A Framework for the Integration of IoT Components into the Household Digital Twins for Energy Communities

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Abstract. The concept of Cognitive Household Digital Twins (CHDTs) was proposed as a mechanism to assist constituent households in Renewable Energy Communities to engage in collaborative actions that are expected to facilitate sustainable energy consumption in these communities. A CHDT represents a digital twin of a unit of physical households in a community. By integrating IoT components at the appliance level of the Physical Twin, a CHDT becomes a "living model" of its physical counterpart by receiving real-time data that reflects the households' energy consumption or appliance use-behaviors. When CHDTs are endowed with some intelligence or cognitive abilities, they become cognizant of the operational state of the physical system using the received data. Based on these data, CHDTs can make autonomous and rational decisions on behalf of the households' owners. Furthermore, through the integrated IoT components, CHDTs can send control signals back to connected appliances to regulate their operations. In this context, a population of CHDTs can engage in collective actions with the aim of promoting sustainable energy consumption in the ecosystem. In this work, we show how the CHDT's architectural framework enables them to collaborate. A multi-method approach that integrates systems dynamics, agent-based, and discrete event modeling techniques is used for the development of a prototype model. Several scenarios are then implemented in this environment to verify the validity of the approach.

Keywords: Digital Twins · IoT · Collaborative Networks · Cognitive Digital Twins · Renewable Energy Communities

1 Introduction

It is widely acknowledged that the Earth's resources are depleting at a very alarming rate. This is partly due to the proportion of overexploitation of resources to meet the insatiable demands that modern-day society places on these resources. In a recent study [1], it was claimed that 40% of global resources are consumed by buildings alone.

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Furthermore, these buildings were noted to consume about 40% of global energy as well as 25% of global water [1]. Consistent with these numbers, from the perspective of the European Commission, buildings account for roughly 40% of the EU's energy consumption and 36% of CO2 emissions in Europe [2]. As a result, buildings have been labelled as Europe's single greatest energy consumer. Other comparable studies, such as [3] have also expressed concerns about the steady rise in energy consumption within buildings. The authors in [4] have attributed these escalating concerns to the rising demand for comfort, resulting from the need for larger amounts of home equipment. Other mentioned reasons include increased purchasing power and improvement in the quality of life of residents. As a result, growing attention is being put on more effective energy management approaches and the use of renewable energy sources.

Although several useful contributions have been made toward the solution of this problem, there is still ample room for novel approaches. In a related study [5], two complimentary concepts, namely the Collaborate Virtual Power Plant Ecosystem (CVPP-E) and Cognitive Household Digital Twin (CHDT) were introduced. In the study, the authors described a CHDT as a digital twin (DT) or replica/model of a real household that could be endowed with some level of intelligence, allowing it to take input from the Physical Twin counterpart to make some basic energy consumption choices on its behalf. It was also suggested that CHDTs could be programmed to have cognitive and autonomous capabilities, allowing them to play complementary roles as decision-making agents in households.

Virtualization of the physical household into DTs as suggested in [5] is intended to help manage the complexities that arise when multiple actors, who are autonomous, heterogenous, and geographically distributed, each with different energy consumption preferences, options, priorities, and expectations, come together to form a community, and more specifically, a Renewable Energy Community. The underlying management technique relies on the notion of collaboration as demonstrated in other studies such as [6, 7]. In this paper, we propose a framework for the CHDTs showing the roles that the integration of IoT components can play in the feasibility of the concept. To guide the work, the following research questions are addressed:

- How can the integration of IoT components in household appliances enable the feasibility and functionality of the Cognitive Household Digital Twin (CHDT) concept?
- How can the integration of IoT components facilitate the cognitive and decision-making capabilities of the CHDTs?

2 Related Works

Some related works in the application of Digital Twin (DT) concepts in the domain of energy are as follows. In [8], a household digital twin, which is a data-driven multi-layer digital twin that aims to mirror households' actual energy consumption is proposed. Another study described in [9] also proposed a forecasting approach where the DT of a physical household could use data from the physical twin to forecast the energy consumption for the next day. Similarly, in [10] a DT-driven technique was adopted for improving the energy efficiency of indoor lighting based on computer vision and dynamic building information modelling (BIM). A case study conducted in [11] proposed a battery energy storage system digital twin that forecasts the state of charge by applying artificial intelligence. Finally, a novel DT-based day-ahead scheduling method is proposed [12]. In this case, a deep neural network is trained to make statistical cost-saving scheduling by learning from both historical forecasting errors and day-ahead forecasts.

3 Theoretical Background

In this section, we provide a brief overview and discussion of the underlying concepts of the CVPP-E and their related CHDTs.

3.1 The Concept of Collaborative Virtual Power Plant Ecosystem (CVPP-E)

A renewable energy community (REC) is based on free and voluntary participation, according to the European Parliament and the Council of the European Union [13]. It is autonomous and managed by the involved stakeholders. Members of RECs can generate renewable energy (e.g., photovoltaic) for local use and store, sell, or share the excess with other members of the community. We focus on the REC notion by creating a digital twin replica of the community. The CVPP-E represents the community environment in our model. This ecosystem is a kind of Virtual Organizations Breeding Environment or business ecosystem [14] in which members approach energy use and exchanges collaboratively. As a result, members participate in collaborative efforts aimed at achieving some goals that may be shared by the entire community.

