Modelling "Cognitive Households Digital Twins" in an Energy Community

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Abstract Available literature suggests that households consume a considerable amount of energy in contemporary societies. Many techniques expected to help reduce the impact of households' energy consumption have been suggested in several studies. Cognitive Household Digital Twins (CHDT) is one of such ideas perceived to facilitate rational decision-making regarding energy consumption. A CHDT could be described as a digital replica/model of a household within the cyber-physical space. Such digital twins could possess some attributes such as cognitive capabilities, enabling them to make decisions based on some level of delegated authority from their physical twin. The outcomes of their decisions are expected to increase the sustainable energy consumption of the physical twin. In this study, we demonstrate how CHDTs can exhibit such cognitive and decision-making capabilities using software simulation. In our approach, we modelled a community of CHDTs who collaborate to jointly execute a common task, in this case, jointly minimize consumption, hoping to maximize the opportunity to sell energy to the grid. We adopted a multi-method simulation technique that involves multiple simulation paradigms integrated onto a single simulation platform. The adopted paradigms include System Dynamics, Agent-Based, and Discrete Event simulation techniques. The study's outcome suggests that CHDTs can be a valuable form of autonomous entity that can assist as complimentary decision-making agents in households.

Keywords Collaborative networks · Digital twins · Cognitive agents · Sustainable consumption · Decision-making

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1 Introduction

Reports from the European Commission suggests that buildings are responsible for approximately 40% of the EU's energy consumption and 36% of CO_2 emissions in Europe [1]. Consequently, buildings have been declared the single largest energy consumer in Europe. Globally, households are claimed to contribute nearly 72% of greenhouse gas (GHG) emissions [2]. These empirical data unveil the significant role households play towards the global emission of GHGs. Albeit this also suggests the potential contribution that households could make towards the mitigation of the problem.

Advancements in internet-based technologies, as well as emerging concepts and tools in machine learning, artificial intelligence, IoT, 3D visualisation, immersive environments, and big data analytics, are having a profound effect on the way the physical and cyber worlds interact. The effect of this complex synergy is a gradual convergence of the cyber and physical worlds in such a way that entities in the physical realms could have their replica in the cyber space, resulting in the notion of a "Digital Twin" (DT). A DT, according to [3], is a digital replica of a physical object or system. However, the application of DT concepts today is more extensive. It is applied in areas such as process management, behaviour modelling, system optimization, etc., and across a wide range of disciplines too.

In a previous study [4] the concept of Cognitive Household Digital Twin (CHDT) was proposed, where the authors envisioned that DT concepts could have a useful application in the domain of energy. It was claimed that CHDTs could be designed to possess some cognitive and autonomous attributes that could enable them to play complementary roles as decision-making agents in households. The authors further described a CHDT as a digital replica/model of a physical household that is equipped with some level of intelligence, so that it can receive some input from its Physical Twin (PT) and based on that input, make some basic energy use decisions on behalf of the PT. The input from the PT shall be referred to as "delegated authority".

In this study, we aimed at adopting software simulation to model the cognitive (intelligent) capabilities of these proposed CHDTs. The study was guided by the following research questions:

RQ-1. How can the cognitive capabilities of CHDTs be modelled?

RQ-2. How can CHDTs utilize these cognitive capabilities to make decisions that facilitate collaborations?

2 Related Works and Theoretical Framework

The Collaborative Virtual Power Plant Ecosystem is a concept that was derived from the merger of principles and concepts from the disciplines of Collaborative Networks (CNs) and Virtual Power Plants (VPP). Central to these concepts is the notion of collaboration, which happens to be fundamental to the discipline of CNs

[5, 6]. A VPP on the other hand is a virtual entity involving multiple stakeholders and comprising decentralized multi-site heterogeneous technologies, formed by aggregating deferrable and non-deferrable distributed energy sources [7]. The mix of these two concepts led to a hybrid concept called the Collaborative Virtual Power Plant Ecosystem (CVPP-E) introduced in [7] and [8]. A CVPP-E can be a replica of a renewable energy community such as described in [9]. The CVPP-E could also be described as a form of business ecosystem and a community of practice where members approach energy generation, consumption, and conservation from a collaborative point of view. The governing structure is polycentric and decentralized with a manager who plays a coordinating role and promotes collaborative behaviours.

