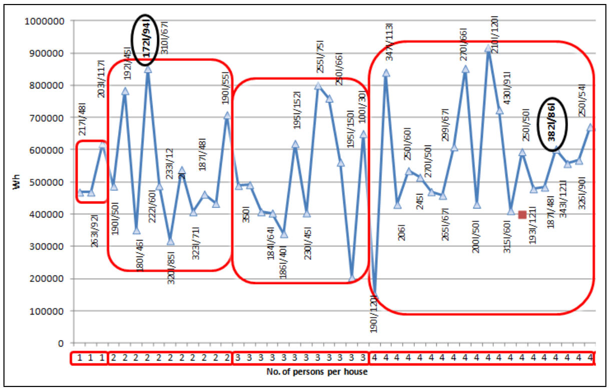


Fig. 1: Full year fridge-freezer consumption

agents that control appliances and sources [6]. It adapts power consumption to the available power resources. Agents in the MavHome project [7] predict the mobility patterns and device usage of inhabitants to satisfy the tradeoff between cost and comfort. Liao and Barooah developed a MAS approach to predict and simulate the occupancy at room and zone level in commercial buildings [8]. The anticipatory and reactive control of HVAC and lighting within smart homes has been implemented in a MAS [9]. [10] used an agent based control system in order to optimize the energy usage of a simulated residential water heating system. The above approaches do not take into account the impact of inhabitants' complex behaviour on the energy consumption for appliances. We argue that humans must be considered as active, intelligent agents for energy waste reduction in buildings.

2.2 Importance of inhabitants' actions on the energy consumption

Since human behaviour strongly influences energy consumption [2], an experiment has been performed on the IRISE database in order to see how inhabitants' behaviour affects energy consumption[1]. In figure 1 the number of people in the houses are shown on x-axis and the appliance consumption on y-axis. It shows the results of an experiment taking into account the number of people in each house and the specifications for the appliance. It can be seen that consumption does not depend solely on the number of people in the house and the size of the fridge freezer, but also on how the appliance is used by the people. For example, the first oval on the left in the figure shows that a fridge freezer with a capacity of 172l/94l in a 2-person house is consuming even more than the fridge freezer of almost double size in a 4-person house. The above experiment shows that human behaviour strongly affects energy consumption.

[1]This dataset is part of the European Residential Monitoring to Decrease Energy Use and Carbon Emissions (REMODECE) project. It contains energy consumption data, for each appliance from 98 French houses, recorded at every 10 minutes, over a one year period.

2.3 Human behaviour representation

The term "behaviour" refers to the actions or reactions of an object, usually in relation to its environment. In the literature, perception, cognition, memory, learning, social and emotional behaviour and psychomotor are considered to be the basic elements of human behaviour [11], [12], [13]. Human behaviour has also been analyzed through contextual factors including user, time, space, environment and object. These authors presented a user behaviour modeling approach called 5W1H for: what, when, where, who, why and how, which they then mapped to a home context (object, time, space, user and environment) [14]. Sempé and Quijano implemented an agent based modeling and simulation environment in order to study the use of electrical appliances by inhabitants [15]. Human behaviour can range from being very simple to very complex. The purpose here is to capture the behaviour that not only represents a simple presence or absence of an inhabitant in an environment but also represents a realistic interaction of the human with the environment. This means that the dynamic, reactive, deliberative and social behaviour of inhabitants must also be taken into account in order to fully understand its possible effect on energy consumption. This will help to consider the inhabitants as reactive, intelligent agents instead of simply "fixed metabolic heat generators passively experiencing the indoor environment" [16].

