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Delegating Autonomy on Digital Twins in Energy Ecosystems

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Abstract- The concepts of "Collaborative Virtual Power Plant Ecosystem" (CVPP-E) and "Cognitive Household Digital Twin" (CHDT) have been introduced to support sustainability and effective energy performance at the level of households within Renewable Energy Communities (RECs). In this context, a CVPP-E can be viewed as a digital twin representation of a REC. Likewise, CHDTs can also be represented by digital twins of each member household of the CVPP-E. Moreover, the CHDTs may be implemented as software agents with some level of cognitive intelligence, which allows them to perform as autonomous decision-making entities that can assume some "delegated autonomy" on behalf of the owners of the physical households. Their decisions are expected to lead to the promotion of collaborative behaviours that will increase the ecosystem's resilience and sustainability. This work examines the scenario of a CVPP-E with prosumer CHDTs that may directly consume energy from a solar energy generation system installed in the household, from a local battery storage system, from a community battery storage, or from the power grid. The scenario also considers consumer CHDTs whose sole choices for energy consumption are the community storage and the grid. The CHDTs given some "delegation" to make decisions on energy consumption. This "delegated autonomy" is given by their physical twin (owner), which may indicate the owner's contribution to a common objective, hence enabling a collaborative approach towards sustainable energy consumption. The outcomes of the performed analysis, obtained through a multi-method simulation methodology, show the feasibility and potential utility of having CHDTs with complementary decision-making capabilities. The adequacy of the adopted modelling technique is also demonstrated.

Keywords: Collaborative networks, Collaborative decision-making, Sustainable energy consumption, Digital twins, Cognitive agents.

1. Introduction

According to some recent research [1], buildings utilize roughly forty percent of world's energy, twenty-five percent of water, and forty percent of global resources. Furthermore, this study also states that residential and commercial buildings produce almost one-third of the global greenhouse gas emissions. Other recent studies have also stated that due to the population and economic growth [2], urbanization and industrialization [3], and technological advances [4], energy demand in contemporary societies has increased substantially. This increase results from the need to meet the energy needs of people, namely in their households. This changing energy landscape is putting severe pressure on the Earth's limited resources and subsequently contributing to a potential environmental catastrophe that endangers the survival of the planet and its inhabitants. The Paris agreement [5] and other initiatives [6] have shown the urgent need to adopt practical measures by all key players, including households, which are the main cause of it.

While various management strategies such as microgrids [7], [8], improving the integration of renewable sources into the power grid [9] and others have been discussed in the literature, various other studies, including [10] and [11], further highlighted the potential role of the "Collaborative Virtual Power Plant Ecosystem" (CVPP-E) and the "Cognitive Household Digital Twin" (CHDT) concepts as promising constructs for improving energy use in these households, helping to reduce the greenhouse gas emission problems that currently threaten the planet. In [10] and [11] the authors envisioned that these concepts could have a significant role in the implementation of Renewable Energy Communities (RECs), as well as the Smart City concept. Building on these concepts, a renewable energy community can be described as an ecosystem composed of various prosumers who have a photovoltaic system installed on the roof of their homes, and consumers who do not have this system. Furthermore, the community is assumed to have a shared community energy storage that receives surplus energy from the prosumers. Both prosumers and consumers have access to energy from the community storage when it is available.

Given the description of the considered REC, we further assume that both prosumer and consumer households, which are located within the physical REC environment, could have their equivalent representation in the cyberspace as digital twins. The implication is that the cyber environment will be composed of both prosumer and consumer digital twins. By endowing these digital twins with some cognitive intelligence, it is anticipated that they will be able to act autonomously and have complementary decision-making capabilities. We refer to these types of intelligent digital twins as “Cognitive Household Digital Twins” (CHDTs). In this study, CHDTs are implemented by software agents that possess some level of autonomous decision-making capabilities, which allow them to make autonomous decisions on behalf of their physical twins towards collaborative endeavours within the CVPP-E ecosystem. CHDTs can accept some "delegated autonomy" from their physical twins and, depending on the embedded intelligence, perform certain basic energy utilization choices on behalf of the physical twins (PTs).

The aim of this study is twofold: (a) to evaluate the adoption of a multi-method simulation technique in modelling the cognitive intelligence of the CHDTs, and (b) to demonstrate how this cognitive intelligence can be used to realize “delegated autonomy”. Here, "delegated autonomy" refers to a command given to the CHDT, which can incorporate the (a) needs, preferences, priorities, objectives, and expectations of the PT in terms of energy consumption, and (b) the PT’s contribution to a particular goal that may require a collaborative action by the members of the community (CVPP-E). We further assume that the “common goal” that the community wants to pursue is to minimize the level of grid energy consumption while maximizing energy consumption from renewable sources, namely energy generated within the ecosystem. By leveraging the capability of these CHDTs to use their cognitive intelligence in making rational decisions, this study explores the involvement of CHDTs in collaborations or collective actions that may lead to achieve the suggested goal of reducing consumption from the grid while maximizing the level of consumption from renewable energy sources. This technique is expected to increase the sustainability and survivability of the ecosystem. Thus, this research work is guided by the following questions:

RQ-1. *Using a muti-method simulation approach, how can the cognitive intelligence of CHDTs be modelled?*

RQ-2. *In case the ecosystem has a specific goal, such as minimizing consumption from the grid while maximizing consumption from renewable energy sources, how can “delegated autonomy” be used to achieve this goal?*

This article is a revised and extended version of a preliminary work presented at ICRERA 2022 [12]. The remaining of the article is organized as follows: Section 2 focuses on the theoretical framework and related works. In Section 3 we discuss the adopted simulation techniques. Some selected scenarios that are used to demonstrate the adopted simulation technique are discussed in Section 4. Section 5 presents some results and their discussion. The study ends by drawing some conclusions and highlighting future research directions.

2. Background Knowledge

2.1. Collaborative Networks

The literature in the field of Collaborative Networks (CNs) clearly shows that its knowledge base has greatly expanded in the last two decades [13]. This expansion is attributable to the myriad of challenges that society today faces as we continue to pursue the "digital transformation" agenda, which is expected to transform our current society into a digitalized society, namely, Society 5.0 [14]. This agenda seeks to integrate intelligence into all aspects of technology and promote the hyperconnectivity of millions of organizations, individuals, and things. Moreover, the merging of virtual and physical spaces as in Cyber-Physical Systems and the Internet of Things is likely to lead to future scenarios in which billions and billions of networked actors, smart devices, intelligent systems, and ecosystems can coexist and cooperate. For such synergy to be effective, beneficial, and dependable, the parties involved must learn to collaborate in a trustable way that benefits all parties involved. The scientific field of CNs involves the development of concepts, mechanisms, and models that can help support and understand these challenges in a collaborative setting.

Models, mechanisms, and tools from the CNs field have been proposed as promising enablers, and have subsequently been used to address challenges in various domains, including the smart grids [15], Industry 4.0 [16], Society 5.0 [14], Internet of Things [17], cyber-physical systems and digital twins [18], etc. According to [19], collaboration is known to provide benefits to all parties involved, which offers the rationale and impetus for pursuing collaboration in a digitalized and hyperconnected society. As the same authors state in [19], collaboration is the process by which a group of entities strengthen their reciprocal capabilities. Collectively addressing a problem as a group is an integral part of the process. Collaboration also enhances the ability of an organization to compete with other comparable organizations and groups. In addition, it can improve the ability of the involved entities to survive turbulent times.

2.2. Virtual Power Plants

A VPP is an entity composed of distributed, multi-site, and homogeneous systems that are coupled with dispatchable and non-dispatchable distributed energy sources. Furthermore, a VPP necessitates interaction among several participants [11]. According to [20], VPPs are capable of a wide range of functions. They can be used to monitor, forecast, optimize, and exchange the energy of distributed energy resources like solar parks, wind farms, and “combined heat and power” (CHP) units. By increasing and decreasing the power generation / consumption of controllable units, fluctuations in of renewable energy generation can be balanced in this way. But the VPP does more than just support the stability of the power grid. It also establishes the prerequisites for incorporating renewable energy sources into the grid or energy markets. Typically, individual small plants cannot offer enough flexibility in energy exchanges or balancing services. This is either due to the excessive variation in their generation profile or because they fall below the minimum bid size accepted by the energy marketplace. By aggregating the output from several generating units, a VPP can provide level of service and resilience similar to that of large power plants, allowing it to trade in the same energy markets just like industrial users.

2.3. Digital Twins

A digital twin constitutes a kind of dynamic digital “copy” of a physical asset, process, system, or environment, with identical appearance and behaviour to its physical counterpart. A digital twin gathers data from the physical asset and replicates processes to enable prediction of potential outcomes and performance issues that the real entity may encounter [21].

Over the past decade, companies of all sizes and all over the world have been confronted with increasingly rapidly changing, uncertain, and complex conditions. Complementarily, the increasing digitalization has forced companies to explore other efficient and cost-effective alternatives for their operations. Coincidentally, digital or virtual engineering has also been shown to help companies address some of these challenges. Mainly over the past decade, the concept of Digital Twin has developed in response to these changing trends. This term, as explain earlier, refers to the replication of a physical system in a virtual environment. Digital Twins initially had a purely descriptive character, but as a result of advances in the information and communication technologies, it has become feasible to establish bidirectional connections between the physical and the digital systems [22]. Since its conception in 2002, the importance of Digital Twins has been steadily increasing. For instance, the notion of Intelligent Digital Twins (IDT) has been suggested as one of the viable approaches to consider in managing the complexity of a Smart City ecosystem [23]. As stated in [24], “complete integrated twins” are foreseen as a major industry trend until 2040. The anticipated benefits of digital twin technology are enormous. The advantages of the "twinning" concepts include improved accuracy and fidelity, as well as decreased time/cost and workload during the creation of real-time virtual representations or the implementation of digital replicas of physical systems. However, despite numerous occurrences in published work, there is still no consistent and comprehensive definition of the concept [25].