Similar works found in the literature include [10], where the authors created a digital twin that accurately reflects the behaviour and characteristics of buildings. The building was reproduced using Autodesk REVIT. Another study discussed in [11] proposed the connection of a digital building twin with blockchain-based smart contracts to execute performance-based digital payments. Finally, a review presented with empirical evidence validated DT technologies as novel ways of implementing consumer-oriented demand-side management. The authors further identified some barriers that are associated with the adoption of energy services, particularly as they relate to the implementation and overall adoption of the digital-twins concept.

3 Modelling Framework

To help replicate the attributes or preferences of the PT in its equivalent DT, we adopted a multi-method simulation technique which enabled the integration of simulation paradigms such as System Dynamics, Agent-Based, and Discrete Event simulation methods as supported by the Analogic platform [12]. Using this approach, each CHDT was modelled as a software agent. All relevant attributes of the PT were modelled inside the CHDT as a logical sequence of internal states using state charts. State charts are one of the UML languages that are often used to model the dynamic behaviour of a system in response to time and changing external stimuli [13]. The various aspects of the prototype model are discussed below.

3.1 Modelling Households as CHDTs

The replica of all the PTs is modelled as autonomous software agents, referred to as CHDTs. In terms of behaviour and preferences, a CHDT is similar to its PT counterpart. Each PT is characterized by a unique set of attributes such as types and quantity of appliances, energy use preferences, the capacity of installed Photovoltaic (PV) systems, etc. In a similar manner, a CHDT is modelled to mimic its corresponding PT by replicating these unique attributes in them.

3.2 Modelling Appliances and Their Use-Behaviours

Each CHDT is modelled to possess some embedded household appliances which are equivalent to that, owned by the PT. The number of embedded appliances may vary from household to household. Parameters that are used to model each appliance include (a) Appliance power ratings, (b) Duration-of-use, (c) Time-of-use, and (d) Frequency-of-use. The behaviours of all embedded appliances are modelled to yield stochastic outcomes. The data for these parameters were obtained from [14]. These parameters are modelled using a probability distribution function expressed as a *triangular distribution (X,Y,Z)*, where *X* and *Z* are the possible minimum and maximum values of the parameters respectively and *Y* is the average value of the parameter.

3.3 Modeling a Community of CHDTs (i.e. CVPP-E)

In the model, CHDTs are placed in an environment called CVPP-E. The CVPP-E represent the community within which the CHDTs live. The CVPP-E is modelled as constituting a population of CHDTs. The population size and the ratio of different household sizes can be configured in the prototype. Within the CVPP-E environment, CHDTs can communicate among themselves via messages. The CVPP-E manager plays the role of the community manager and is responsible for the proposition of all vending opportunities to community members. The manager communicates such information through messages.

3.4 Modelling the Cognitive Capabilities of CHDTs

Community Status This item defines the long-term attributes that enable a CHDT to play specific roles in the community. A CHDT can assume the status of either a prosumer or a consumer. This status is determined at the model initialization stage. Once a status is assumed, the CHDT maintains it for the entire model run. A prosumer CHDT inherits a prosumer attribute (i.e., PV and a battery storage system) which enables it to play the roles of energy producer and consumer simultaneously.

A CHDT that inherits a consumer status fundamentally consumes energy and does not produce any. The ratio of prosumers to consumers population can also be configured. For instance, if there are a total population of 20 CHDTs in the community, a ratio of say: 90% prosumers to 10% consumers can be configured. Any combination or ratios between these two populations is possible.