The CVPP-E idea results from incorporating collaborative concepts and methods from the field of Collaborative Networks (CNs) into the area of Virtual Power Plants (VPP). The result of this synthesis is a type of REC that uses collaborative principles and mechanisms in its operation to ensure sustainable energy consumption and exchange, while also exhibiting VPP characteristics, such as the ability to aggregate excess energy from the community and sell it to the grid. A CVPP-E in the proposed formulation includes: (a) the community manager who promotes collaborative activities and behaviours, (b) multiple actors who may include prosumers and consumers, and finally (c) a common community-owned energy storage system.

3.2 The Notion of Cognitive Household Digital Twin (CHDT)

In the developed prototype, each CVPP-E actor is modelled as a software agent that mimics the actual actor's traits and actions. These software agents are designed to live and interact with one another within a digital REC environment, namely the CVPP-E. A Cognitive Household Digital Twin represents a unit of household in this environment. CHDTs are also modelled to possess some cognitive abilities, allowing them to serve as supplementary decision-making agents on behalf of their physical counterparts. These software agents can make logical and independent judgments on their owners' behalf (owners of the physical households). We thus mimic the population of households in a typical community by aggregating many CHDTs. Using agent-based technology, we simulate each household as having distinct behaviours, resulting in a community with stochastic global behaviour. The CDHTs' decisions are based on their preferences for sustainable energy usage or value systems. CHDTs are expected to be able to engage in collaborative initiatives such as pursuing common goals, sharing common resources, mutually influencing one another, and engaging in collective actions due to their cognitive and decision-making capacities.

The implementation of collaborative characteristics in CHDTs is expected to improve the CVPP-E performance and sustainability. The diversity of households in terms of size, as well as the number of inhabitants dwelling in each one, is critical to the community. To address this point, we divided the constituent households (and hence the corresponding CHDTs) into five groups. This classification and accompanying data were derived from a survey performed in [6]. The following categories are considered: (a) Households with single pensioners, (b) Households with single non-pensioners, (c) Households with multiple pensioners, (d) Households with children, and (e) Households with multiple people but no dependent children. The CVPP-E (community) population size may always be configured to include any number of households from each category.

3.3 Abstraction Levels of CHDTs in Line with Digital Twin Technology

According to [15], DTs can have three levels of abstraction. By relating these abstraction levels to the CHDT concept, the following definitions are proposed:

Household Asset Twins: When two or more components work together, they form what is known as an asset. Asset Twins according to [15] allow the analysis of interactions that occur at the components level. This helps to provide a plethora of asset performance data that can be evaluated and transformed into actionable insights or actions. In the context of the CVPP-E/CHDT concepts, each embedded household appliance can be considered a Household Asset Twin.

CHDT System or CHDT Unit Twin: A unit constitutes a collection of assets that enable one to see how different assets come together to form an entire functioning system. System twins help to provide visibility regarding the interaction of assets and may be used for performance enhancements. In the context of the CVPP-E/CHDT concepts, each unit of a household can be considered a CHDT System Twin or CHDT Unit Twin.

CVPP-E Process Twin: The third abstraction level is called the Process Twins. According to [15], this is a collection of systems that work together to form an entire production facility. In this case, all these systems are synchronized to operate at peak efficiency. This can help to determine the precise timing schemes that ultimately influence the overall effectiveness of the process. The CVPPE in this case can be considered as a type of a Process Twin.

4 Architectural Framework of a CHDT

In this section, we discuss the architectural framework for the CHDTs. As shown in Fig. 1, the framework is constituted of four main blocks: (a) the cognitive block, (b) the decision block, (c) the control block, and (d) the influence block. In the following sections, a brief description of each block is provided.

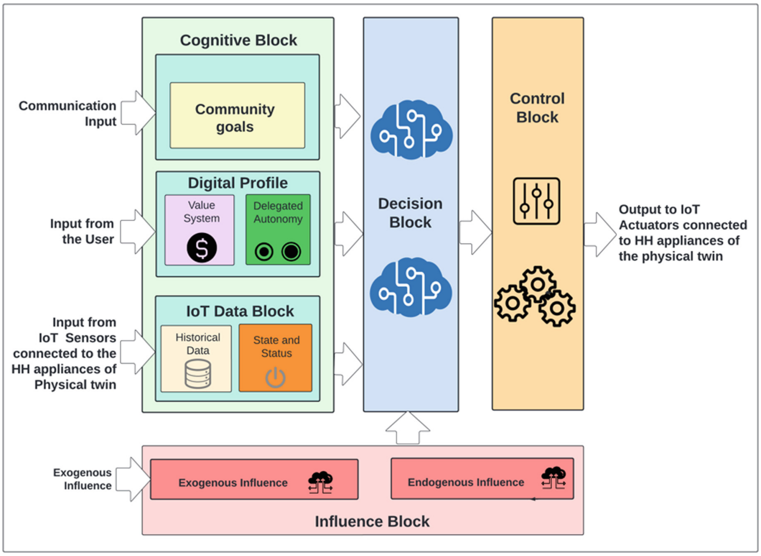

Fig. 1. The architectural framework of the CHDT

4.1 Cognitive Block

CHDTs are not only digital replicas of physical assets but are also expected to have some level of intelligence that enables them to have cognizance (explicit knowledge) of different attributes of their physical counterpart besides the current operational states of the asset. The considered attributes may include the behavioral preferences of the user. The cognitive block is constituted of the following sub-blocks:

Community Goals: As part of its cognitive capabilities, a CHDT would often have cognisance of all the goals that are suggested or proposed by the community manager. Although it may possess knowledge of the community goals, it would only join a coalition or participate in collaboration activities that are compatible with the goals of its physical twin.