2.4. CVPP-E as a Digital Twin Representation of a Renewable Energy Community

The concept of Collaborative Virtual Power Plant Ecosystem (CVPP-E) results from the integration of concepts and mechanisms from the fields of Collaborative Network and Virtual Power Plants (VPPs). The merging of these concepts led to the hybrid concept of CVPP-E. From a CNs perspective, a CVPP-E can be considered a business ecosystem [26] consisting of prosumers who have solar panels mounted on the roof of their houses and can use the locally generated energy as well as store or share their excess with other members who are recognized as consumers, through a community storage system. Membership in these ecosystems is motivated by mutual interests, which may include sustainability, economic, social, and technological interest. This ecosystem is similar to a REC which, according to the [27], is described as being self-sufficient and effectively governed by shareholders or members who reside nearby to the energy asset. Members of a REC can generate renewable energy for their own use, but also have the option to store, share, or sell surplus energy with their neighbours. Participation in the community is usually free and voluntary.

While the synergy in the ecosystem is based on some common goal(s) and voluntary participation, the concept of collaboration enables individual members to contribute flexibly to the achievement of these goals without having to make significant sacrifices to their needs, preferences, priorities, objectives, and expectations. Moreover, when viewed through the lens of Collaborative Networks, the CVPP-E concept can be classified as a Virtual organization Breeding Environment (VBE) that creates the enabling conditions (preparedness) for a subset of its members (a virtual organization) to pursue a collective objective when an opportunity presents itself. Conceptually, the CVPP-E consists of two main layers, as illustrated in Fig. 1. The first layer is the cyber/collaborative layer, which consists of the CVPP-E manager and the Cognitive Household Digital Twins, which are digital twins of the physical prosumer and consumer households, located within the ecosystem. At a second level there is the physical layer which consists of the collection of the physical household appliances, the community energy storage system, the energy sources (e.g., photovoltaic), and the grid. It is proposed that the governing structure of the ecosystem is polycentric and decentralized, with a manager whose responsibilities include coordination, opportunity brokerage, and administration of collaborative ventures. By adopting this interpretation, we describe the CVPP-E as a grouping of autonomous software agents that are used to represent each unit of a physical household that is located inside the community and that are assigned some level of delegated control, enabling them to perform commands corresponding to the value systems of the physical twins.

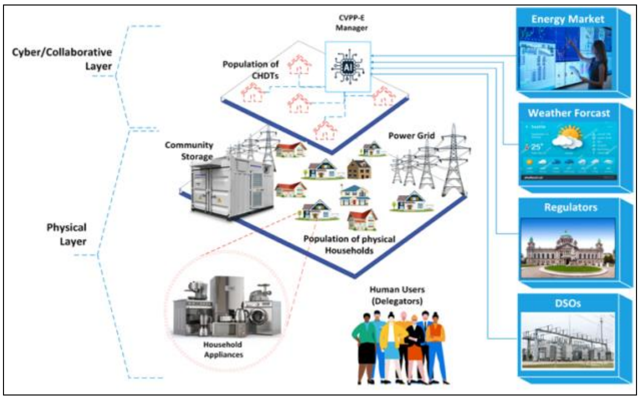

Fig. 1. A high-level view of the CVPP-E framework

2.5. CHDTs as Digital Twins of the Constituent Households in the REC

In accordance with the characteristics of digital twins as discussed in Section 2.3, we propose the concept of the Cognitive Household Digital Twin (CHDT). As such, we represent each physical household within the REC ecosystem by its replica in the form of a digital twin equivalent within the cyberspace. In the developed prototype, which is discussed in section 4, each CHDT is implemented as a software agent that replicates the actual attributes and actions of the physical household. Such agents are conceived to coexist and interact with each other within the digital REC i.e. the CVPP-E. CHDTs are also created to be embodied with some cognitive intelligence, designed to allow them to make complementary decisions on behalf of their owners (i.e. owners of the physical households). Fig. 2 shows the logical structure of the CHDT. It consists of a cognitive block, a decision block, a control block, and an influence block. Key aspects of the CHDT model are discussed in the following paragraphs.

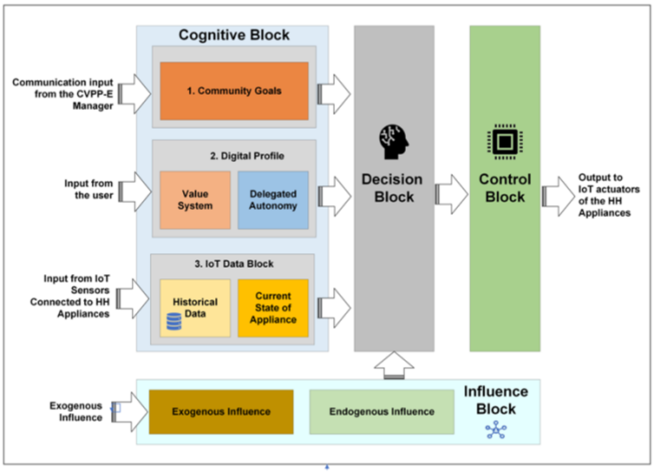

Fig. 2. A logical structure of a CHDT

The cognitive block. This element serves as a representation of the cognitive intelligence of the CHDT. This block essentially allows the CHDT to be cognizant of itself and subsequently its environment. Being cognizant of itself which means it is cognizant of (i) its status as a prosumer or consumer, (ii) its status as an influencer of "influencee", (iii) its delegated autonomy, (iv) the capacity of installed PV system, and (v) delegated/undelegated states. Furthermore, being cognizant of its environment means it is cognizant of (i) the community goals, and (ii) the coalition formation which involves scheduling and execution of goal(s). Furthermore, the cognitive block contains the digital profile of the CHDT, which comprises (i) the value system of the physical twin, (ii) the delegated autonomy of the physical twin, (iii) the historical record of behaviours, and (iv) the current states and behaviours of all embedded household appliances inside the physical home. The key components of the cognitive block are discussed in the following paragraphs.

Community goals. As noted earlier, the main objective of the CVPP-E is often to accomplish a specific goal(s) shared by all ecosystem members. The ecosystem could pursue multiple goals concurrently. For instance, the ecosystem could work toward economic, social, technological, and sustainability goals all at the same time.

Value system. As was mentioned earlier, participants of these ecosystems may have diverse preferences, needs, goals, and expectations. To help replicate these attributes of the physical entity into the corresponding Digital Twin, we introduce the notion of a value system. This enables reflecting these attributes of the PT into its DTs. By adopting this technique, each CHDT can be materialized by a software agent with the necessary PT attributes. The multi-agent system-derived idea of state charts is utilized to describe the recommended attributes of the value system of every PT as internal states embedded in the corresponding CHDT. State charts are a UML-included formalism that is commonly used to express the several states and behaviours that dynamic systems can go through in response to internal and external stimuli. A state is the situation in which an object is and which may change when some event occurs. A state chart can be used to describe in which state a software agent could be as well as what could possibly cause a transition from that state. Triggers can be used to alter the internal state of an entity or to transmit information to other agents to alter their states. A modelling alternative could be the use of Petri nets. States may have varying degrees of significance, which may affect the timing of initiation and whether or not they can be interrupted. Instructions, rules, heuristics, formulae, or processes can be used to incorporate various types of intelligence into an agent using state charts [28].

Delegated autonomy. Delegated autonomy refers to a household owner giving explicit instructions to his/her CHDT to be followed in implementing or execution of his/her value system. For instance, the CHDT could receive a delegation to defer the use of any specific appliance(s) within a certain period. It is however expected to be possible to achieve this without compromising the user's experience.

The decision block. The main decision-making unit of the CHDT is this block, where all decisions are made. The decision block receives inputs from the influence block, from the digital profile block, from the IoT data block, and from the community objectives block.

The control block. This block links the embedded household appliances to the CHDT. The control block accepts as input the output from the decision block. The actuator components of each appliance (lately smart appliances) receive the output of the control block as input.

The influence block. Incentives can help motivate people to modify their behaviours. In [29], "incentive" is defined as the act of changing external circumstances while mobilizing internal forces to support the behaviour of a motivated person to evolve in the way intended by the motivator. An incentive can be positive or negative. Positive incentives are often fruitful and can benefit the beneficiaries since they increase productivity because individuals naturally desire to obtain things. Similar to positive incentives, negative incentives can encourage recipients to increase productivity by making them desirous of a different outcome.

Numerous incentive programs have been suggested in [30]. In the context of energy conservation, these incentives are suggested to help change unsustainable energy consumption behaviours. The influence block in this case is used in the context of the CVPP-E to allow scenarios that can help understand how incentives can influence decision-making. This block consists of two parts:

(a) Exogenous influence. This term refers to influences that arise as a result of incentives from a CHDT's external environment. This may entail, for example, managerial influence.

(b) Endogenous influence. The type of influence is caused by internal drives or forces.