3. Modeling the household behaviour with an agent based approach

A belief-desire-intention agent model of the household's behaviour specifically for their interaction with the fridge is derived from an activity journal. The data was collected by a 2-person household, husband and wife, in which they had to specify the actions that they performed on the fridge as well as the reasons behind those actions. This reasoning mechanism when implemented into the agent based language gives them the power to think and behave the way humans do. Figure 2 shows that the agents in our model set their beliefs based on some perception from the environment. For example, perception of the other agents, objects, location and time etc. The environment could be the surroundings or the inner self for the agent. For example, in order to have the dinner, the perception from the inner self is the feeling of hunger, which now becomes a desire to eat. However, this desire will not be fulfilled by the agent until it reaches a certain threshold level and/or based on some cognitive influence. This cognition constitutes the reasoning mechanism that why the agent take or avoid taking some decisions. The social norms of the family, for example, could be one of the influencing factors on cognition. In this case, if the threshold for hunger is reached but the other agent has not arrived yet, based on the cognitive influence a new threshold level will be attained. If however the threshold

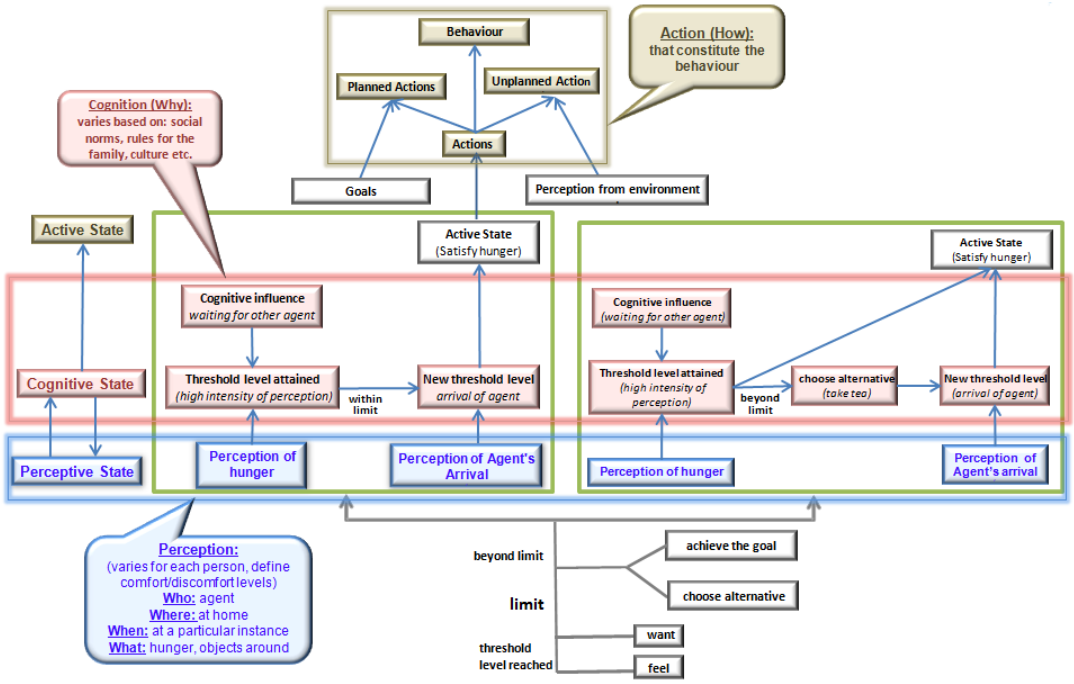


Fig. 2: Behaviour representation

level has crossed its limit, the agent will either take some alternative or his desire will be converted to an intention and he will achieve the goal, i.e. fulfill hunger. The actions caused by the agent's intentions are the planned actions, but if there is some new perception from the environment before he fulfilled the intention, it may lead to some unplanned actions. For example the planned actions to fulfill the hunger are to open the fridge, take the food out, cook it and then eat, but the unplanned actions upon the perception of a sudden pleasant change in the weather is to go to the restaurant and eat there. How the actions are performed finally constitute the behaviour of the agent. Brahms is a descriptive language to record and simulate the causal relations of inhabitant behaviour. The Brahms language [13] is compatible with our requirements. It is an agent oriented modeling/simulation environment and programming language based on belief-desire-intention agent architecture. It is able to represent people, things, places, behaviour of people over time, tools and artefacts used, when and where they are used. It also supports the communication between co-located and distributed people to support social behaviour. The key concepts are the workframes and thoughtframes. Workframes are the condition-action-consequence rules that allow agents to perform certain actions based on their beliefs and set new beliefs about the perception of the environment. Thoughtframes are used to trigger the reasoning behaviour of agents, they let the agents derive new beliefs based on existing beliefs