Digital Profile: The digital profile of a CHDT is used to represent the preferences of the user. The digital profile of a CHDT is constituted of (a) the value system, and (b) the delegated autonomy of the CHDT.

Value System: The value system represents the preferences, choices and options of the physical twin that has been transferred to the CHDT. In the context of this study, the value system of a CHDT is a list of preferences that represent the values of the owner. This informs the kind of choices and decisions that the CHDT makes. Technically, the value system of individuals may differ from one person to another, therefore, the notion of a value system enables the collective objective of the community to be met without compromising the individual preferences and expectations of each user or actor. In Fig. 2 we illustrate six types of value systems. These are:

(a) 100% renewable sources. For this type of value system, the preference of the owner is to consume energy from only renewable sources. Any other source of energy that is non-renewable is forbidden to this actor.
(b) The mixed energy sources value system. For this type of value system, the user considers the use of energy from mixed sources. These mixed sources may include a mix of renewable and non-renewable sources. It may be possible for the owner to specify the preferred ratio of renewable sources to non-renewable.
(c) The free rider's values system. Technically this is not a value system. It rather represents an instance where the owner fails to define a value system.
(d) Cost savings value system. This represents users whose priority is to save cost and therefore prefer to use certain appliances at times when tariffs are at the lowest.
(e) Revenue or income values system. This may represent owners who want to participate in activities like demand response actions to earn revenue or sell energy from their roof-mounted photovoltaic system (PV system) to earn additional income.
(f) Load management value system represents owners who are willing to have some appliances (interruptible loads) be interrupted for the purpose of grid load management.

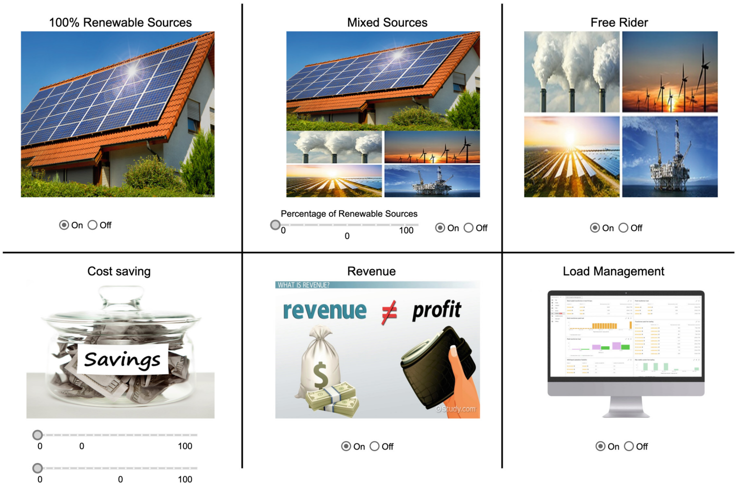

Fig. 2. Examples of value systems in the context of the CVPP-E

Delegated Autonomy: The notion of delegated autonomy is the specific instruction that a household owner assigns to its CHDT to be followed in carrying out or executing its value system. In the implemented prototype, this may include (a) the delegation of deferrable loads (DDL), which means deferring the use of certain appliances until a later time without affecting the quality of service (QoS) to the user. In the prototype model, three appliances are used for DDL. These include (i) a washing machine, (ii) a dishwasher, and (iii) a clothes dryer. DDL can be carried out by either deferring any single appliance out of the three, any two appliances, or all three appliances. (b) Interruption of Interruptible Loads (IIL). Some appliances are considered to have good thermal inertia, which is the capacity of a material to store heat and delay its transmission [16]. For such appliances, their normal use can be interrupted for a period without affecting the QoS of the user. Appliances such as refrigeration, air conditioning, and electric boilers are considered to have such properties. An IIL is a grid management strategy where an energy supplier can shut off or disconnect such appliances at the supplier's discretion or per a contractual agreement. In the context of the proposed CVPP-E, this technique can also be adopted as a strategy for delegated autonomy. Figure 3 below shows how DDL and IIL can be implemented. A user can implement delegated autonomy by selecting the radio button labelled "delegate". By selecting "undelegate", the appliance becomes undelegated. The coordination process between a user and a CHDT can be achieved through three simple steps. These are step 1: The user loads the appliance. Step 2a: For smart appliances, the CHDT automatically detects the presence of a load and is turned on automatically. Step 2b, for non-smart appliances, the user may manually turn the appliance on after loading. Step 3, once the appliance is in the "on" state, a signal will be sent to the CHDT indicating its readiness to be used. The CHDT will then take over the process and operate the appliance based on the pre-defined digital profile of the user.