3. Related Works

Among related studies, a DT is used in [31] to monitor the efficiency of buildings and associated renewable energy generation systems. The objective of that work is to increase the overall performance of a smart city through optimal scheduling. Other related studies, such as [32], employed DTs featuring machine learning, combined with an urban-scale program called EnergyPLUS, to analyse demand response opportunities in buildings and provide flexible services to the grid. The concept of DT was also discussed in [33], in which the authors applied Building Information Management (BIM) and Geographic Information Systems (GIS) in an Italian case study. Using artificial intelligence, the proposed DT model was adopted in this work to optimize the use of BIM and GIS. As concluded by the authors, the proposed DT is able to model loads optimally, thus leading to increase self-consumption from renewable sources and reduce total energy consumption. In addition, [34] describes a data-driven multi-layered DT of the energy system which attempts to replicate the pattern of real household energy consumption. The Household Digital Twin and the Energy Production Digital Twin (EDT) were proposed as two distinct types of DT which are connected. According to the findings of the study, the EDT permits a household-centric energy optimisation system to achieve the desired level of efficiency of energy consumption.

4. The Modelling Framework

This section of the study is in two parts. The first part discusses the simulation methodology that was adopted for this work. In the second part, the various components that constitute the CVPP-E and CHDTs are explained. The cognitive intelligence aspects of the CHDT are emphasized. The used modelling techniques are also highlighted.

4.1. Modelling Methodology

The adopted multi-method modeling technique consists of system dynamics, agent-based, and discrete even modelling.

Multimethod Modelling Technique. Historically, simulation and modelling were based on a single method, as stated in a recent white paper [35]. However, modelling complex systems and the interactions between their constituents is a complex feat and therefore requires new modelling techniques that can address the different dimensions and aspects of the system. This capability was severely lacking in single method approach. For this reason, a thorough understanding of how the system is structured in the real world and how it can be accurately represented by a model [35] is essential for creating an adequate model. Due to the limitations of single-method simulations, several researchers, including [36], [37], and [38], have proposed a multi-method simulation strategy. A multi-method simulation is a simulation/modelling approach that combines two or more simulation techniques. In [38], the authors state that the popularity of this strategy has increased at an almost exponential rate over the past two decades. The advantage of seamless integration of different modelling and simulation methods is that it allows the modeler to overcome the limitations of a single modelling method and capitalize on the strengths of each method. Combining diverse methods results in efficient and manageable models that do not require workarounds. According to [39], three major simulation methodologies, namely (a) System Dynamics, (b) Multi-Agent Systems, and (c) Discrete Event Modelling, are frequently combined to produce a multi-method model.

System dynamics. System dynamics postulates that the distinctive feature of a system is influenced by the interaction between its constituents and their interaction with the environment. Furthermore, these elements are found to influence each other in a dynamic and complex way over time. This modelling technique has often been used to analyse complex, nonlinear processes and inter-element synergy. System dynamics allows the integration of multiple perspectives of a complex and dynamic system into a software model for straightforward analysis, as stated in [39]. By adopting a framework that adapts the use of modelling blocks such as stocks, feedback, flows, delays, etc., system dynamics can simplify and dynamically simulate complex problems involving numerous variables or factors.

Multi-agent systems. Multi-agent System (MAS) technology, on the other hand, has gained enormous attention in the last decade due to its accommodating use in various domains. These domains include artificial intelligence, distributed computing, software engineering, the smart grid, electronic commerce, adaptive virtual environments, and social networks [40]. Myriad disciplines have used MAS to solve a wide range of problems. According to [41] and [42], MAS can be used as a simulation technique, suitable for modelling autonomous, dynamic, and adaptive systems, based on three fundamental concepts: (a) agency, (b) dynamics, and (c) structure. The agency aspect implies that that agents are autonomous entities with distinct properties, behaviour, and possibly goal oriented. The dynamics facet involves the growth, transformation, and evolution of both agents and their surroundings. The interaction of agents results in the formation of a structure. Agents inhabit an environment, perceive it, and choose their actions based on the current state of that environment, their own state, and the outcome of predefined decision rules. Furthermore, agents can have explicit objectives to minimize or maximize, in addition to the ability to learn and adapt based on their experience. To support autonomy, agents can be designed with cognitive intelligence that allows them to perform tasks such as sensing, planning, scheduling, reasoning, and making *decisions*.

Discrete event modelling. Discrete Event Systems (DES) simulation approach involves discrete-states and event-driven systems whose state changes are solely determined by the occurrence of discrete events. The majority of business processes may be described as DES because they involve a series of discrete actions or steps. For instance, in the context of a warehouse, a forklift may arrive at a warehouse, approach the loading bay, load or discharge its cargo, and then exit. DES are suitable for modelling discrete processes. Using this modelling technique, processes involving queuing, scheduling, priorities, delays, seizing a resource, releasing a resource, arrival of an agent, and the capacity of a system etc., can be modelled efficiently using DES. The AnyLogic platform [43] is an example of a simulation environment that combines the three modelling techniques (multi-method or hybrid). This platform was adopted for the implementation of the prototype used in this study.

4.2. Modelling a REC as a CVPP-E

Let us now show how the CVPP-E and CHDTs are modelled using the mentioned modelling techniques.

Modelling the population of CHDTs in a CVPP-E. As an ecosystem, the heterogeneity of the population's households is crucial. Consequently, our approach classifies the involved households (CHDTs) into five distinct types. The classification and associated data were obtained from [44].

The categories of households considered in this study are:

- Pensioner-only households
- Household with single non-pensioner.
- Household with several pensioners.
- Households that have children.
- Several persons household with no dependent children.

The Anylogic simulation software enables multiple software agents to run simultaneously. By adopting this feature, different population representing each category of households was formed. In the prototype model that was used for this study, a CHDT population of 100 is considered. Details about the composition of this population is provided in Table 1. Although CHDTs may belong to the same household category, their behaviours are distinctly different and non-deterministic. This is because the usage behaviours of the embedded household appliances are modelled using stochastic techniques. More light is shed on this stochastic modelling technique in section 4.7. Additionally, prosumer households are modelled as prosumer CHDTs while consumer households are modelled as consumer CHDT. Prosumer CHDTs are considered to possess embedded photovoltaic (PV) systems of varying capacities. A scenario to illustrate the varying capacity of the embedded PV system is discussed in Section 5. Finally, a centralized Community Storage System (CSS) is integrated into the CVPP-E ecosystem. Prosumer CHDTs will share their surplus energy with this storage system. Once the storage system is fully charged, both prosumer and consumer CHDTs can access energy from the storage. Fig. 3. illustrates the configuration of the CSS.

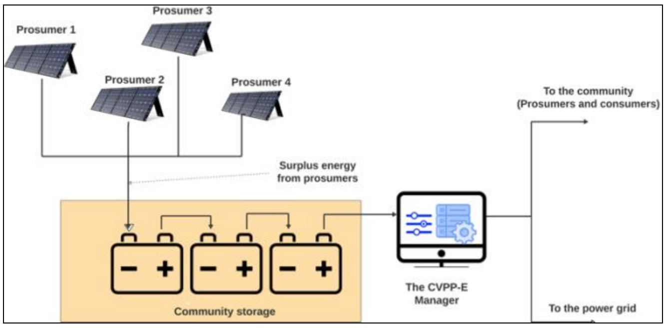

Fig. 3. A logical structure of a CSS, prosumers and the community manager

Modelling CHDTs and their cognitive intelligence - Modelling Cognizance of the self. The recognition of the self is the intelligence or knowledge that the CHDT has about itself. In this regard, we consider the following attributes of the self: (a) as a prosumer, (b) as a consumer, (c) with installed PV capacity, (d) with delegated/undelegated states, (e) the kind of delegated autonomy, (f) its value system.

In general terms, the cognitive intelligence of CHDTs is modelled through state charts that are used express the behaviour of software agents in multi-agent system simulations. A state chart, according to [45], is used to define the behaviour of objects or a system by detailing how they react to both external and internal stimuli. The claimed reaction may involve a transition between states and possibly to carry out some actions. State charts are popular, well accepted, intuitive, and highly visual. Key components of a state chart include the "states" and "transitions". Sates are represented as rectangular shapes while transitions are represented with lines with arrowed heads. A state, according to [45], is set of conditions or characteristics that characterize a person, a system, or thing at a given time, a way or form of being." A system's behaviour is often governed by rules. These rules guide the transition between the system's various states. A transition is therefore a legal state change. Pairs of states are usually connected by a transition.

A state diagram may be composed of composite and simple states. This is illustrated in Fig. 4. The top level which is the composite state defines a general condition or state of the CHDT. Other subsequent levels internal to the composite state are simple states that are used to represent attributes of the top level (composite state). Several simple states that are internal to a composite sate can be used to represent several attributes of the composite state. Both the composite and simple state can be toggle between being active and inactive. An active state represents the "true" condition of the state and an inactive state represent the "false" condition of that same state. The active state can therefore be used to represent an attribute of the CHDT that is active, while the inactive state can be used to represent attributes of the CHDT that are dormant. Active states are shown as a shaded area.

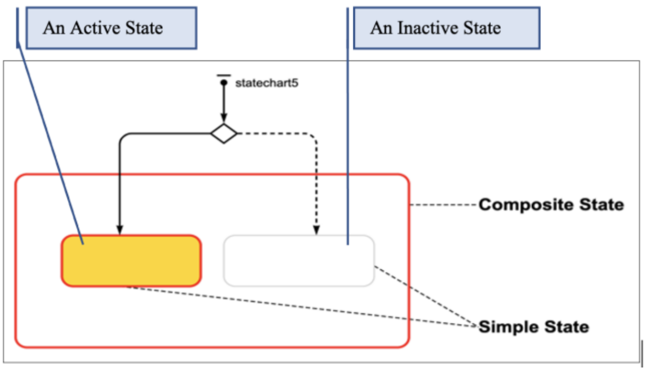

Fig. 4. Illustration of a composite and a simple state of a CHDT

Cognizance of its status as prosumer with installed PV capacity and cognizance as a consumer. In Fig. 5a, we illustrate a prosumer CHDT who is cognizant of its prosumer status (active prosumer state) and also cognizant of an installed PV named "BrainSystem" which has a capacity of 6.930kW, also being active. Similarly, in Fig. 5b, we illustrate a consumer CHDT that is aware of its status as consumer (active consumer state); a state indicating that it has "no installed PV" is represented as well. When a particular state of a CHDT is active, the digital twin executes some algorithmic code linked to that state, allowing the CHDT to function according to that code. The associated algorithmic code can include rules, heuristics, formulae, or processes, that are associated with a state, letting the CHDT behave in accordance with the embedded algorithm while in that state. The cognitive intelligence of the CHDT is grounded on its awareness of its active states (both complex and simple) and associated algorithmic code, as well as its capacity to make reasonable judgments based on this information.