and facts about the environment without performing some action. The BDI based behaviour model has been implemented in the Brahms environment. An example is shown in figure 3 where the agent (agentAdult1) is watching TV, he has some belief about the threshold level of his hunger. In the figure this belief is shown with the help of thoughtframes represented by a bulb symbol. The hunger level gradually increases as the simulation progresses. The agent will continue watching TV until he detects that the hunger level has reached beyond the threshold level. This detection mechanism is implemented using the concept of detectables in Brahms language which are used to interrupt, abort or continue the current activity. The first bulb symbol after 7:49:50 pm shows a pop-up of thoughtframes changing the agents' belief about the perception of hunger which is converted into the desire to eat. This desire finally becomes his intention as there is no other constraint or belief avoiding him from fulfilling the desire and he moves to the kitchen to prepare food, where he interacts with the appliances e.g. the fridge. The horizontal yellow bar just beneath the

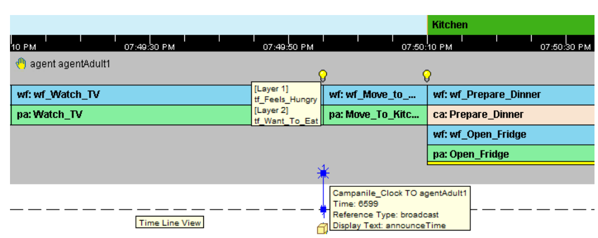


Fig. 3: Brahms simulation output

"Open_Fridge" primitive activity is used to represent the interaction of agents with some appliances. A brief example of the model presented in figure 2 is presented in section 5, where a link is established between human and appliance behaviour.

4. Fridge simulation model

The activities of inhabitants, their presence at different locations in the house, their control over different appliances and objects, and their communications can be modeled in the Brahms simulation environment. However in order to model the appliance behaviour a physical simulator is required which provides the information about physical aspects such as temperature inside the fridge, compressor states etc. We have developed our physical model as shown in figure 4. The description of the model variables is given in table 1.

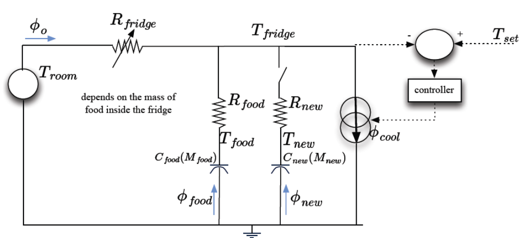


Fig. 4: Physical model for the fridge consumption cycle modeling

In this model we have made assumptions: (i) variation in the quantity of food inside the fridge is negligible, (ii) R_{food} = 0 and food temperature inside the fridge is assumed same as the inside temperature of the fridge. Figure 4 presents

Variable	Description
T_{fridge}(k)	inside temperature of the fridge during reactive time k, $\Rightarrow T_{fridge}(k) \in$ [Tmin; Tmax]
T_{room}(k)	ambiant temperature of the room
T_{new}	New food temperature
C_{new}	$M_{new}C_p$, capacity of a new food added to fridge
R_{fridge}	R_{open} + ζ(Rclose - Ropen) resistivity for heat exchange between inside fridge and room
R_{food}	resistivity to heat exchange between food and fridge
R_{new}	resistivity to heat exchange between new food and fridge
M_{food}	food quantity
M_{new}	quantity of a new food
T_{set}(k)	set-point temperature
$\pm\sigma$	Dead zone: $+\sigma$ and $-\sigma$ represent the upper and lower limits, above and below the set point temperature, where the compressor starts or stops respectively