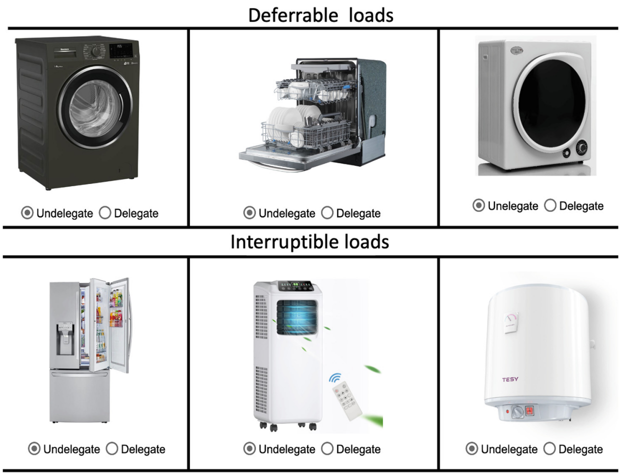

Fig. 3. How delegated autonomy (DDL & IIL) can be implemented in the CVPP-E prototype

IoT Data Block: This block represents the IoT interface between the household appliances and the CHDT. This block is constituted of two sub-blocks:

(a) the historical data block, which is a database that contains historical data of each appliance's use-behaviour, over time. By integrating AI techniques, the CHDT can glean some behavioural patterns from these historical data for prediction and decision-making purposes, on behalf of the physical twin.

(b) Status data: This block communicates the operational status of an appliance to the CHDT. Such data may include information such as whether the appliance is currently in the "On "or "Off" states. For appliances such as refrigerators and air conditioners, sensorial data such as the operating temperature etc. could be collected. In future studies, data about the thermal comfort of rooms or the living environment in households may also be useful for the CHDTs in their decision-making, particularly concerning the regulation of temperature in the living environment.

In Fig. 4, we illustrate how the integrated IoT components communicate wirelessly with a central router to reach the CHDT that is hosted in the cloud. Control signals can also be sent from the CHDT via the router to the various appliances to enable control instructions to be carried out. A firewall at the interface ensures the security of users.

Generally, DTs are hosted and operated in an environment called Digital Twin Environment. The connection between the physical and virtual objects can be achieved through several communication channels. However, the Institute of Electrical and Electronics Engineers has proposed a standard namely, IEEE 1451 which constitutes a family of smart transducer interface standards, that defines a set of open, common, network-independent communication interfaces for smart transducers (sensors or actuators) to achieve sensor data interoperability between cyber and physical components of CPS. The standard defines a smart transducer as either a sensor and/or actuator that can identify and describe itself, has the data processing capability to present sensor data or accept actuation values, respectively, in measurement units, has network communication capability, and is easy to use, enabling plug-and-play functionality [17].

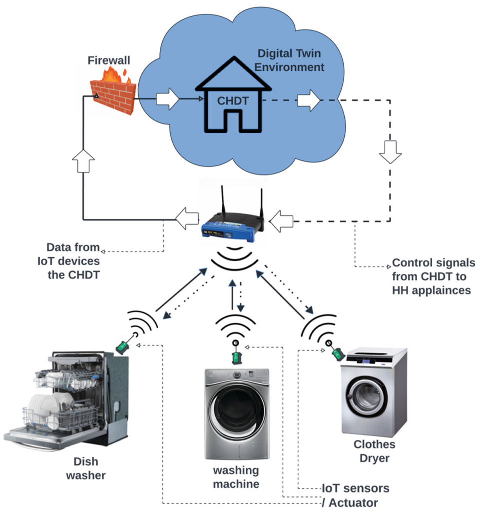

Fig. 4. Communication framework between IoT sensors/actuators and the household appliances

4.2 Control Block

This block connects the CHDT to each of the embedded appliances. The input of the control block accepts output from the decision block and the output of the control block serves as input to actuators that are connected to each of the appliances. At this stage of the study, an open loop control system is considered. This is because the expected control actions at this level may include switching off appliances between the “on” and “off” states. In future studies where complex actions like controlling thermal comfort by monitoring and adjusting room temperature or using CHDTs in demand response techniques such as interruption of loads, other control models may be suitable.

4.3 Influence Block

Knowledge from social network analysis has shown that the decision of participants on social networks can be influenced by network influencers. As claimed by [18], people usually look up to influencers on social media to guide them with their decision-making. There are various strategies for spreading influence in a social system or network. One powerful strategy that has been used to favourably impact individuals in a variety of ways is the power of internet information dissemination [19, 20]. Companies have used this technique, known as the “viral phenomenon” or “viral marketing,” to encourage sharing amongst individuals with social connections, because it is recognized that social recommendations may assist improve traffic to business websites, resulting in increased engagement and income. In the developed prototype model, two types of influences are considered. These are:

Exogenous Influence: This represents influences that originate from the external environment of a CHDT. This may constitute an influence from the community manager or other influencer CHDTs within the community. The outcome of some preliminary results obtained by studying endogenous influences within the CVPP-E can be seen in Sect. 5.