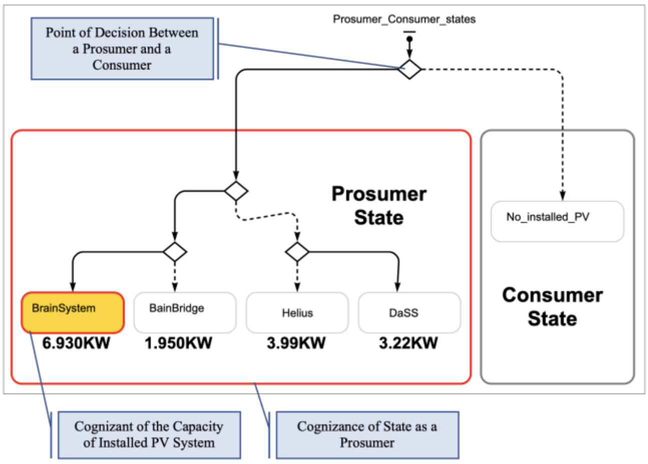

Fig. 5a. A CHDT being cognizant of its status as a prosumer with an installed PV capacity of 6.930 kW (BrainSystem)

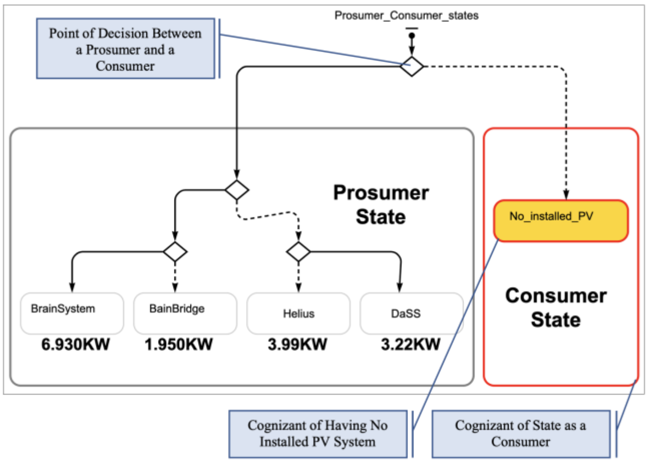

Fig. 5b. A CHDT that is cognizant of its status as consumer CHDT with no installed PV system

Cognizance of delegated/undelegated states. According to [46], delegation is the transfer of authority from one entity to another for the execution of specific tasks on its behalf. In our work, delegation refers to the process by which the user or owner of the physical twin delegates authority or responsibility to the CHDT, allowing it to act or make rational decisions on his/her behalf. Figs. 6a and 6b shows the components that are used to determine the "delegated" and "undelegated" states of a CHDT respectively. In the case of delegation/"undelegation", only one of the two states can be active at any given time. When a CHDT is delegated, the active state is "delegated." As shown in Fig. 6. However, if the CHDT is not delegated, the "undelegated" state becomes active. Under the undelegated state, a CHDT is unable to make decisions on behalf of the physical twin and, as a result, cannot engage in collaborative activities.

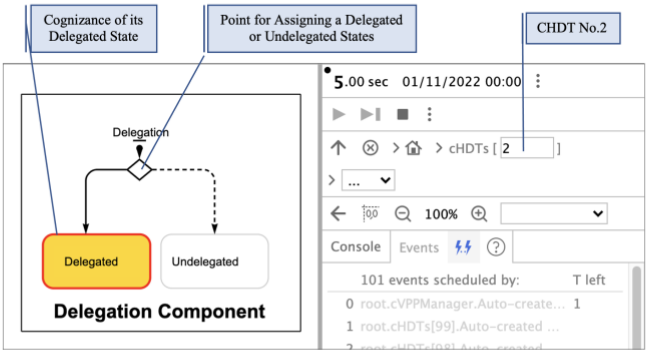

Fig. 6a. CHDT Number 2 being cognizant of delegation state.

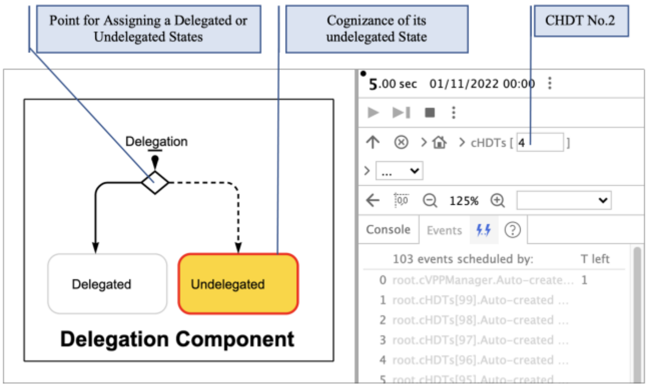

Fig. 6b. CHDT Number 4 being cognizant of its "undelegated" state.

Cognizance of delegated autonomy. A household owner can delegate autonomy to his or her CHDT so that its value system is carried out or executed according to specific instructions. In this work, delegated autonomy was considered for three appliances, namely a dishwasher, a washing machine, and a clothes/tumble dryer. In addition, we assume that delegated autonomy can be realized at three levels: (a) partial delegation for a single appliance (PD1), (b) partial delegation for double appliances (PD2), and (c) full delegation (FD). PD1 indicates that the CHDT has a delegation of authority regarding any of the three appliances. Similarly, PD2 means the authority to delegate any two of the three appliances, whereas FD signifies the authority to delegate all three appliances. Fig. 7 illustrates component of the model that is used to simulate the delegated autonomy mechanism.

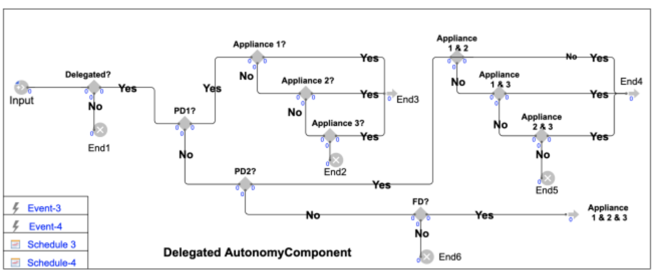

Fig. 7. Illustration of delegated autonomy

Cognizance of the value system. Each CHDT has a value system that is used to represent user's requirements, preferences, objectives, and goals. In addition, a CHDT can have multiple value systems to represent different needs, which can be arranged hierarchically to represent different priorities and alternatives. For illustrative purposes, we assume that each CHDT has two value systems: value system 1 (VSG1) and value system 2 (VSG2). A value system can be in only one state at any given time, either the "true" or "false" state.

Using stochastic modelling techniques, it is possible to model both the "true" (active) and "false" (inactive) states of a value system as having a 50% probability of occurrence each. This method helps simulate stochastic scenarios that can result in different value system for all CHDTs in the population under consideration. A value system that is in the true/active state indicates that it is the dominant value system for the associated CHDT, while a value system that is in the false/inactive state indicates that it is dormant for that CHDT.

In Fig. 8a to 8c we illustrate three different value systems for three different CHDTs. Fig 8a shows a CHDT number 15 with both value system 1 and value system 2 in the true/active states (dominant). In Fig 8b, we illustrate a CHDT number 30 with only one active value system, which is value system 2. Value system 1 for this CHDT is in the false/inactive state (dormant). Finally, Fig. 8c illustrates a CHDT number 7 in which both value system 1 and value system 2 are in the false state (inactive or dormant).