Table 1: Description of model variables

the physical model of the fridge energy consumption cycles. The cooling power ϕ_{cool} is provided by the controller to maintain the setpoint temperature of the fridge. Similarly ϕ_o is the heating power coming from the room and affects the inside temperature of the fridge depending on the resistance R_{fridge}. ϕ_{food} and ϕ_{new} are the heating power coming from the food already present in the fridge and the newly introduced food respectively. Their affect on the fridge temperature depends upon their heat capacity and mass as well as the corresponding resistivity. In modeling the fridge cycles, the heat pump is an important element, let ρ be the performance factor of heat pump that yields $C_{elec} = \rho\phi_{cool}$ and fridge controller is made to follow the following criteria:
i) compressor stops working when the fridge temperature goes below the lower limit of the dead zone

$$T_{fridge}(t) - T_{set}(t) < -\sigma \rightarrow \xi(t+dt) = 0 \tag{1}$$

ii) compressor starts working when the fridge temperature goes above the upper limit of the dead zone

$$T_{fridge}(t) - T_{set}(t) > \sigma \rightarrow \xi(t+dt) = 1 \tag{2}$$

iii) otherwise it follows its current state

$$-\sigma \leq T_{fridge}(t) - T_{set}(t) \leq \sigma \rightarrow \xi(t+dt) = \xi(t) \tag{3}$$

cooling power at a particular instance is given by:

$$\phi_{cool}(t) = \xi(t)\phi_{cool} \tag{4}$$

We have modeled three major events for the fridge as (a) permanent mode, where the fridge operates in the normal refrigeration cycles, (b) temporary mode when the fridge door is opened and closed, as a result heat is exchanged and inside temperature rises to impact the instantaneous refrigeration cycles and (c) temporary mode when food is introduced in the fridge.
a) The model for the permanent state or normal cycles is proposed as under that computes the rate of change in the fridge temperature over the simulation period:

$$\frac{d}{dt}[T_{fridge}] = \left[-\frac{1}{R_{fridge}C_{food}}\right][T_{fridge}] + \left[\frac{-\rho\phi_{cool}}{C_{food}} \quad \frac{1}{R_{fridge}C_{food}}\right]\left[\begin{array}{c}\xi \\ T_{room}\end{array}\right] \tag{5}$$

The model of the permanent state (1st order) is obtained when $T_{new} = T_{fridge}$.
b) The model for the temporary mode when the fridge door is opened and closed. It follows the model for the permanent state with only change in the resistance of the fridge as under:

$$R_{fridge} = R_{new} + \zeta(R_{close} - R_{open}) \tag{6}$$

c) The model for the mode when new food is introduced is proposed as under that computes the change in temperature over time for both the fridge and the new food introduced into the fridge:

$$\frac{d}{dt}\left[\begin{array}{c}T_{fridge} \\ T_{new}\end{array}\right] = \left[\begin{array}{cc}-\frac{R_{new}+R_{fridge}}{R_{new}R_{fridge}C_{food}} & \frac{1}{R_{new}C_{food}} \\ \frac{1}{R_{new}C_{new}} & -\frac{1}{R_{new}C_{new}}\end{array}\right]\left[\begin{array}{c}T_{fridge} \\ T_{new}\end{array}\right] + \left[\begin{array}{cc}-\frac{\rho\phi_{cool}}{C_{food}} & \frac{1}{R_{fridge}C_{food}} \\ 0 & 0\end{array}\right]\left[\begin{array}{c}\xi \\ T_{room}\end{array}\right] \tag{7}$$

We have followed following assumptions wile modeling the fridge: (i) Opening the door modifies R_{fridge} (ii) Removing food from fridge is assumed to have a very small impact (except the door opening) (iii) Adding food sets a new value to T_{new} and parameters like C_{new} and R_{new} may be adjusted depending on the food.

