A Framework for Collaborative Virtual Power Plant Ecosystem

Kankam O. Adu-Kankam[1,2](✉) and Luis M. Camarinha-Matos[1]

[1] School of Science and Technology and UNINOVA - CTS, Nova University of Lisbon, Campus de Caparica, 2829-516 Monte de Caparica, Portugal
k.adu@campus.fct.unl.pt, cam@uninova.pt

[2] School of Engineering, University of Energy and Natural Resources (UENR), P. O. Box 214, Sunyani, Ghana

Abstract. The notion of Collaborative Virtual Power Plant Ecosystem (CVPP-E) contributes to an effective organization of Renewable Energy Communities (RECs) in such a way that they can act or exhibit the attributes of Virtual Power Plants (VPPs). This concept is derived by merging or integrating principles, organizational structures, and mechanism from the domain of Collaborative Networks (CN) into the area of VPPs. The expectation is that if actors in the RECs engage in collaborative actions this would enable a REC to perform functions that are similar to a VPP. Conceptually, the CVPP-E is constituted of a community manager, a common community energy storage system, prosumers who own a combination of photovoltaic and a battery storage system, and passive consumers, all connected to an energy grid. The key attribute of this proposed ecosystem is that members engage in collective actions or collaborative ventures that are based on a common goal and aimed at achieving sustainable energy generation, consumption, and vending. In this study, we present a high-level model for the aspects of collaboration in the CVPP-E. This involves the compatible/common goals framework, the sharing framework, and the collective actions framework. These frameworks serve as the backbone of the CVPP-E and play a vital role in the modelling of a CVPP-E. Various simulation scenarios are used to assess the proposed model.

Keywords: Collaborative networks · Common goal framework · Sharing framework · Collective action framework · Energy sharing · Energy community

1 Introduction

Until recently, the integration of Photovoltaic (PV) sources from households (HH) into the traditional grid system was negligible [1]. However, several changing factors such as declining prices of solar panels [2], favourable public opinion towards the energy transition [3], coupled with sound governmental policies [4], are changing the narrative. For instance, currently in Europe, the number of HHs with installed PV systems is rising steadily [5]. Concurrently, battery storage technology is also maturing rapidly [6]. This opens the opportunity for individual dwellings as well as communities to incorporate

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energy storage into their PV systems. A Community Energy Storage System [7] is an energy storage technology that enables energy sharing between members of a community. Available literature suggests that an increasing number of groups of neighbours who are motivated by a common goal such as reduction of their energy costs or promotion of sustainable energy consumption are coming together to form Renewable Energy Communities (RECs). These RECs can operate in stand-alone mode or have a grid-connected architecture [8]. According to [9], a REC can be described as a community that is based on open and voluntary participation. It is usually owned, managed, and controlled by shareholders or members who are autonomous and located within the proximity of the projects. Essentially, members of a REC, who possess roof mounted PV systems can generate renewable energy for their own local consumption and may store, sell, or share the excess with other community members, therefore, acting as prosumers. Other passive members may not generate own energy but may join the REC to enable them consume energy from renewable sources.

Currently, the organization and management of RECs appear as a daunting task due to the complex interaction between multiple and heterogenous actors who are largely autonomous and may have diverse preferences. Many research works have suggested several approaches to the efficient and effective management of the constituent actors of RECs. In [10–12] the authors suggested a collaborative approach which resulted in the proposition of the notion of a Collaborative Virtual Power Plant Ecosystem (CVPP-E) and Cognitive HH Digital twins (CHDTs) in [13]. These concepts are further explained in Sect. 2. The key objective of the CVPP-E and related CHDTs is to approach the management of energy consumption and exchange in a REC from a collaborative point of view.