Endogenous Influence: The type of influence that originates from inside of a CHDT.

4.4 Decision Block

This block forms the central part of the CHDT. It is the place where all decisions of the CHDT are made. The decision block accepts inputs from (a) the community goal block, (b) the digital profile block, (c) the IoT data block, and (d) the influence block. In Fig. 5, a Business Process Management Notation language is used to illustrate how CHDTs make decisions based on the various inputs.

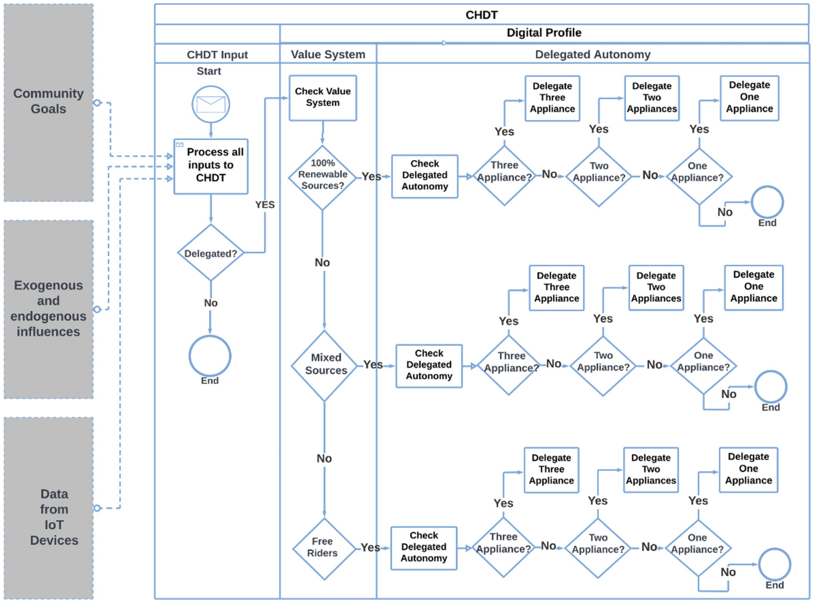

Fig. 5. A BPMN representation of the decision-making process of a CHDT

4.5 Addressing Ethical and Other Relevant Concerns

Addressing Ethical Concerns: The CVPP-E concept is designed to be less intrusive and would not require users to submit sensitive personal data besides their digital profiles, which reside in the users' CHDT memory and will not be shared with any third party inside or external to the community. Furthermore, the notion of influence will not work on CHDTs who have already defined their digital profiles. It is rather intended to influence free rider CHDTs who are part of the community and yet have not defined their digital profiles, and therefore their behaviours are inimical to the collective interest of the community. This is a common phenomenon in communities where some members do not conform to the community norms. A typical example is the notion of the "tragedy of the commons," where some members abuse or overexploit a shared community resource for their personal or parochial gains. Furthermore, since this is a closed community, it will not be possible for external and malicious influences to access the CHDTs.

Addressing Appliance Heterogeneity: In developing the prototype model, appliance heterogeneity for all the appliances was taken into consideration. A key parameter that differentiates these appliances is their power ratings. This, parameter determines how much electricity an appliance may consume per unit time, usually measured in watt-hours (Wh) or kilowatt-hours (Kwh). This parameter may vary from appliance to appliance based on the size, features, and year of manufacture, among other factors. To help cater for the wide variety of appliances, a uniform probability distribution function expressed in the form of *"uniform discrete function (x, y)"* is adopted. Where x is the possible minimum appliance power rating and y is the possible maximum appliance power rating. Using this technique, the model will stochastically assign a value between x and *y* to every unit of an appliance in the model. This technique does not only make each appliance assume a different rating but also enables them to behave differently.

Addressing Multiple Value Systems: In the CVPP-E, CHDTS can have multiple value systems. For instance, a prosumer CHDT could have a value system of (a) 100% renewable energy consumption, (b) revenue generation, and (c) cost-saving. However, these value systems should be arranged in a hierarchical order of priority (priority list).

Addressing Collision of Value Systems: This can be addressed in two ways. These are: (a) at the CHDT level. Here, the value system that is higher in the priority list of the CHDT will override the lower priority value system. (b) at the community level, the community may also define some values, such as sustainability values, as a priority in their value system. In such instances, the sustainability values will always override any other values that conflict with them.

5 Scenario for Testing the Control Capabilities of CHDTs

To illustrate the control capabilities of the CHDTs. We consider a scenario where a CHDT sends a series of control signals to switch appliances between the "on" and "off" states. Three appliances, namely a washing machine, dishwasher, and tumble dryer are controlled. Table 1 shows the time at which the control signals are transmitted and the corresponding control action that the signal is expected to achieve. Figure 6 shows the use behaviour of the three appliances without the control signals. In Fig. 7 we illustrate the use behaviour of the three appliances when control signals are received by these appliances. The period between each "on" and "off" cycle is 10 h.

Table 1. Periodic control signals to test the control capabilities of CHDTs

	Time (hours)									
	20	30	50	60	80	90	110	120	140	150
Control action	Off	On	Off	On	Off	On	Off	On	Off	On

In Fig. 10, we show the outcome of the model without any control signals. The figure shows continuous consumption without any interruptions.