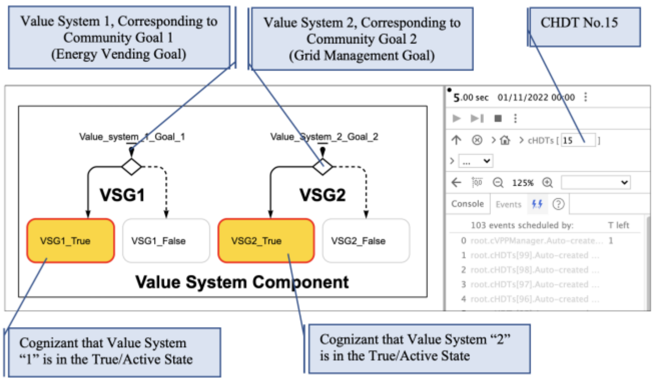

Fig. 8a CHDT No. 15 with value system 1 and value system 2 in true states (Active or dormant)

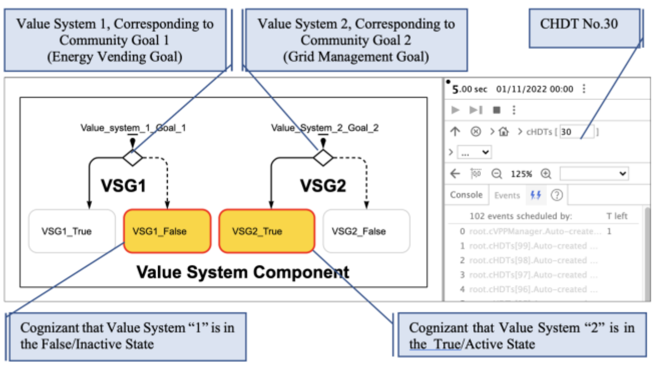

Fig. 8b CHDT No. 30 with value system 1 in the false state (dormant) and value system 2 is true state (active or dominant)

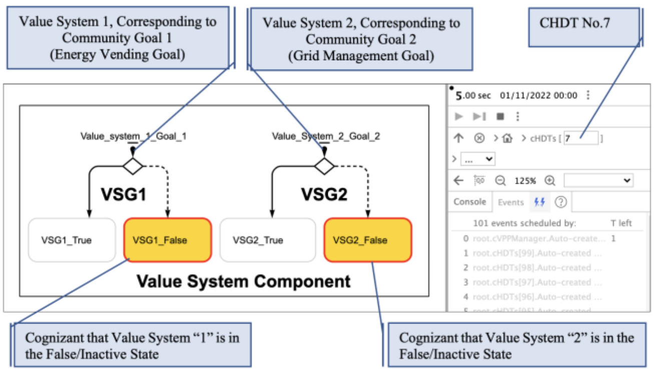

Fig. 8c. CHDT No. 7 with value system 1 and value system 2 in the false state (inactive or dormant)

Modelling Cognizance of the environment. Since CHDTs exist and interreact with each other within an environment, it is necessary for that the CHDT also knows its environment. In this regard, we consider it to be cognizant of community goals and cognizant of coalitions formation.

Cognizance of community goals. Community goals are used to represent the objective(s) that the ecosystem desires to achieve using a collaborative approach. The community goal is usually formulated at the top level of the model, usually by the CVPP-E manager or coordinator. However, at the CHDT level, each community goal is replicated inside the CHDT. This technique enables all CHDTs to have a replica of the community. This approach allows any changes made to the community goal at the top level to be reflected at the CHDT level. Thus, this technique allows the CHDTs to be aware of the prevailing community objective(s) at all times. The concept of a "common goal," which is a crucial requirement for collaboration, is satisfied when all CHDTs are individually aware of the community's goals and able to make decisions based on such knowledge. In Fig. 9, we show CHDT number 0, that is aware of the fact that community goal 1 is true (active or dominant) while community goal 2 is false (inactive or dormant).

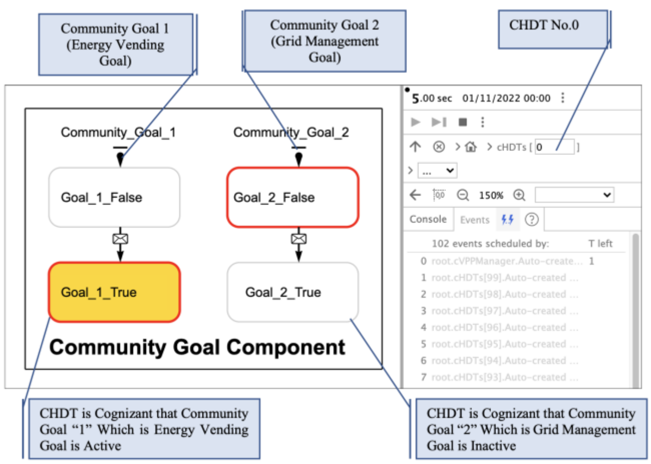

Fig. 9. CHDT number 0 is cognizant that community goal 1 is active (dominant) and community goal 2 is inactive (dormant)

Cognizance of the formation of a coalition (Virtual organization - VO). In terms of collaborative networks, a VO is a temporary coalition that can be formed by members within an ecosystem with the aim of achieving some specific goals or solving a common problem [19]. Once the objective is achieved, the VO can be dissolved. In Fig. 10, we illustrate the formation of two different VOs that correspond to two goals, namely goals-1 and goal-2. For example, goal-1 could represent a vending opportunity and goal-2 could also represent a grid management opportunity. Goal-1 describes the case where a market opportunity is found to sell energy to the grid, while in goal-2, the ecosystem leverages its control over appliances (i.e., washing machines, dishwashers, and clothes dryers) to help contribute to grid management by lowering consumption at peak times. Deferrable loads are a common name for these energy assets, whose use can be deferred without compromising the quality of service provided to the user.

The invitation to form a VO is usually communicated to the ecosystem when the manager finds an opportunity. The ecosystem members can choose to accept the invitation or decline it based on the kind of delegated autonomy assigned to them by the user. Being cognizant of the formation of a VO therefore implies that the CHDT has knowledge of its acceptance or decline towards its participation in a VO. Furthermore, in case a CHDT accepts the invitation, it becomes cognizant of the schedule of the goal (when to start and when to end). In Fig. 10, the CHDT is cognizant that two VOs have been formed, thus VO-1 and VO-2. Schedule-1 and Schedule-2 provided the CHDT with the scheduling of Goal-1 and Goal-2, respectively. Event-1 and Event-2 are used to start and end Goal-1 and Goal-2, respectively.

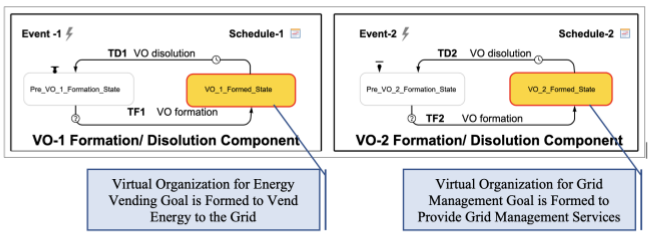

Fig. 10. Coalition or VO formation for Goal-1 and Goal-2

CDHT decision-making modelling. Fig.s 11a, 11b and 11c are discrete event models that are adopted for the simulation of the CHDT's decision making processes. The models are used by CHDTs to determine which action to take while considering all CHDT's cognitive states. Fig. 11a is used to make decisions concerning Goal-1, while Fig. 11b is the decision component for Goal-2.

For the decision-making process, the CHDT first receives an invitation from the community manager to participate in the formation of a coalition to pursue a specific goal. The CHDT first checks its delegated state to determine if it is delegated or not. If the check returns a "NO" (false), the CHDT will decline the invitation based on "undelegation" or "non-delegation (Fig. 11a)." However, if the check returns "true" (thus, delegated), the CHDT proceeds to check its assigned value system. If the assigned value system is compatible with the proposed goal, the CHDT will proceed to accept the invitation (Fig. 11b). However, if the value system compatibility check returns false (non-compatible goal), the CHDT will decline the invitation based on the non-compatibility of goals (Fig. 11c).

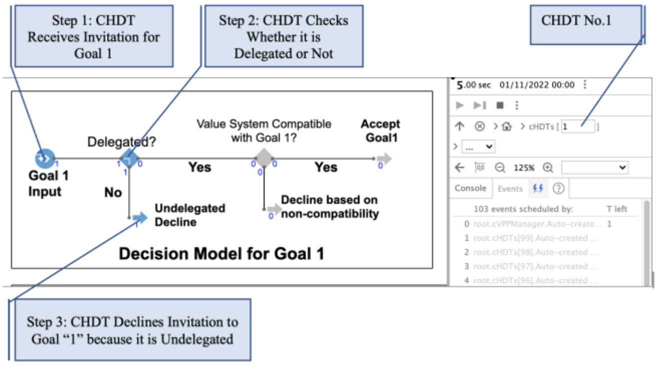

Fig. 11a. Component of the model for making decision in relation to goal 1 (CHDT number 1 declines invitation to goal 1 base on "undelegation")

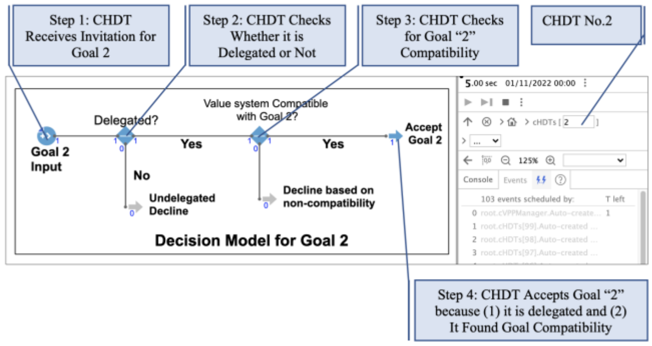

Fig. 11b. Component of the model for making decision in relation to goal 2 (CHDT 2 accept invitation to goal 2 based on (1) delegation and (2) compatible value system

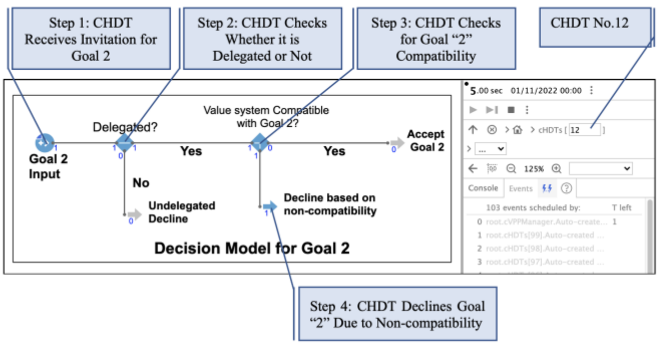

Fig. 11c. Component of the model for making decision relation to goal 2 (CHDT number 12 declines invitation to goal 2 based on non-compatible goals)