The purpose of this research is to present a framework that illustrates various collaborative behaviours within a CVPP-E. This objective can be achieved by breaking the various collaborative actions down into discrete steps using the Business Process Modelling Notation (BPMN) language. The framework shall serve as the collaborative component for a prototype model which is intended to be used to study how collaborative actions can facilitate sustainable energy consumption and exchanges in the ecosystem. The following research question is therefore adopted to guide the work:

> RQ. What framework can support the modelling of each collaborative behaviour by a population of CHDTs within a CVPP-E?

The considered behaviours are as follows:

a. Communication and information exchange (ComIEx) towards a common goal.

    i. ComIEx towards coalition formation (Joining a Virtual Organization (VO)): In this context, members are expected to have different, but compatible goals. The community manager proposes a goal and through ComIE, members whose preferences are compatible with the suggested goal will accept the invitation and participate in coalition formation towards the achievement *of the proposed goal.*
    ii. ComIEx towards the execution of a specific goal: In this context, the manager proposes a goal and through ComIEx each member who accepts the invitation

schedules their appliances and execute the necessary instruction when the time for collective action is due.

b. Sharing common resources: In this context we consider the scenario were CHDTs share energy that is stored in a common community storage.
c. Collective actions. The behaviour exhibited by members when they all act in the same way in order to achieve a collective objective.

2 Background Knowledge and Theoretical Framework

According to the European Parliament and the Council of the European Union [9], a REC is based on open and voluntary participation. It is autonomous and controlled by stakeholders who live in the same proximity. Members of RECs can generate renewable energy for local consumption, and may store, sell, or share the excess with community members. In this context, we attempt to replicate the REC concept by developing a digital twin replica of the community. In our replica model, we represent the community environment as the CVPP-E. The CVPP-E can be described as a form of a Virtual organizations Breeding Environment (VBE), business ecosystem or a community of practice where members approach energy consumption and exchanges from a collaborative point of view. Thus, members engage in collective actions towards the achievement of some goals that may be common to the entire community.

The CVPP-E concept was derived by integrating collaboration principles and mechanisms that were borrowed from the discipline of Collaborative Networks (CNs) into the domain of Virtual Power Plants (VPP). The outcome of this synthesis is a form of REC that adopts collaborative principles and mechanisms in its operations to ensure sustainable energy consumption and exchanges and as well, exhibiting characteristics of a VPP, thus having the capability of aggregating excess energy from the community and have it vended to the grid. In the proposed formulation, a CVPP-E includes: (a) the community manager who promotes collaborative activities and behaviours, (b) multiple actors, thus, a population of prosumer and consumer HHs, each having a different energy use preference. The Prosumers in this case have roof-mounted solar panels and can consume their locally generated energy and share the excess with the community, but the consumers do not. (c) a community owned energy storage system.

In the prototype model, each suggested actor of the CVPP-E is modelled as a software agent that replicates the characteristics and behaviours of the physical actor. These software agents are modelled to reside and interact with each other inside a digital REC environment, namely the CVPP-E. Each HH is represented by a Cognitive HH Digital Twin (CHDT). CHDTs are modelled as software agents possessing some cognitive attributes so that they can act as complementary decision-making agents on behalf of their physical counterparts. These software agents can make rational and autonomous decisions on behalf of their owners. The energy use-behaviours of each physical actor are accommodated in their counterpart CHDT using the notion of a Digital Profile (DP). The DP enables the actors to clearly define their energy use preferences, priorities, and options, that is usually in line with the community goals. The DP is constituted of (a) the Value System (VS), and (b) the Delegated Autonomy (DA) of the actor. The VS describes the values of the actor, which may, for instance, include his/her preferred energy source, which community goal is of priority to him/her, how often his/her resources are available for collaboration, etc. DA, on the other hand, is the instruction or authorisation that is given to the CHDT by the actor, specifying how to carry out or execute the suggested values of the actor. In Fig. 1, we illustrate how a CHDT makes decisions based on its DP. The figure shows a CHDT with three values that are arranged in order of priority. The first priority is 100% consumption from renewable sources, the second priority is to consume from mixed sources and the third is free rider or indifferent option. It also shows three levels of DA, thus (a) delegate (control over) three appliances, (b) delegate two appliances, and (c) delegate one appliance.