Internal States. After a CHDT has assumed its community status, the attributes or preferences of the PT are modelled inside the CHDT as internal states. Having a replica knowledge of the current attributes and preferences of the PT, and making basic decisions based on this knowledge is what gives the CHDT its cognitive capabilities. The internal states are modelled using state charts. State charts are used to represent the dynamic changes of behaviours in a system. State transitions are used to model changes in behaviour and these transitions can be triggered either by some internal or external event.

Degree of Delegation. This is also an internal state that is used to represent the level of delegated authority that the PT assigns to its counterpart CHDT. Two types of delegated authority are considered. These are:

*Full Delegation***.** This means that the CHDT has received delegated authority to defer or suspend the use of all deferrable loads embedded in it. For instance, a CHDT with four embedded deferrable loads may defer all four appliances.

Partial Delegation. A CHDT with this kind of delegated authority has limitations regarding the number of appliances that it can defer. In such instances, the PT may place some restrictions on the deferral of certain specific appliances.

Sizes of PV and Battery Systems. All prosumer CHDTs inherit a PV and battery storage system. A prosumer CHDT has cognisance of the capacities of installed PV and battery storage systems.

4 Scenario Selection and Demonstration of Modelling Technique

In this aspect of the study, we define some scenarios as well as parameters to be used in demonstrating the modelling technique as well as testing our developed prototype. To achieve this, we create a scenario that will enable the CHDTs to collaborate. Collaboration in this sense involves joint action by all the involved CHDTs to achieve a specific goal that is common to them all. The common goal, in this case, is termed "collaborative consumption" which involves a collective action taken by all CHDTs which is aimed at minimizing community consumption (within the proposed vending window) hoping to maximize the opportunity of vending renewable energy to the grid. The following parameters described below are used:

Communication for Collaboration. The community manager communicates via messages to the CHDTs in advance, giving them notice of an impending vending opportunity (VendOpp). The information that is communicated includes (i) Time for vending (V_T), and (ii) Vending window (V_W), which is the duration of vending. As an example, for this test scenario, $V_T = 24$ h after receiving notification and $V_W = 10$ h. The waiting time is the period between the time the CHDT received notification and the time vending begins.

Community Population. A population of 50 CHDTs were used in the simulation.

Table 1 Parameters for modelling the embedded household appliances [14]

Type of appliance	Annual power (kwh)			Peak periods		Number of wash cycles year
	Min	Average	Max	P1	P2	
Washing machine	15	178	700	5am–4 pm	5 pm–2am	284
Tumble dryer	64.25	497	1600	5am–12 pm	6 pm–11 pm	280
Dishwasher	33.32	315	608	5am–3am	6 pm–2am	270

Household Appliances. A total of three household appliances (deferrable loads) were considered. These are (a) Washing machine, (b) Dish washer, and (c) Tumble dryer. The parameters used to model each of these appliances are shown in Table 1. These parameters are data obtained from a survey conducted on domestic appliance usage in the UK in 2012 [14].

Installed PV System. For prosumers, four different types of installed PV systems are considered. A prosumer CHDT can inherit only one of these systems. The considered PV systems are: (a) BainSystem = 6.930 kW [15], (b) BrainSystem = 1.950 [15], (c) Helius = 3.99 kW [15], and (d) DaSS = 3.22 kW [15]. Data from these real-life systems are used to model the generation side of the model. These PV systems are not discussed in this study.

Degree of Delegation, The following delegated authority cases are considered:

- **Full Delegation**. A CHDT with this level of delegated authority can defer all three embedded appliances.
- **Partial Delegation, Double Appliance.** A CHDT with this level of delegated authority can defer any two of the embedded appliances.

Partial Delegation, Single Appliance This means the CHDT has delegated authority to defer any one of the embedded appliances. A flowchart showing the possible combination of the "degrees of delegation" is shown in Fig. 1. Furthermore, in Table 2, we have defined five different scenarios constituting different degrees of delegation in combination with different population sizes. The results and discussion section (Sect. 5) discusses the outcome of the model, considering these scenarios.