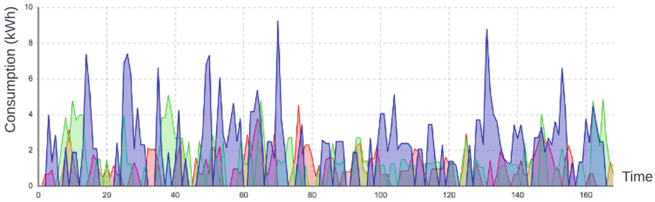

Fig. 6. Profile of three appliances without control signals

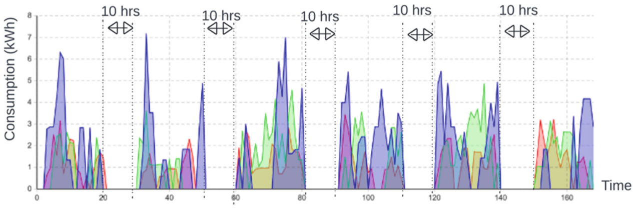

Fig. 7. Profile of three appliances with "On" and "Off "control signals

To further illustrate the decision-making and control capabilities of these CHDTs, we discuss in Sect. 5 some outcomes of previous studies, that were conducted using two different scenarios. However, to better understand these studied cases, it may be relevant to provide some insight into the prototype model that was used for the study. Firstly, the prototype model is constituted of several sub-models that are integrated to function as a single model. This technique allows modeling the different actors and systems that interact to allow the CVPP-E to accomplish its intended functionalities. Some of the sub-models are as follows:

(a) the PV and local storage sub-model (Fig. 8) which is used to model the embedded PV systems for prosumers,
(b) The embedded household appliances model (Fig. 9) is used to model all embedded appliances. Nine appliances were considered in the model
(c) The prosumer model (Fig. 10), which is used to model prosumers, and
(d) The consumer model (Fig. 11) is used to model consumers.

Depending on the intended use, a sub-model in AnyLogic [21] can be created using one of three modelling strategies. For example, all models that display dynamic behaviours, with continually changing parameters, are simulated using System Dynamics modelling techniques. The photovoltaic system (PV system) and local storage sub-model, as well as the embedded household appliances sub-models, are examples of system dynamics models. Multi-agent system approach was also used to model the changing states (active and inactive states) of prosumer and consumer CHDTS. Finally, all aspects of the model that needed the formation of an entity endowed with autonomous qualities were also modelled using agent-based modelling techniques.

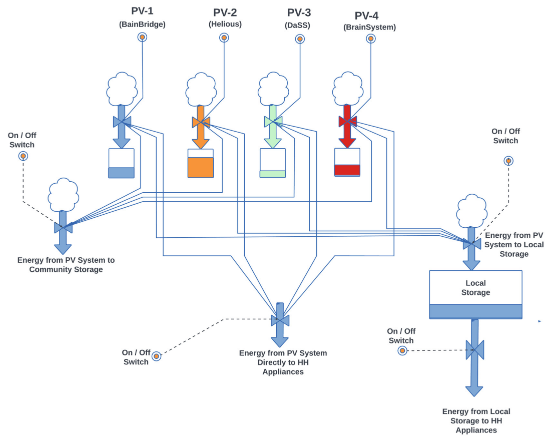

Fig. 8. A model of a four PV system, local storage and the three outputs of the PV system

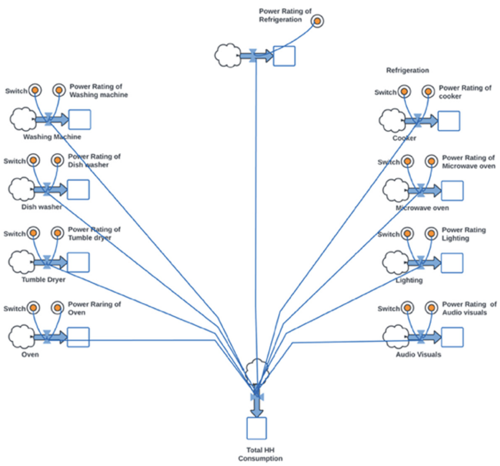

Fig. 9. A System Dynamics model of all nine embedded household appliances

Although the prototype model is constituted of several other sub-models, the shown ones, thus, Figs. 8, 9, 10 and 11 form the core of the prototype. Discussed in the next section are the outcomes of some previous studies.