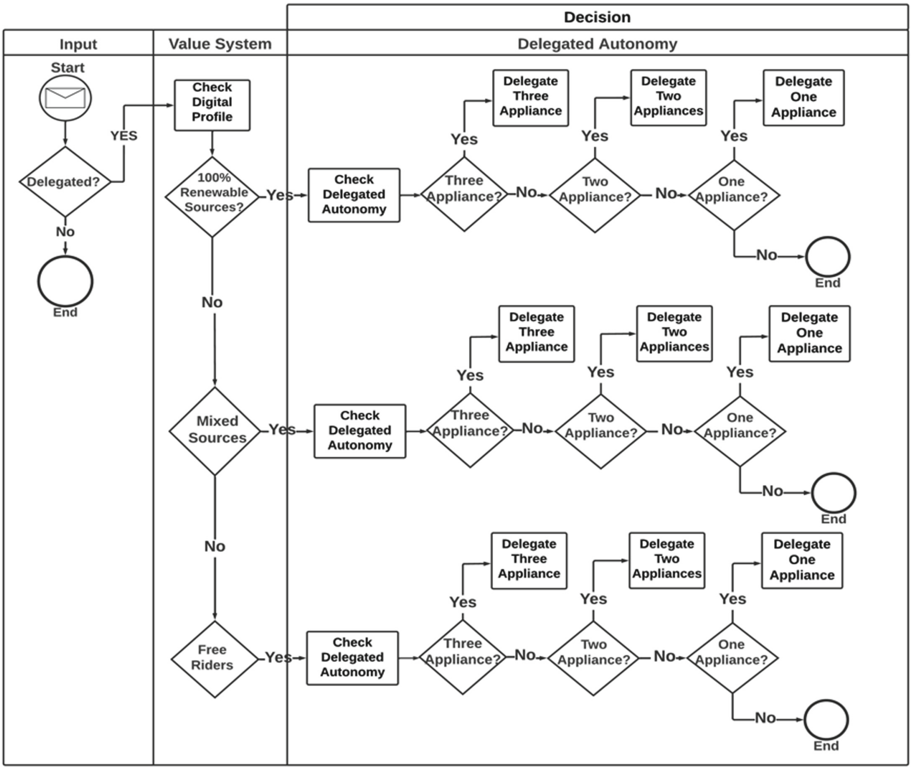

Fig. 1. Decision making based on a CHDTs digital profile

Therefore, by aggregating several CHDTs, each having a different or unique DP, we aim to replicate a physical community in the virtual space (CVPP-E) that has the capacity to accommodate the varied user preferences of each actor or unit of HH. The adoption of agent-based technology allowed the simulation of each HH as a software agent, each having a different DP. By incorporating a level of intelligence into these CHDTs, they could be made to have some cognitive capabilities. Due to their cognitive and decision-making capabilities, these CHDTs are envisaged to have the capability to engage in some collaborative ventures such as pursuing common goals, sharing common resources, mutually influencing one another, as well as engaging in collective actions, without necessarily compromising individual preferences, priorities and options.

The collaborative attributes of CHDTs are envisioned to increase the survivability and sustainability of the CVPP-E. As a community, the diversity in HH sizes, including the number of occupants residing in each HH in the population, is highly essential. To help address this concern, we categorized the constituent HHs (and thus the corresponding CHDTs) into 5 different categories. This categorization and related data were sourced from a survey conducted in [14]. The considered categorization is: (a) HHs with single pensioners, (b) HHs with single non-pensioner, (c) HHs with multiple pensioners, (d) HHs with children, and (e) HHs with multiple persons with no dependent children. The population size of the CVPP-E (community) can always be configured to constitute any number of HH, from each category.