5 Results and Discussion

In RQ-1, we sought to find a way to model the cognitive capabilities of CHDTs. Figures 2a-c demonstrate the outcome of the model. As shown below, all active states of the model are depicted with dotted boundary lines, and inactive states are shown with continuous boundary lines. The active states are used to replicate the current attributes or preferences of the PT. In Fig. 2 the prosumer state of the

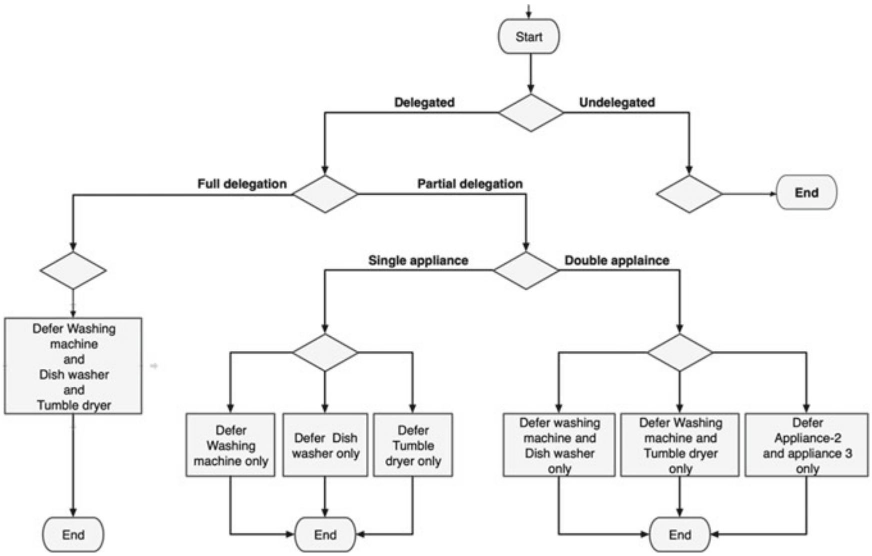

Fig. 1 Flow chart of the delegation process

Table 2 Scenario selection

Scenarios		Degree of delegation	Number of delegated appliances	Percentage of CHDT population (%)	
				Delegated	Undelegated
1	High population of delegated CHDTs	Full	3	100	0
2	Low population of delegated CHDTs	Full	3	10	90
3	High population of delegated CHDTs	Full	3	90	10
4	High population of delegated CHDTs	Partial	2	90	10
5	High population of delegated CHDTs	Partial	1	90	10

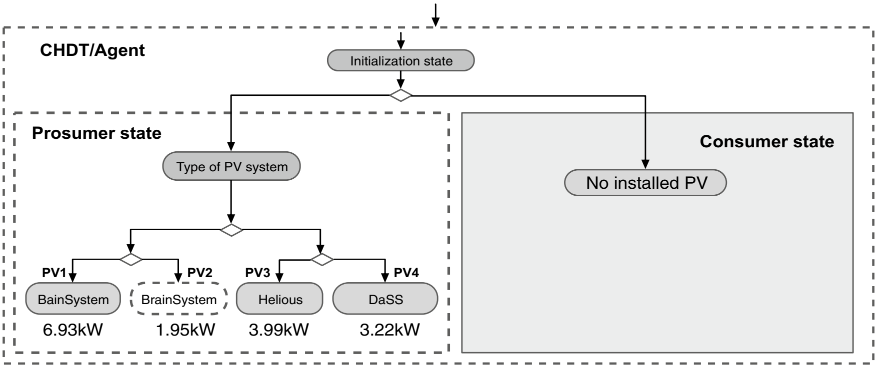

Fig. 2 Status as a prosumer with a 1.95 kW installed PV system (PV2-BrainSystem)

CHDT is active. Furthermore, an installed PV, named BrainSystem, with an installed capacity of 1.95 kW is also active. Similarly, Fig. 3 shows a CHDT with attributes of a consumer with no installed PV system. Finally, in Fig. 4, we illustrate a prosumer CHDT with full delegated authority.