5. Co-simulation environment

Human behaviour is dynamically modeled and simulated in a multi agent simulation environment (Brahms), as intelligent agents. An agent based approach is well suited since agents are a natural and intuitive way to model humans and their characteristics and are a key towards implementing group behaviour. Agents like humans evolve in the environment, perceive it and act accordingly. The changes in the environment are perceived by the agents, who then take actions dynamically to change the state of the objects and appliances in the building. This dynamic behaviour is fed to the physical simulator containing the model of the fridge using an interface developed in java. It generates energy consumption cycles of the fridge and maintains the setpoint temperature. Physical simulator is implemented in Matlab and simulation results are monitored and analyzed with Simulink. In order to perform certain activities, the inhabitants change their locations, perform certain actions on appliances e.g. opening the fridge, putting food inside etc. As soon as these state changes happen, this information is sent to the physical simulator, where appliance behaviour is changed and its consumption is computed. The proposed co-simulation platform is presented in figure 5 with 3 distinct elements as (i) Brahms MAS, (ii) Brahms Java Interface and (iii) physical simulator (model for the fridge). The Brahms MAS element simulates the agent behaviour for the fridge. The Brahms java interface establishes the connection between Brahms and the physical model of the fridge. This interface actually drives Brahms virtual machine and manipulates different attributes of the occupant's behaviour model to be simulated by setting agents and objects attributes and handling the starting time of the simulation. It also keeps track of the current location of agents and of the current values of different attributes of objects. The physical simulator is created in Matlab/Simulink and consists of the model of the fridge and the controllers for appliances. The model of the fridge is defined in the Matlab function file which uses the output of the Brahms simulation such as opening the fridge, putting food in fridge and based on the inside temperature of the fridge turns the refrigeration cycles on or off. It computes the inside temperature of the fridge to maintain the setpoint temperature.

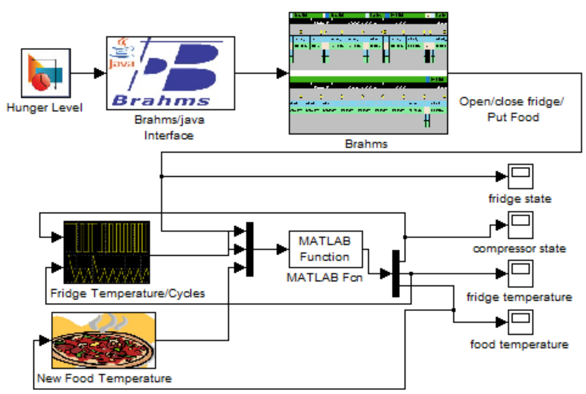
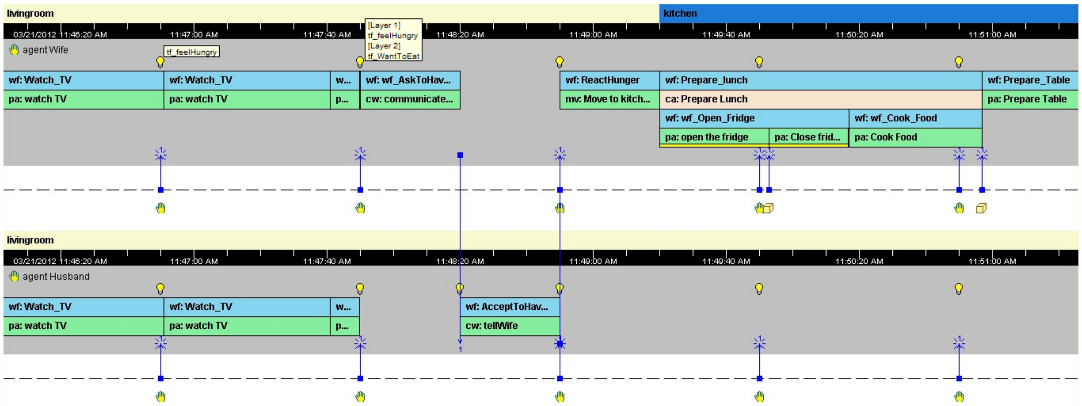