3 Modelling Collaboration Aspects of a CVPP-E

In this section, we present the collaborative framework of behaviours that were mentioned in association to the RQ. We consider the frameworks for (a) common goals, (b) sharing resources, and (c) collective actions. The BPMN language is used to model the various collaborative actions that are considered.

3.1 Modelling Communication and Information Exchange (ComIEx) towards a Common Goal

According to [15] a common goal gives a group of entities a shared purpose. It inspires them to work together as a team to help them achieve the group's objectives. Information exchange for mutual benefit is also a key element of collaboration. Therefore, under this subsection, we consider two cases: (a) ComIEx towards coalition formation (Joining a VO), and (b) ComIEx towards the execution of a specific goal. In the exemplified cases we assume that a CVPP-E was already formed and populated with agents representing the HHs (CHDTs). This ecosystem is a kind of virtual organizations breeding environment where different coalitions of CHDTs (i.e., different virtual organizations, VOs) can be formed to achieve some common goals.

3.1.1 ComIEx Towards Coalition Formation (Joining a VO)

This process is expected to precede a collaborative venture, e.g., minimize energy consumption over a certain period. In other words, it is a process of forming a coalition (a kind of VO) to achieve some goal proposed by the CVPP-E manager. In terms of information exchange, we show the major communication steps that are expected to occur. With reference to the BPMN model of Fig. 2, the following steps are observed:

a) **Invitation**: The community manager extends invitations to achieve goal "x" to the entire community, particularly, prospective CHDTs, whose value system or preferences are in line with this goal "x".

b) **Acceptance/Rejection stage 1**: CHDTs may respond either in the affirmative, expressing readiness to join, or a rejection. The CHDTs shall refer to their digital profile which constitute the users predefined preferences and set of instructions.
c) **Knowledge of coalition conditions**: For CHDTs that accepted the invitation, further information is shared by the community manager, detailing the conditions for the coalition.
d) **Review of the coalition conditions**: The prospective CHDTs may review the conditions and make further decisions whether to pursue or decline joining the coalition.
e) **Acceptance/Rejection stage 2**: The prospective actors will communicate their final acceptance or rejection of the coalition to the community manager.
f) **Confirmation**: The entire process is completed with a confirmation message from the manager.

Throughout these processes, it is observed that information exchange is a crucial prerequisite for coalition formation.

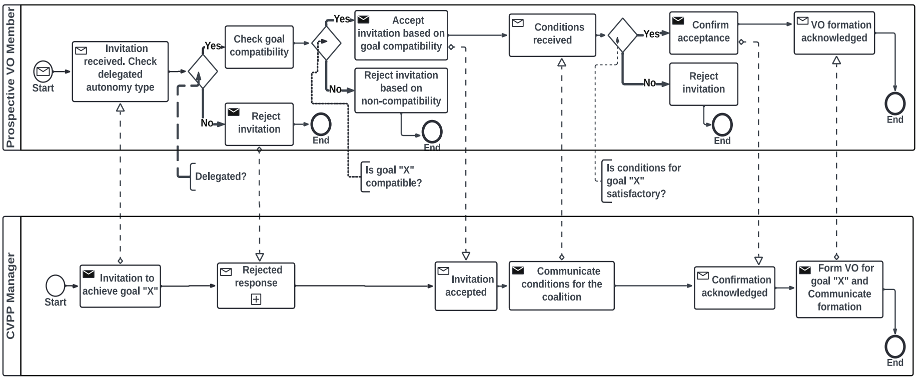

Fig. 2. Process of information exchange towards the formation of a coalition - joining a VO