In RQ-2, we sought to demonstrate how these CHDTs could use their cognitive capabilities to engage in some decision-making. In this instance, we seek to achieve collaborative consumption which requires the involved CHDTs to collectively adjust their energy consumption, aimed at achieving a common community goal.For the CHDTs to successfully make such collective decisions it is necessary that each one of them have cognisance of the flowing conditions: (a) The proposed vending time, (b) waiting time (c) vending window, and (d) degree of delegation. Using the scenario described in Table 1, the following global behavior is observed from the 50 CHDTs after they have made their respective decisions. Figure 5 represents scenario 1. In this scenario, we considered a high population of delegated CHDTs. The degree of the

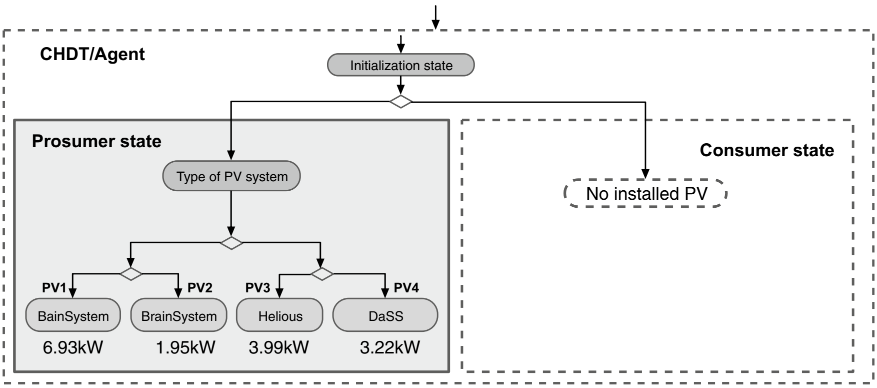

Fig. 3 Status as a consumer with no installed PV system

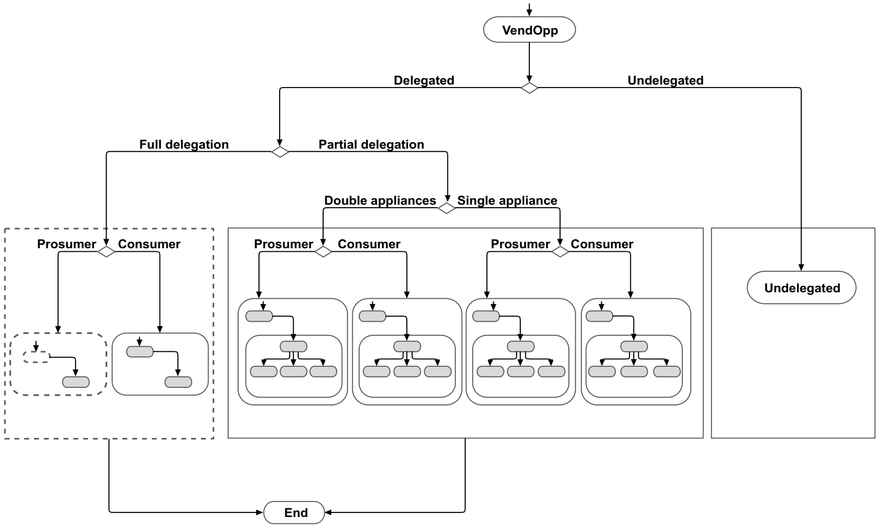

Fig. 4 Status as a prosumer with full delegation (All three appliances deferred)