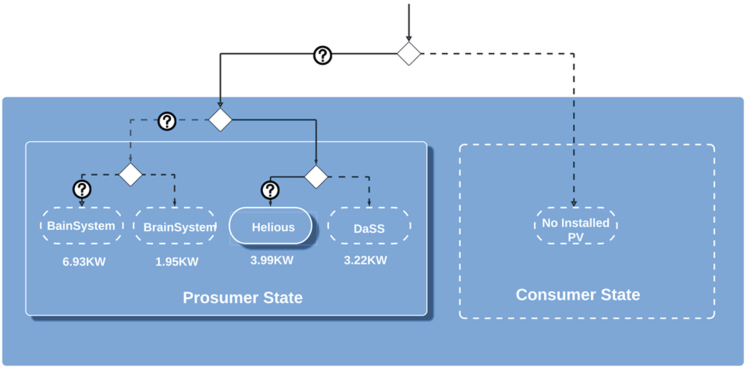

Fig. 10. An agent-based model of an active prosumer CHDT with an active 3.99 kW PV system

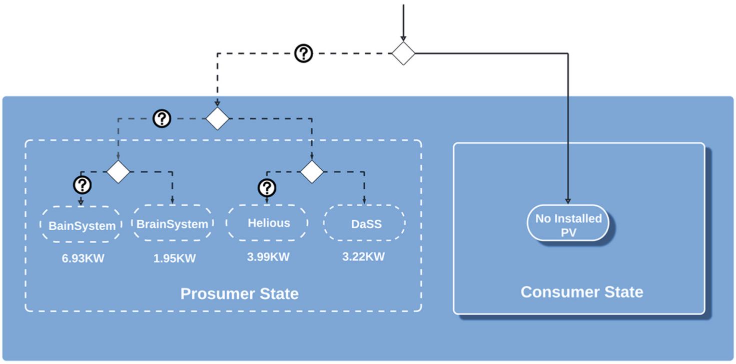

Fig. 11. An agent-based model of an active consumer with no installed PV system

6 Discussion of the Outcome of Preliminary Studies Conducted Using the Developed Prototype

In this section, we present the outcome of some preliminary studies conducted using the prototype model. We illustrate with two examples, thus, (a) modelling delegated autonomy and (b) modelling mutual influences.

6.1 Scenario 1: Modelling Delegated Autonomy

In Tables 1 and 2, we show some selected scenarios that were used to test the CVPP-E prototype at an earlier stage [22]. For instance, the data shown in Table 2 was sourced from [23]. For demonstration purposes, Table 2 shows data for only three out of the nine household appliances that were embedded in each CHDT. These parameters were used to model each of the appliance´s use-behaviours. Furthermore, in Table 3, we considered different scenarios of varying prosumer and consumer populations. For each scenario, we tested different degrees of delegated autonomy. Delegation in this sense means that the CHDT has been given authority by its owner to make some rational decisions on his/her behalf. In this example, the goal is to minimize community consumption within a certain period namely the "vending window" (Fig. 12) so that the saved energy could be vended to the power grid. We tested different delegated autonomy options, i.e., delegating either 1, 2, or 3 of any of the appliances mentioned in Table 2. In Fig. 12 we show the outcome of one scenario, thus, scenario 1 (Table 3). This outcome shows that, within the vending window, the CHDTs carried out the control instruction (delegated autonomy) which is to defer the use of these appliances within the defined period (vending window), thus resulting in zero consumption.

Table 2. Parameters that were used to model the various household appliances [23].

Type of appliance	Annual power (kwh)			Peak periods		Number of wash cycles year
	Min	Average	Max	P1	P2	
Washing machine	15.00	178	700	5am–4pm	5pm–2am	284
Tumble dryer	64.25	497	1600	5am–12pm	6pm–11pm	280
Dishwasher	33.32	315	608	5am–3am	6pm–2am	270

Table 3. The population size of the various HH in the sample scenario

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

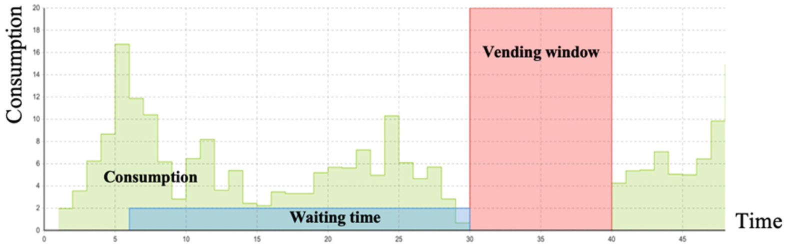

Fig. 12. The outcome of collective action behaviours for scenario 1 (Table 3)

6.2 Scenario 2: Modelling Mutual Influence of CHDTs

In a study conducted in [24], the concept of mutual influence was explored. Under this scenario, the following parameters were assumed: (a) Positive influence: Uniform distribution (0, 2), (b) Negative influence: Uniform distribution (−2, 0), (c) Frequency of transmission: Uniform distribution (0, 3) times per week, (d) Impact: Uniform distribution (0, 5) hours from the moment of receiving the influence, (e) Decision constant ($\propto$) = 50. Details of other relevant parameters such as Duration of Use, Appliance Power Rating, Frequency of Use etc. can be found in [24].

Table 4 below, describes two different cases, constituting of different population sizes, that were considered. In all cases, the influencer CHDTs attempt to influence the "influencee" CHDTs to use the loads mentioned in Table 2 only when the energy available is from renewable sources, thus, directly from PV sources, local storage or community storage and to avoid using energy from the grid. A total population size of 50 CHDTs was used. Two scenarios as shown in Table 4 were considered.

Table 4. Two cases with varying population sizes are used to test collective decision-making.