3.1.2 ComIEx Towards the Execution of a Specific Goal

In Fig. 3 below, we model the processes of information exchange toward the execution of a specific goal. The specific goal, in this example, is to minimize local energy consumption so that unused or saved energy can be vended to the grid. For this to be feasible, the CHDTs may have to engage in some form of collective action based on their individual DPs. This may involve the deferral of the use of either one, two or three of appliances that are considered deferrable. This may include appliances such as washing machines, dishwashers, or tumble dryers, whose delayed use may not affect the quality of service (QoS) to user. This process can also be called delegation of deferrable loads (DDL) as mentioned and discussed in [13]. The key collaborative processes are as follows:

a) **Invitation to pursue a Vending Opportunity (VendOpp)**: The CVPP manager identifies and communicates a VendOpp to community members.
b) **Acceptance or rejection**: CHDT checks their DP assigned to it by its owner. Based on the assigned DP, a CHDT may either accept or decline to participate in the VendOpp.
c) **Scheduling vending**: Upon acceptance, the CVPP-E manager communicates the following vendOpp information to prospective CHDTs: (i) the vending time, (ii) the vending window, and (iii) the duration of vending.
d) **Scheduling the execution of delegated autonomy**: After receiving details concerning the VendOpp, all CHDTs shall schedule themselves in readiness to collectively execute their various "delegated autonomy" actions in line with the vending schedule.
e) **Execution of delegated autonomy**: When the scheduled "vending time" is due, all CHDTs will collectively execute their respective delegated autonomy, thus their DDL. This collective action will result in the general minimization of consumption in the community for the period (vending window). As shown in Fig. 3, for both consumers and prosumers, DDL will result in the minimization of consumption. However, for prosumers, DDL will also result in excess energy from their locally installed PV or storage system.
f) **Sharing unused energy with the community storage**: Thus, the unused energy as a result of reduced consumption shall be sent to the community storage for onward transfer to the grid during the vending window.
g) **Execute VendOpp**: The community manager will ensure that the community storage supplies the grid with the pre-agreed quantity of energy at the proposed time.

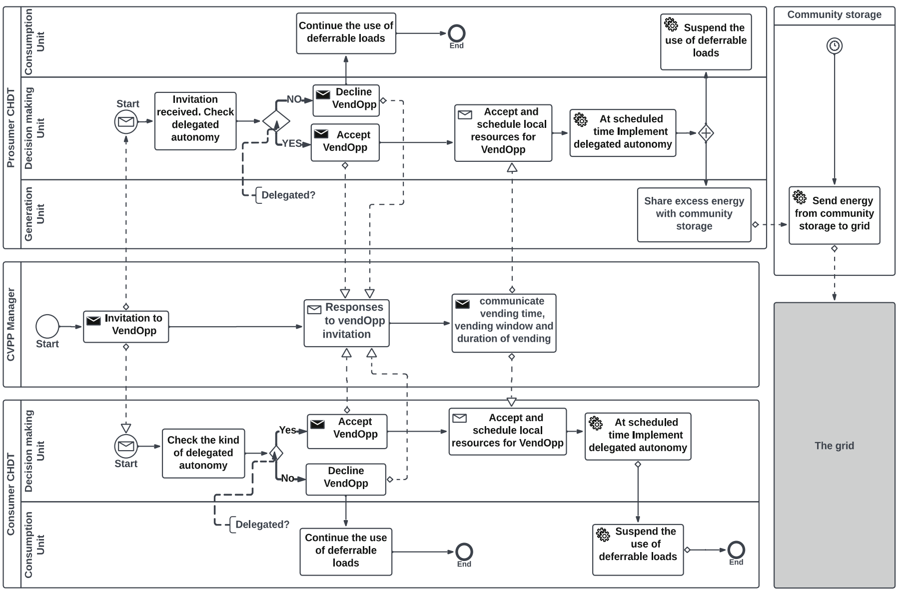

Fig. 3. Process of information exchange towards the execution of a specific goal

3.2 Modelling Sharing of Common Resources

Resource sharing (RS) is a common characteristic of collaborative cases. In the CVPP-E, members engage in resource sharing to help fulfil their collaborative objectives. The case shown in Fig. 4 is used to demonstrate sharing of common resources within the CVPP-E. It demonstrates two modes of sharing (L1RS and L2RS). L1RS refers to sharing excess energy that was produced by prosumer CHDTs with the community storage (charging the community storage). L2RS involves the sharing of energy that was stored in the community storage back with either prosumer or consumers CHDTs (discharging community storage). The following steps are used to describe L1RS and L2RS in detail (also assuming that a VO was previously established for this goal):