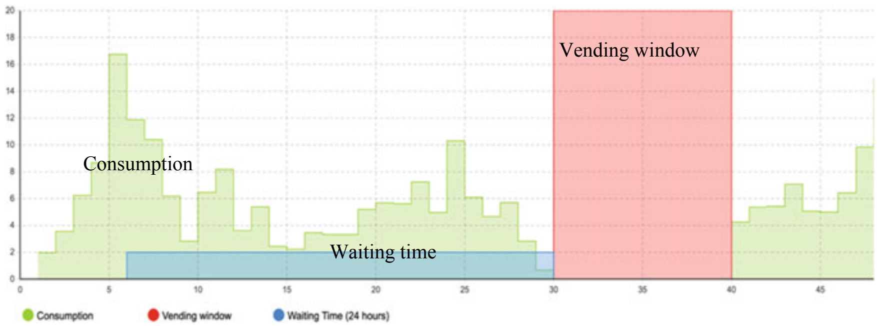

Fig. 5 Scenario of high population of delegated of CHDTs (100%) with full delegation

delegation was "full delegation". Furthermore, all CHDTs were delegated (100%). The results as shown in Fig. 5 suggests that all the CHDTs were cognisant of the waiting time. They were also cognisant of the vending window (10 h). It can also be observed that all the CHDTs implemented their delegated authority which was "full delegation". Evidence of the implementation of full delegation can be seen in the figure. It can be observed that during the vending window, consumption was zero. This is because they all suspended the use of all three embedded appliances when the waiting time was due, and the suspension lasted for the duration of the vending period. They all resumed consumption immediately after the vending period had elapsed. Figure 6 also represents the outcome of the model considering scenario 2. This scenario considered a low population of delegated CHDTs (10%). The degree of the delegation was full. It can be observed from the vending window that energy

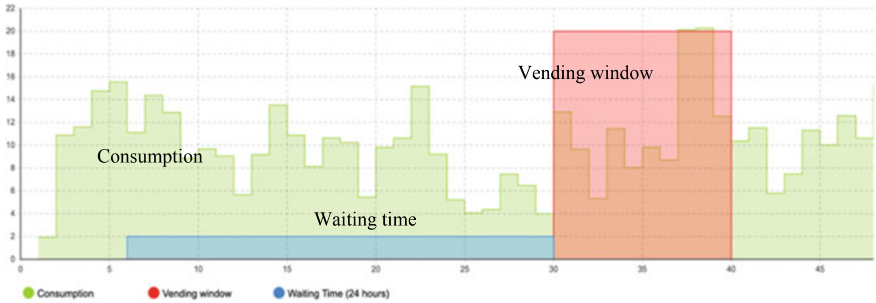

Fig. 6 Scenario of low population of delegated CHDTs (10%), high population of undelegated CHDTs (90%), full delegation

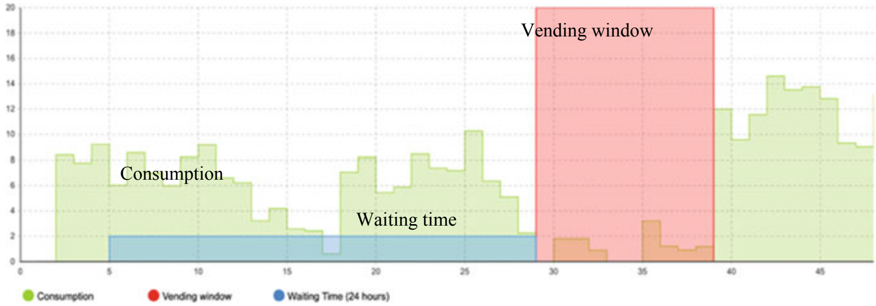

Fig. 7 High population of delegated of CHDTs (90%), low population of undelegated CHDTs (10%), full delegation

consumption was not affected as the number of CHDTs that deferred the use of their appliances were few (10%). The consumption observed within the vending widow was because of the 90% undelegated CHDTs. Furthermore, in Fig. 7, we considered scenario 3 which constitutes a high population of delegated CHDTs (90%) and a low population of undelegated CHDTs (10%). The degree of the delegation was full. It was observed that consumption was significantly reduced within the vending window. This was because the majority of the CHDTs (90%) delegated all three appliances during the period. The relatively small consumption that was recorded could be attributed to the 10% undelegated CHDTs.