4.3. Modelling the Process of Energy Generation, Consumption, and Storage

For this part of the work, we borrowed techniques from the field of system dynamics to represent the dynamic characteristics of the ecosystem. Fig.s 12 and 13 represent dynamic elements of the system. This technique is adopted to model all aspects of the energy generation, storage, and consumption in the prototype model. In Fig. 12, the "flow" element is used to simulate the rate of flow of any quantity (the flow of electrical energy in this example). The flow rate is determined by "Parameter A". This parameter could be a variable or a constant. In the case of this study, this parameter may represent the power rating of an appliance, or, in the instance of a photovoltaic system, the amount of energy produced by the PV system. The "stock" element acts like an accumulator for the amount that arrives from the "flow" element. Consequently, this "stock" element can be used to represent an energy storage device, such as a battery or a unit that consumes energy. Finally, the "cloud" element represents an infinite supply such as solar energy. In addition, Fig. 13 depicts a flow from "Stock-2" to "Stock-3." The element Stock-2 can represent a finite supply of energy source, such as the case of a battery storage system or the power grid, while Stock-3 can symbolize an item that pulls energy from Stock-2. The cumulative value of "Stock 3" may also be used to determine how much energy it has drawn from "stock 2". Mathematically, the rate of flow from an infinite source (the cloud) into stock-1 (Fig. 12) is given by equation (1).

$$\frac{d(Flow)}{dt} = Parameter\ A \qquad \text{...(1)}$$

The rate at which stock _1 is accumulated is given by equation (2)

$$\frac{d(stock\_1)}{dt} = \frac{d(Flow)}{dt} \qquad \text{...(2)}$$

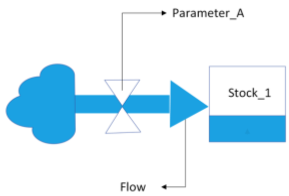

Fig. 12. Example of stock and flow diagram representing generation and storage

With respect to Fig 13, the rate of flow is given by equation (3). Similarly, the rate at which stock_2 depreciates is given by equation (4). Finally, the rate at which stock_3 is accumulated or is given by equation (5)

$$\frac{d(Flow)}{dt} = Parameter\ B \qquad \text{...(3)}$$

$$\frac{d(stock\_2)}{dt} = -\frac{d(Flow)}{dt} \qquad \text{...(4)}$$

$$\frac{d(stock\_3)}{dt} = \frac{d(Flow)}{dt} \qquad \text{...(5)}$$

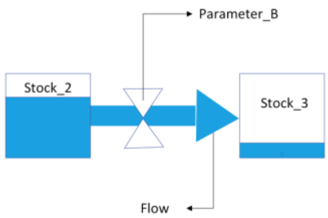

Fig. 13. Example of a stock and flow diagram of consumption

4.4. *Modelling Prosumer CHDTs*

In our prototype, a prosumer CHDT is implemented as a software agent which embeds stock and flow diagrams. Similar stock-and-flow elements, such as the one shown in Fig. 12, are used to model solar energy generation and energy storage. The local storage capacity is modelled through a *uniform discrete distribution (X, Y)*, where *X* is the minimum and *Y* is the maximum feasible storage capacity. Appliances such as washing machine, microwave, dishwasher, refrigerator, clothes/tumble dryer, oven, audio-visual system, kitchen appliance, and lighting, are also embedded in each prosumer CHDT. The modelling data for these appliances comes from [44]**.**

To represent the consumption aspects of a prosumer CHDT, another stock-and-flow diagram, identical to Fig. 13, is likewise incorporated in the same agent. Furthermore, a discrete event model, as depicted in Fig. 14, is used to represent the following processes: (a) when an appliance initiates a request to be used, and (b) when determining what type of energy sources are available at the time of the request and directing the appliance to use them.

The consumption priority of a prosumer CHDT is directed first to the locally installed photovoltaic system. When PV energy is unavailable, the second option is to use the local storage. When the local storage energy is unavailable, the third preferred source will be the community storage system (CSS). When all other sources are unavailable, it will consume energy from the grid. The surplus energy that is generated by the local PV system can be shared to CSS, where it is stored and subsequently made available to other community members when needed. The condition for sharing surplus energy with the grid when PV is available is that the local storage is full, and there is no demand for PV in the prosumer household.

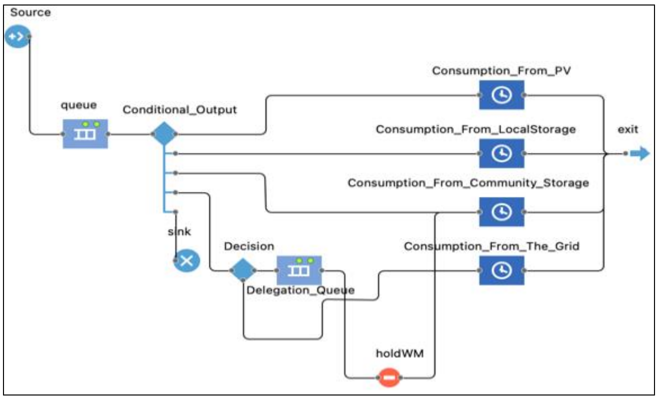

Fig. 14. Discrete event model used to represent the energy usage behaviour of each appliance

4.5. *Modelling a Consumer CHDT*

As mentioned earlier, a consumer CHDT does not possess an integrated PV or battery storage system; therefore, it might just consume energy. Similar to prosumers, consumer CHDTs in the implemented prototype have nine integrated domestic appliances. Consumer CHDTs are limited to consuming energy from the grid and community storage systems only. The grid is the *de facto* source of energy, followed by community battery storage. The CHDT initially consumes energy from the grid. When the community storage becomes available, it switches sources and begins to consume energy from the grid.

The population ratio of both consumers and prosumers in the ecosystem can always be configured in the model. For example, we can create a ratio of, say, 90% prosumers to 10% consumers from a population of 100, and vice versa.

4.6. *Modelling the Grid and the CSS as Agents*

The energy grid, in our prototype, is modelled as a software agent having stock and flow elements incorporated in it. The supply from the grid is accessible to all CHDTs. Likewise, the CSS is also implemented as a software agent. In this case, the stock element of the CSS contains inputs that transmit surplus energy coming from various prosumer CHDTs to the community storage. Similarly, the CSS includes outputs representing CHDTs access to energy from the CSS.
Condition for discharging the CSS: If CSS is greater than X% of the storage capacity and there is community demand for energy, discharge the battery, or else, keep charging.

Condition for charging the CSS: If CSS is less than Y% of the storage capacity, stop discharging the battery and charge, else keep discharging.

In the prototype model X= 90% and Y=30%.

4.7. Modelling Home Appliances and their use Behaviours

The consumption patterns of the considered home appliances are modelled using various probability distributions, as follows.

- **Appliances frequency of use (FoU)**: This metric is used to represent the number of times per week an appliance is utilized. This number is generated using a Pert probability distribution function defined as *Pert distribution (X, Z, Y),* where *X* = minimum number of uses per week, *Z* = average number of uses per week, and *Y* = maximum number of uses per week.
- **Appliances power rating (APR)**: This metric is used to represent an appliance's power rating. This value is generated using a uniform probability distribution function, *Uniform distribution (X, Y),* where X = lowest power rating in kilowatts, and Y = maximum power rating in kilowatts.
- **Appliances duration of use (DoU):** This metric is used to represent how long an appliance is used for each usage cycle. This parameter is generated with a uniform probability distribution function defined as *Uniform distribution (X, Y),* where X is the lowest duration in hours and Y is the maximum length in hours.

5. Selected Scenarios for Illustrating the Modelling Techniques

For the purpose of testing the prototype model, several scenarios and associated data were designed, as. outlined and discussed in the following paragraphs.

Scenario for CVPP-E population. In the simulation test, 100 CHDTs were used as a population. The composition of the population is presented in Table 1.

TABLE 1. CHDT population distribution

Item	Category of CHDT	Population
1	CHDT Pensioner-only households	20
2	CHDT Household with single non-pensioner	20
3	Household with several pensioners.	20
4	Households that have children	20
5	Several persons household with no dependent children	20
Total Population		100

In Table 2, several populations of prosumers and consumers are defined and applied in the simulations. For Case-1, out of a population of 100 CHDTs, 90% are selected as prosumers and 10% are regarded as consumers. Case-2 similarly considers 50 percent of prosumers and 50 percent of consumers. For Case-3, 10% of prosumers are considered as opposed to 90% of consumers.

TABLE 2. Different ratios of prosumer and consumer populationand corresponding delegated autonomy

Cases	CHDT Population (%)		Kind of Delegated autonomy implemented
	Prosumer	Consumer	
Case-1	90	10	a. Sharing disabled
			b. Sharing enabled
Case-2	50	50	a. Sharing disabled
			b. Sharing enabled
Case-3	10	90	a. Sharing disabled
			b. Sharing enabled

Modelling scenario for household appliances. In our prototype, each CHDT is considered to possess a total of nine home appliances. The parameters selected to represent the various appliances are listed in Table 3. This data come from a research on the usage of domestic appliances in the UK, as given in [44].