i. **L1RS.** Under this mode of sharing, the excess energy from several different CHDTs is shared with the community storage system. This is more of an aggregation process. Referring to Fig. 4, L1RS can be achieved in three major steps:

   a) **Local PV resource availability**: PV availability is a time-dependent event. The CHDT is alerted of the availability of solar energy due to the presence of sunlight.

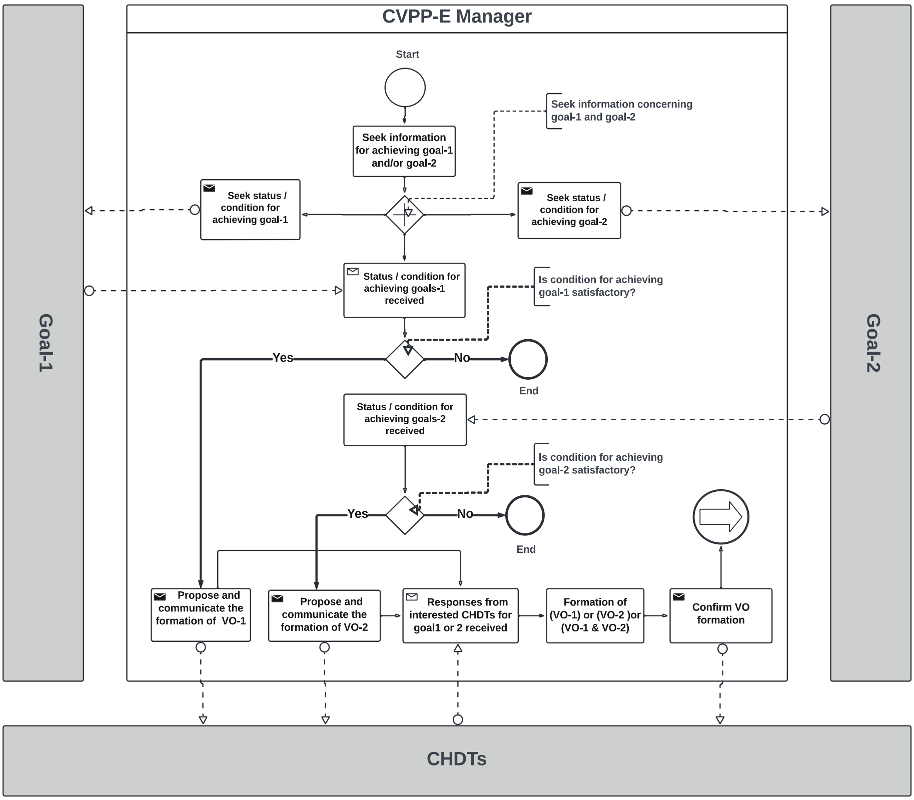

Fig. 4. Information exchange for goal formation

b) **Type of local energy demand:** For this step, the CHDT determines if there is a local demand for the locally generated solar energy (local demand include demand for appliances to use the energy locally or to store it in the local storage). If local demand exists, the generated energy is consumed locally. If otherwise, the generated energy is considered excess it is shared with community storage.
c) **Accept and store**: At this stage of the process, the shared energy is accepted and stored in the common storage system.