The outcomes of scenarios 4 and 5 are captured in Figs. 8 and 9. In both scenarios, we considered partial delegation. In scenario 4 (Fig. 8) we considered partial delegation with double appliance. Subsequently, in scenario 5, (Fig. 9), we considered partial delegation with a single appliance. The results revealed that partial delegation with a double appliance yielded more energy savings as compared to the partial delegation with a single appliance. It can therefore be concluded that having a high population of delegated CHDTs, who have been given full delegated authority, could yield the most significant energy savings, that can facilitate the maximization of the

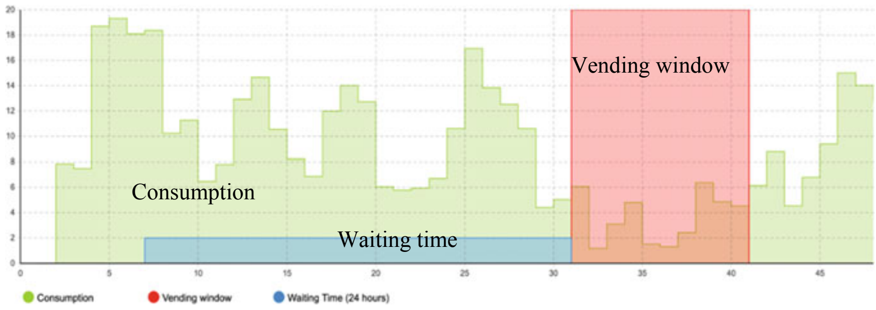

Fig. 8 High population of delegated CHDTs (90%), low population of undelegated CHDTs (10%), partial delegation, double appliances

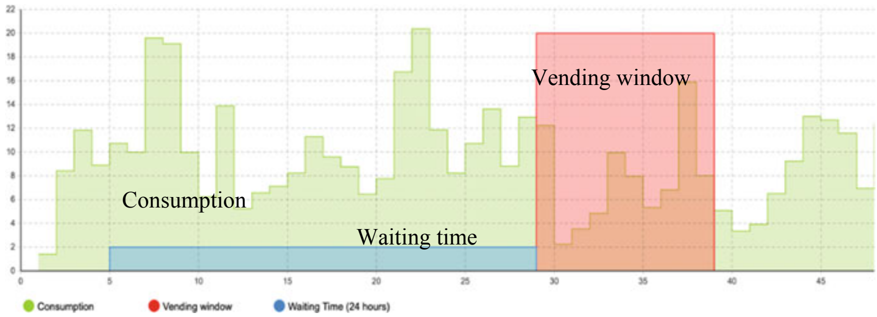

Fig. 9 High population of delegated CHDTs (90%) low population of undelegated CHDTs (10%), Partial delegation, single appliance

VendOpp. On the contrary, having a high population of undelegated CHDTs will adversely affect consumption within the vending window, which could minimize the VendOpp.

6 Conclusion and Future Works

The primary objective of this study was to demonstrate the feasibility of adopting CHDTs as autonomous entities that could assist as complimentary decision-making agents in households. To achieve this objective, a prototype model was developed using a multi-method approach. The prototype was tested using multiple scenarios. The outcome of the study has helped to establish the fact that CHDTs could act as complimentary decision-making agents as they can have cognisance of their status and states. The outcome further revealed that CHDTs could execute delegated instruction such as delegation of deferrable loads in accordance with the preferences of the physical household. Finally, CHDTs have been proven to be goal oriented such as achieving some set goals like minimizing consumption and vending energy to the grid at some stipulated time. They can also take collective actions which are good bases for collaborations.

In future works, the decision-making capabilities, or behaviours of CHDTs will be explored further. Decision-making behaviors such as engaging in other collaborative behaviors will be investigated. Other behaviours such as having the capability to influence one another, particularly in the decision-making process will also be explored. Finally, the ability of CHDTs to adopt some form of social innovations will be studied. Delegation in the aspects of generation will also be investigated further.

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