Fig. 5: Co-Simulation Platform to Find High Energy Consuming Activities

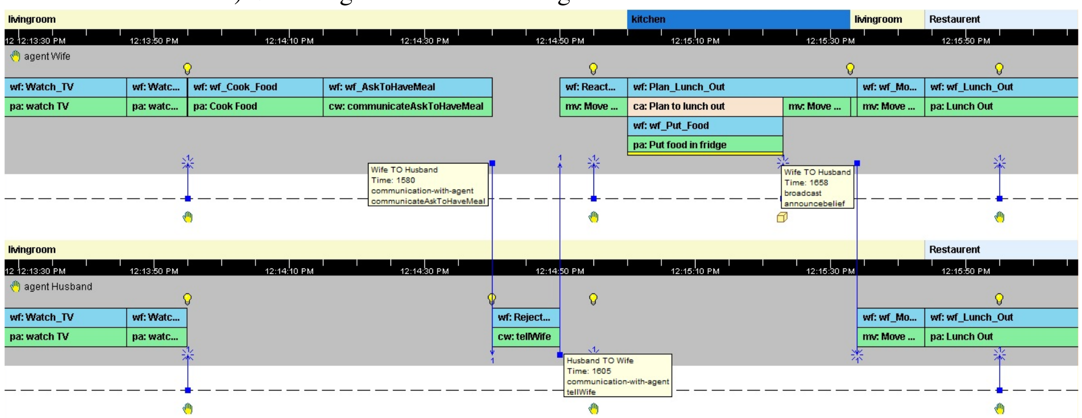
5.1 Agent based scenario and brahms simulation results

We will now consider a scenario consisting of a 2 person house where husband and wife are modeled as agents. It will show how the decisions taken by the agents affect the energy consumption. Figure 6(a) shows that the husband and wife are sitting in the living room and watching TV. The hunger level for the wife gradually increases with time. When it reaches beyond some threshold, she communicates with the husband to have their meal together. The husband usually likes to eat at restaurant if there is a beautiful weather outside; otherwise he prefers to eat at home. In case husband is agreed based on perception about the weather, she moves to the kitchen, opens the fridge, takes the stuff out and prepares the table for lunch. If however, the husband is not agreed to eat at home, she puts the warm food, which she had already prepared for their meal into the fridge and they go out to restaurant. The simulation results are presented in figure 6. The output is generated randomly based on agents' belief certainty. Belief certainty is the concept used in Brahms which assigns a probability between 0 to 100 to agents' beliefs and the facts in the environment. Beliefs and facts with varying probabilistic values influence agents' actions accordingly. For example, if for the communication between the agents, the fact is that the husband doesn't denies to eat at home as often as he agrees to eat at home based on his perception about the weather, there are more chances that the wife will not put the warm food which she had prepared for the meal into the fridge. Similarly, if the husband is agreed to eat at home, the duration of the activity of opening the door of the fridge and taking the stuff out is a random value between a minimum and maximum duration. Based on this duration, every time the wife will open the door of the fridge for different durations resulting in varying behaviour of the fridge. In figure 6[2], the horizontal bar on the top represents the movements of agents in different locations. Below this is the timeline, which shows the simulation time in the agent world. The vertical bars are used to represent the communication between agents. These are also used to represent the broadcast activity where the

[2]In figure 6 wf stands for workframe, tf for thoughtframe, ca for composite activity, pa for primitive activity, mv for move activity and cw for communication activity.