ii. **L2RS.** Under this mode of sharing, the energy that was previously stored in the community storage is shared back with community members according to their various needs. The storage capacity is constantly being monitored to determine if the conditions for L2RS are satisfied. Typically, L2RS is enabled when the state of charge (*SoC*) is greater than a threshold, say $\alpha\%$ of the battery capacity "*C*". If this condition is satisfied, the energy that was previously stored in the community storage is allowed to flow back into the community. L2RS is terminated when the condition changes, thus, *SoC* drops below another threshold, say $\beta\%$ of "*C*", thus, When *SoC* $> \alpha\%$ of "*C* ", L2RS is enabled, When $SoC < \beta\%$ of "*C*", L2RS is disabled

3.3 Modelling the Collective Actions Framework

Collective Actions (CA) refer to the actions taken by a collection or group of entities, acting based on a collective decision. CA is also a key component of the collaborative behaviours that are exhibited in the CVPP-E. In Fig. 5 below, we illustrate the CA behaviours of 3 CHDTs that are based on a common goal. The resultant effect of their CA is shown to have a direct impact on the community-owned energy asset (community storage), which subsequently affects the power grid. There are three major steps involved in the CA processes:

(a) **Condition-based decisions**: In this step of the process, a CHDT makes decisions based on some common goal conditions such as VendOpp.
(b) **Execution of assigned delegated autonomy**: If the decision in step (a) is based on some specific goals, all CHDTs will execute their assigned delegated autonomy simultaneously which can result in a common behaviour.
(c) **Appliance use behaviour:** The effect of steps (a) and (b) will have a direct impact on the use-behaviour of the embedded HH appliances in each respective CHDT. The resultant behaviours could also have a direct impact on the community-owned asset (community storage) and subsequently on the grid.

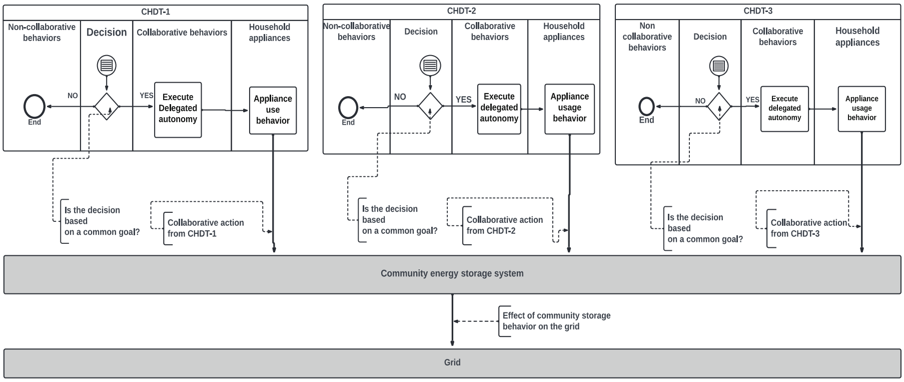

Fig. 5. The process of collective actions towards a common goal

4 How the Collaboration Framework Supports the CVPP-E

Based on the developed prototype, some preliminary partial outcomes have already been demonstrated in [16]. Further demonstration of other behaviours such as modelling “mutual influence” and modelling “delegated autonomy” have also been demonstrated in works that are currently in press awaiting publication. The prototype is constituted of several sub-models that are integrated together to help achieve the desired functionality of the CVPP-E. These sub-models include: (a) The appliance model that is used to model all the embedded HH appliances, (b) The PV model that is used to model the embedded PV systems of prosumers, (c) The community storage model which is also used to model the community storage system, (d) The consumption priority model also used to model (i) The process of initiating the use of an appliance, (ii) The process of selecting a preferred energy source, (iii) the process of having an appliance wait in queue until a preferred energy source is available. Other sub-models include: (d) the consumer/prosumer model that is used to configure a CHDT as either a prosumer or consumer and finally, (e) the influence model that is used to propagate either positive or negative influences from “influencer” CHDTs to “influence” CHDTs.