Cases	Population (%)					
	Influencer population "A"	Influencee population	Positive influencer population	Negative influencer population	Prosumer population	Consumer population
Case-1a	90%	10%	90%	10%	20%	80%
Case 1b	90%	10%	10%	90%	20%	80%

At the end of the model run (728 h), Figs. 13a & b show the characteristics of the modelled influence that was received by two different CHDTs, i.e., CHDT-1 and CHDT-2. The pulses that appear below the X-axis represent negative influences whilst the ones above the X-axis are positive influences.

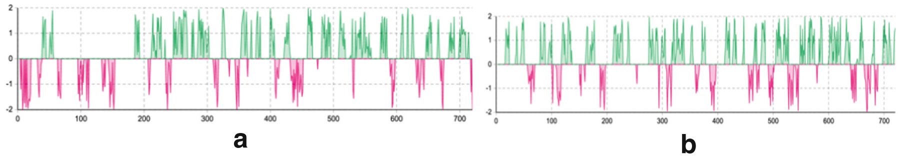

Fig. 13. **a.** Influences received by CHDT-1. **b.** Influences received by CHDT-2.

In Figs. 14a and b, we show how the aggregation of influences over time can be used to determine the overall behavior of a CHDT. We also illustrate how the overall behavior can be used in decision-making. For instance, Figs. 14a, and b show CHDTs 3&4. Initially CHDT 3 was negatively influenced however the general behavior changed into a positive one after 500 h. This CHDT could not decide because its behavior (thus, the aggregation of influence) over time could not cross the threshold "∝". In Fig. 14b, CHDT 4 was positively influenced right from the beginning of the model until the finish. CHDT 4 was able to make a decision at 300 h.

By comparing the outcome of case-1a and case-1b (Figs. 15a & b), the outcome of the model shows that when the population of positive influencers was high (90% in case-1a against 10% case-1b) the majority of the CHDTs were influenced positively, hence, the majority were able to make a decision to switch consumption from the grid to renewable sources hence consumption from the grid was about 51% as compared to 69% in case-1b) where the number of positive influencers was low (10%). Furthermore, consumption from the community storage, local storage and PV appreciated significantly in case of 1a more than in case 1b. This can also be attributed to the difference in the population of positive influencers.

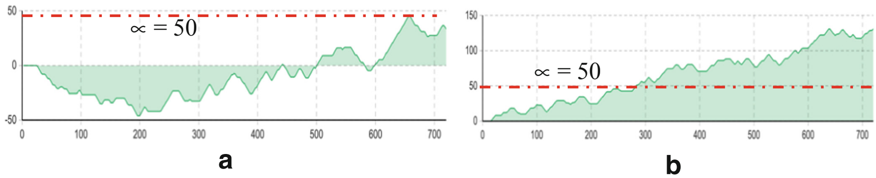

Fig. 14. **a.** CHDT-3. **b.** CHDT-4.

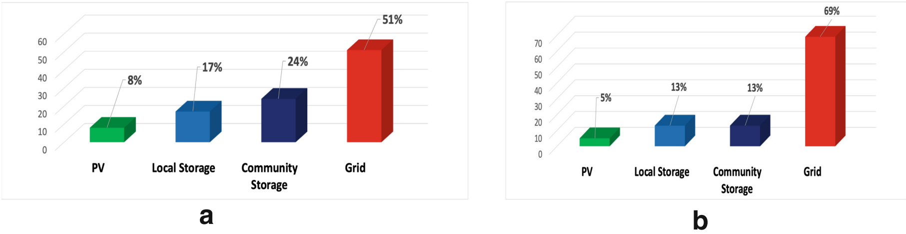

Fig. 15. **a.** Case-1a. 90% positive influencers. **b.** Case-1b. 10% positive influencers.

7 Conclusion and Future Works

This work showed how the integration of IoT devices could facilitate (a) the collection of data from the household asset twins to the CHDT, and (b) how control signals from the CHDT could be used to regulate the "on" and "off" states of the asset twins. In the study, the abstraction levels of the CHDT in the context of the digital twin were also described. An illustration of the control capabilities of the CHDT was also shown. Furthermore, this study showed a detailed architecture of the CHDT and all the necessary components to enable the functionality of the concept. Additionally, outcomes from two previous studies using the developed prototype model were demonstrated. In all, the work has shown that the CHDT concept is feasible. Furthermore, the study has helped to establish the fact that IoT and digital twin concepts are a key prerequisite for the development of the CHDT concept. The IEEE 1451 family of smart transducer interface standards have also been suggested.

In future studies, other collaborative behaviours such as value co-creation which is an aspect of collaboration where members of a community or an ecosystem jointly create a new product or service that results in the generation of value for the mutual benefit of members. In such circumstances, the contribution of each member towards the created value is highly relevant and can be contentious if not managed adequately. In the context of the CVPP-E, some members, particularly, prosumers may contribute tangible value in the form of renewable energy that is contributed from the locally installed PV systems. On the contrary, consumers may contribute intangible value by denying themselves the use of certain household appliances (aka delegation of deferrable loads) to enable the reduction of energy consumption in the community. This kind of self-imposed denial of service could be considered an intangible contribution toward value co-creation. In future studies, these aspects of tangible and intangible value creation shall be explored further and also in detail.

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