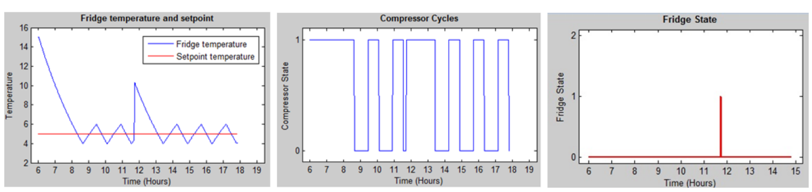


a) Social agreement between agents to have meal at home

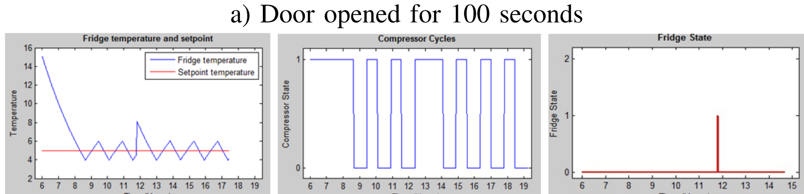


b) Social agreement between agents to eat out

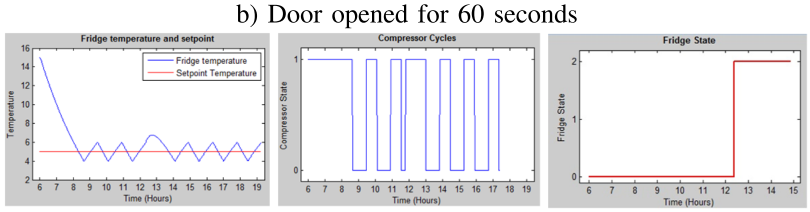
Fig. 6: Simulation Results against Simulated Inhabitants' Behaviour



a) Door opened for 100 seconds



b) Door opened for 60 seconds



c) New food introduced in the fridge

Fig. 7: Simulation Results against Simulated Inhabitants' and appliance's Behaviour

agents transfer their beliefs with each other. For example in the figure 6(b) the vertical bar coming down from agent Wife to agent Husband at the moment when the Wife agent moves from kitchen to living room, represents the Wife agent's belief which she transfers to the husband to move to the restaurant. The bulb symbols are used to represent the thoughtframes or beliefs of agents. Thoughtframes are changed with the passage of the simulation time and based on different perceptions of agents from the environment.

5.2 Co-simulation results

Figure 7 shows the actions of agents on fridge and the resulting effect on the inside temperature and the compressor cycles. Opening the fridge door for different durations affects the compressor cycles accordingly. In figure 7(a) it can be seen that the agent opened the door of the fridge for longer period so the compressor worked longer and hence consumed more energy than as in figure 7(b) where the agent opened the door for fewer seconds. Similarly it can be seen from figure 7(c) that when the agent husband has denied having meal at house, wife put the warm food inside the fridge. As a result, the temperature inside the fridge increased causing the compressor to work longer than usual to bring the temperature back to the setpoint. The fridge states are represented by three levels 0,1 and 2 where $0 \rightarrow$ no action on the fridge, $1 \rightarrow$ door is opened and closed and $2 \rightarrow$ new food is added.

6. Conclusions and future perspectives

Until recently research has focused on active appliances to optimize the energy consumption and reduce energy waste, however cold appliances are not yet explored that constitute a significant source of energy consumption in our daily lives. It is also a fact that to model the cold appliances energy consumption behaviour is not simple as it follows the activity later in time and is quite complex to predict. We believe that these cold appliances have a hidden energy waste component that must be addressed. So, in this article we have presented a co-simulation methodology to demonstrate the hidden energy waste component from actions on the cold appliances linked with the inhabitants' behaviour. This energy waste component is further used to classify the activities as high energy consuming activities and shall help in building the energy advisors within Smart homes to propose alternative actions to the human agents in real life to ensure energy waste reduction and consumption optimization. Our contributions are (i) a multi agent model of human behaviour relating to energy related activities (ii) a physical model for the fridge energy consumption (target cold appliance), (iii) co-simulation methodology to analyze the energy consumption behaviour of cold appliances based on dynamically simulated inhabitants' behaviour. We have demonstrated by dynamically simulating the inhabitants' behaviour using Brahms modeling and simulation environment that actions on the cold appliances do have a hidden energy waste component and can be avoided to support the efforts for energy waste reduction and consumption optimization. Simulation results clearly highlights that opening fridge for long period and putting a hot food in the fridge results in longer compressor refrigeration cycles resulting in the energy waste. In future we shall validate our physical model with experiments on different categories and capacities of the fridge to develop an accurate but generic model for the fridge (cold appliances). We propose the research community to shift their focus towards other cold appliances to model the energy waste component linked with the inhabitants' behaviour.

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