TABLE 3. Duration of use for the household appliances

Type of Appliance	DoU *(hrs)*		APR (kW)		FoU/ week		
	Min	*Max*	*Min*	*Max*	*Min*	*Aver age*	*Max*
Washing Machine	0.50	3.00	0.500	1.000	0	4	8.00
Tumble dryer	0.50	3.00	1.000	3.000	4.38	6.00	5.38
Dishwasher	0.50	3.00	1.000	1.500	4.19	6.19	5.19
Audio-visual equipment	0.50	6.0	0.025	0.148	1.00	11	21.0
Microwave	0.16	1.00	0.600	1.150	1.00	7.00	14.0
Electric Cooker	0.50	3.00	2.000	4.000	1.00	7.00	14.0.
Lighting	0.16	8.00	0.015	0.165	1.00	7.00	21.0
Refrigeration	24-0	240	0.011	0.091	-	-	-
Oven	0.50	2.00	2.000	4.000	1.00	7.00	14.0

Modelling scenario for the roof-top installed PV system. Consideration is given to four distinct photovoltaic (PV) systems with varying capacities for the population of prosumers are used. A prosumer CHDT may only inherit one of these systems at a time. The following PV systems and their capacities are taken into account: (a) BainSystem of 6.930kW [47], (b) BrainSystem of 1.950 [47], (c) Helius of 3.99kW [47], and (d) DaSS of 3.22kW [47]. The power generation in the model is estimated based on data from these real-world systems.

6. Results and Discussion

6.1. Scenario 1

This section discusses the study's findings from a global or community viewpoint. The simulation is executed for 168 simulation hours, which corresponds to seven simulation days. Figs 15 and 16 analyse Case-1 (Table 2). For this case, a CHDT community comprising 90 percent prosumers and 10 percent consumers is selected. Two separate situations of "delegated autonomy" are examined: (a) sharing disabled, and (b) sharing enabled. When "sharing disabled", the CHDTs are denied delegated autonomy regarding sharing surplus of renewable energy with the community. On the other hand, "Sharing enabled" is the reverse of "sharing disabled". As shown in Fig. 15, the findings of the study indicate that, in the absence of energy sharing, 25 percent of the community's total energy consumption originates from the grid and 10 percent from the community storage system. Fig. 16 shows that when energy sharing is implemented, the total quantity of energy used from the grid decreases considerably, from 25 percent to 16 percent. Additionally, the community storage system utilization increases from zero percent to four percent when sharing is permitted. Whether sharing is allowed or disabled, the proportion of photovoltaic and energy from local storage is rather large in both cases, due to the high percentage of prosumers that are analysed in this instance.

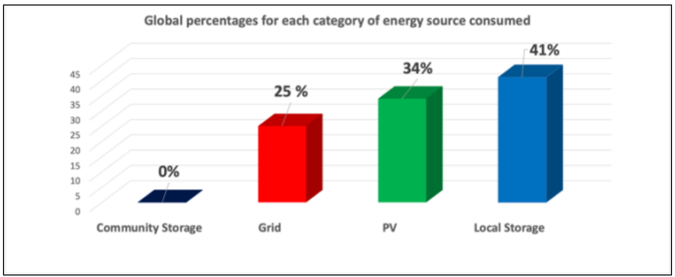

Fig. 15. Case 1a: results for 90% of prosumers and 10% of consumers with "sharing disabled"

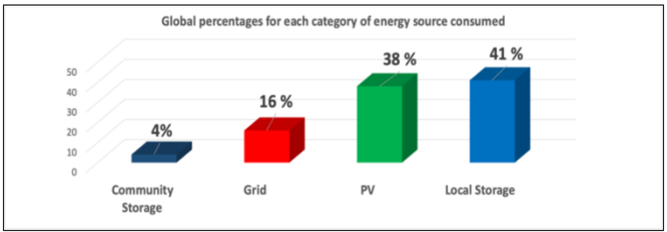

Fig. 16. Case 1b: results for 90% prosumers and 10% consumers with "sharing enabled"

In Figs. 17 and 18, which depict results for Case-2 (Table 2), we assume a homogenous CHDT population composed of 50 percent prosumers and 50 percent consumers. In the case of Fig. 17 for the facet of delegated autonomy is "sharing disabled," while in Fig. 18 it is "sharing enabled." When CHDTs are assigned to share surplus energy, the total energy consumption from the grid decreases from 64 percent to 55 percent, as seen in both Figs. Similarly, the overall consumption from the CSS increases from 0% to 10% when the CHDTs are granted with "sharing enabled" permission. In both circumstances, i.e., Case-1 and Case-2 (Figs. 17 and 18), the proportion of energy derived from photovoltaic and local storage sources is dramatically reduced relative to Case-1 (Fig.s 15 & 16). This result comes from the fact that the number of prosumers in this specific instance has decreased from 90% to 50%. In addition, the overall percentage of energy used from the grid has increased significantly compared to Case-1. Such result can be due to the fact that the consumer population in Case-2 increased from 10% to 50%.

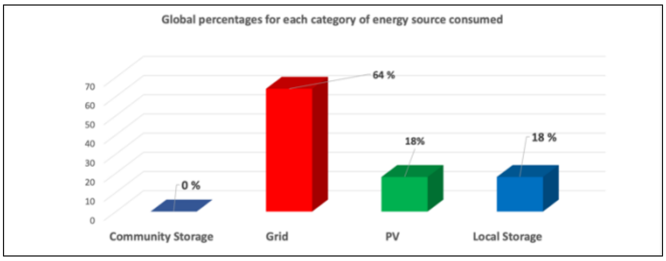

Fig. 17. Case 2a: results for 50% consumers 50% prosumers with "sharing disabled"

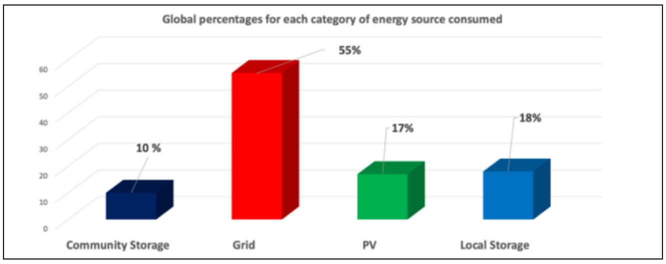

Fig. 18. Case 2b: results for 50% consumers 50% prosumers with "sharing enabled"

Regarding Case-3 (Table 2) of this scenario, Fig.s 19 and 20 illustrate the model's outcome. This example examines a population composed of 10% prosumers and 90% consumers. As shown in Fig.s 19 and 20, when CHDTs are authorized to exchange energy, grid usage drops from 97 percent to 93 percent. Additionally, when sharing autonomy is activated, CSS usage increases from 0% to 3%. Compared to Case-1 and Case-2, the share of photovoltaic and local storage decreases in this scenario as well. In this instance, the population of prosumers is rather small. Consequently, 80 percent less than in Case-1 and 40 percent less than in Case-2. In addition, the contribution from the grid grows dramatically relative to Case-1 and Case-2. This is due to the fact that the number of consumers increased from 50 percent to 90 percent, as in Case-2, and from 10 percent to 90 percent, as in Case-1. From the above scenarios, it can be concluded that CHDTs can leverage "delegated autonomy" to alter the proportions and contributions of energy from varied sources. Therefore, this may be utilized as a technique to increase consumption from renewable sources in such environments.

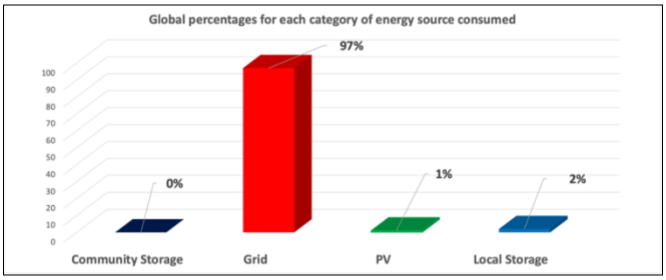

Fig. 19. Case 3a: results for 10% of prosumers and 90% of consumers "sharing disabled

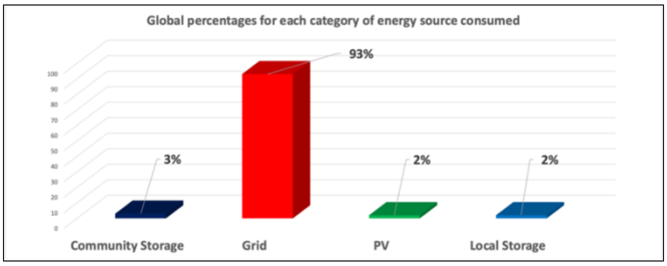

Fig. 20. Case 3b: results for 10% of prosumers and 90% of consumers with "sharing enabled"

6.2. Scenario 2

This section's results are focused on the case of Delegation of Deferrable Loads (DDL). This type of "delegated autonomy" enables CHDTs to run their deferrable loads with their preferred energy source (DLs). DLs in this context relate to postponing the use of appliances without compromising the quality of service provided to the consumer [48]. In this instance, the DLs under consideration are a washing machine, a dishwasher, and a clothes dryer. For this scenario, CHDTs are given the authority to delay the usage of all embedded DLs until their chosen energy source, often renewable energy, is available. The preferable alternatives for prosumers are restricted to direct consumption from local PV, consumption from local storage, consumption from CSS, and consumption from the grid. The only options available to consumer CHDTs are grid and CSS. In the event that none of the appliance's preferred alternatives are accessible, i.e., when just the grid is available, the CHDT decides to suspend the appliance's function until one of its preferred energy sources becomes available. This feature of the model's result is also analysed from a global perspective. Nevertheless, in our prototype, the global view is restricted only to three deferrable loads and not to all embedded appliances.

TABLE 4. Delegation of defferrable loads

Cases	CHDT Population (%)		Percentage of the Population with delegated autonomy instruction out of the total
	Prosumer	Consumer	
Case-1	10	90	**a.** 10 percent of the population
			b. 90 percent of the population
			c. 100 percent of the ttal population
			d. 0 percent of the population
Case-2	90	10	**a.** 90 percent of the population
			b. 10 percent of the population

After running the model over a simulated seven-day period (168 hours) with a CHDT population of 100, the results of the study are presented in the subsequent paragraphs. In Case-1a (Fig. 21), the population is composed of 10% prosumers and 90% consumers, while considering that 10% of the entire population has delegated autonomy.

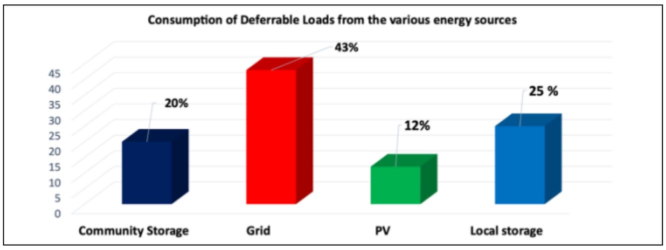

Fig. 21. Case 1a: results for 10% prosumers, 90% consumers. 10% of the total population having the DDL authority"

As shown in Fig. 22, the proportion of prosumer and consumer populations in Case-1b (Table 4) is identical to Case-1a. For Case-1a, 10 percent of the population has DDL authorization, while for Case-1b, 90 percent of the population has DDL authorization. Comparing the outcomes for both scenarios (comparing Figs. 21 and 22), it is evident that the use of the grid decreases from 43 percent in Case-1a to 20 percent in Case-1b. In addition, CSS usage appreciated substantially, from 20% in Case-1a to 49% in Case-1b. Case-1a has an average of 12 percent usage of PV and local storage, whereas Case-1b has an average of 15 percent usage of PV and local storage. For Case-1a, the high grid utilization is caused by the 90 percent undelegated CHDTs, whereas for Case-1b, the low grid utilization is caused by the 10 percent undelegated CHDTs. Case-1c (Fig. 23) is used to illustrate the output of the model when the same population distribution is used as in Case-1a and Case-1b. Here, 100 percent of the population was granted DDL permission, and the results indicate that grid usage dropped to zero. Additionally, consumption from the CSS increases by 58%, while consumption from the PV and local storage increases by 18% and 24%, respectively. Lastly, Fig. 24 depicts the model's output for Case-1d. In this situation, none of the CHDTs (0 percent) have DDL authority. For this situation, the usage of the grid has climbed to 87 percent, while the usage of the other energy sources decreased significantly. This is due to the large number of consumers without delegated authority.

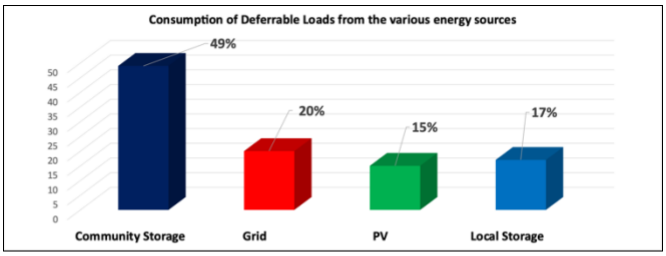

Fig. 22. Case 1b: results for 10% prosumers, 90% consumers, with 90% of the total population having the DDL authority"

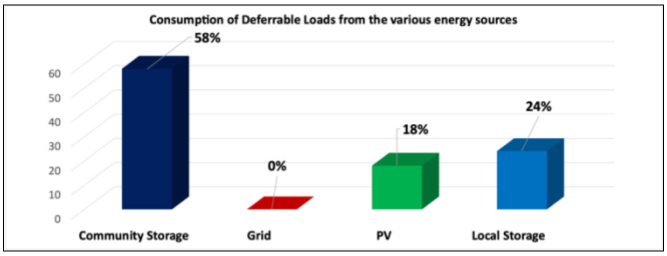

Fig. 23. Case 1c: results for 10% prosumers, 90% consumers, with 100% of the total population having the DDL authority

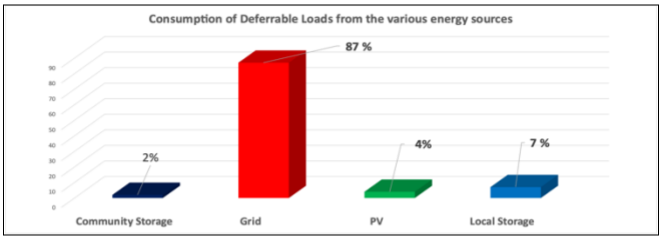

Fig. 24. Case 1d: results for 10% prosumers, 90% consumers, with no DDL authority"

In Case-2 (Table 4), the number of CHDTs remained constant at 100. The composition of the population is diverse, consisting of 10 percent consumers and 90 percent prosumers. In Case-2a (Fig. 25), we examined a scenario in which 90 percent of the population got DDL authority. Similar considerations are made for Case-2b (Fig. 26). In this case, however, the entire population having DDL authorization is decreased to 10%. In contrast to Case-1a, Case-1b, and Case-1c, where just 10 percent of the population are prosumers, Case-2a and Case-2b reveal much higher PV and local storage utilization. Moreover, with DDL implemented for both Case-2a and Case-2b, it is evident that grid consumption is relatively minimal compared to Case-1a, Case-1b, and Case-1c. This is due to the low percentage of consumer population and the high percentage of prosumers. Comparing Case-2a (Fig. 25) to Case-2b (Fig. 26) it can be seen that 90 percent DDL reduces grid usage from 9 percent to 3 percent, whereas CSS consumption increases from 2 percent to 10 percent.

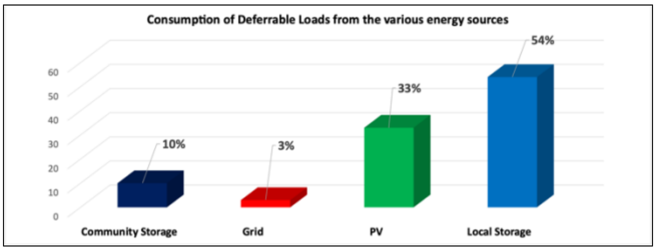

Fig. 25. Case 2a: results for a population of 10% Consumers 90% prosumers 90% of the population with delegated autonomy

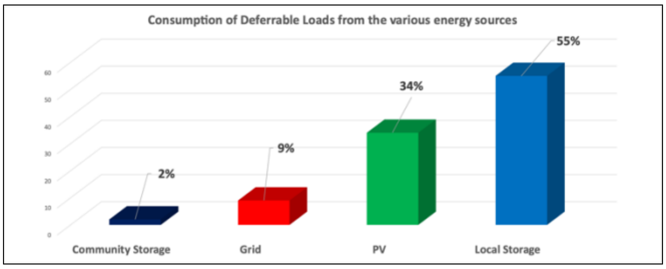

Fig. 26. Case 2a: results for a population of 10% Consumers 90% prosumers 10% of the population with delegated autonomy

7. Conclusions

Buildings have been identified as one of the key contributors to greenhouse gas emissions, as well as the current trend in escalating demand for energy. The consequent impact of these demands is the overexploitation of the Earth's limited resources, which has contributed to the ongoing environmental deterioration that plagues the planet and continues to threaten its survival. This study is aimed at contributing to building´s energy consumption from two perspectives. First, to demonstrate the applicability of the concept of "delegated autonomy" using a multi-method simulation technique. In this context, we simulated the involved buildings/households as digital twins that are located within the framework of a community. These digital twins are simulated to have cognitive intelligence so that they can make rational and autonomous decisions. Second, we attempt to evaluate how this cognitive intelligence of the household digital twins can be used to execute "delegated autonomy" instructions. We considered two distinct collaboration scenarios, which include jointly allowing or disallowing energy sharing,

The results of the study have helped to demonstrate the plausibility of the CVPP-E and CHDT ideas. Furthermore, it is shown that these ideas, particularly CHDTs, can be implemented with features that allow them to autonomously execute delegated instructions on behalf of their owners. As illustrated by the model results, the implementation of delegated autonomy allows these agents to work towards a common objective, therefore attaining sustainable energy consumption. The outcome of the study has helped establish the following facts: The pertinence of these proposed concepts can be seen from two perspectives, First, from a global or community perspective, communities can adopt these techniques to help provide grid management services such as helping to shift loads from peak periods to off-peak periods using "delegated autonomy." Similarly, the community can adopt the same technique to help minimize consumption from the grid by ensuring that deferrable loads are delegated to make maximum use of renewable energy sources when available. Additionally, the community could use these techniques to aggregate and export surplus energy from within the community to the grid. This can be accomplished through a collaboration effort between the CVPP-E manager, a distribution service operator, the energy market, and the CHDTs themselves. Second, at the household level, the idea of "delegation" can be a useful technique that can be adopted to help consumers overcome everyday tasks that are found to be repetitive, monotonous, and difficult to maintain. Such tasks may include sustainable energy consumption decisions, choices, and behavioural modifications that confront consumers on a daily basis. It is anticipated that, through delegation, such mundane activities could be assigned to CHDTs to perform.

Moreso, the idea of a "values system" can help community members overcome the apprehensions and anxieties that are often barriers to adoption and participation in sustainable energy consumption programs such as demand response. By assigning an individual´s value system to his/her CHDT, a consumer can flexibly contribute to sustainable energy programs without having to suffer a loss of their comfort, convenience, or quality of service. In future work, the implementation of additional collaborative behaviours of the CHDTs is planned to be investigated further. The plan includes the adoption of other collaborative behaviours such as co-creation of value, estimation of the individual contribution to goal achievement / value creation, sharing of rewards, and conflict resolution in such an ecosystem.

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