Depending on the intended purpose, a sub-model could be designed using one of three modelling techniques in AnyLogic. For instance, all models that exhibit dynamic behaviours, thus, having parameters that are constantly changing are modelled using System Dynamics (SD) techniques. Some examples include the community storage sub-model (Fig. 6), the HH appliances sub-model (Fig. 7) and the PV sub-model. Furthermore, all aspects of the model that require systematic procedures and discrete processes are developed using discrete event modelling techniques. One of such examples is the consumption priority model shown in Fig. 8. Finally, all aspects of the model that require the creation of an entity that is endowed with autonomous attributes is achieved using agent-based modelling techniques. Typical examples include prosumer and consumer CHDTs.

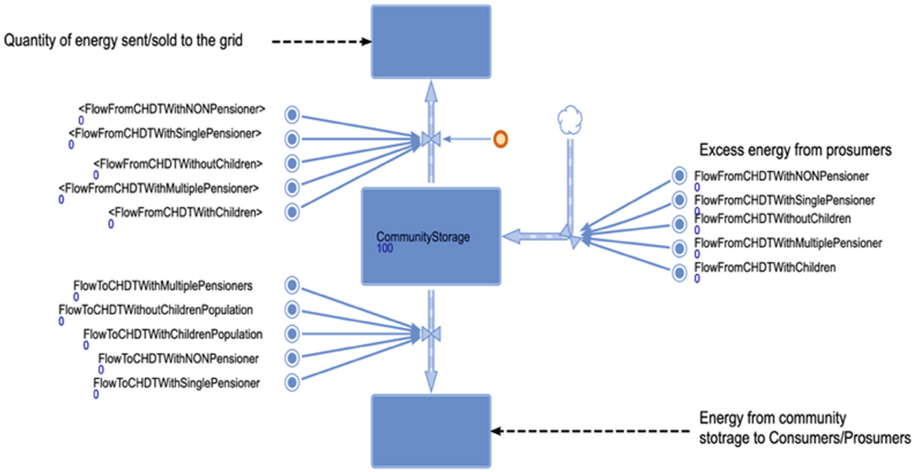

Fig. 6. A system dynamics model of the community storage system

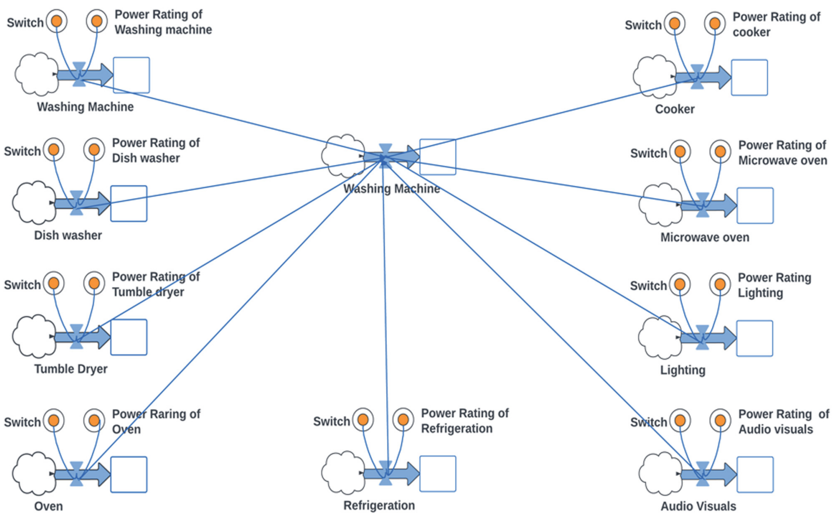

Fig. 7. A system dynamic model of the embedded HH appliances (9 appliance).

In Tables 1 and 2 below, we show some selected scenarios that were used to test the CVPP-E prototype in an earlier study [16]. For instance, the data shown in Table 1 was sourced from [14]. For demonstration purposes, the table (Table 1) shows data for only three out of the nine HH appliances that are embedded in each CHDT. These parameters are used to model each of the appliance's use-behaviour. Furthermore, in Table 2, we consider deferent 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 have been given authority by their owner to make some rational decisions

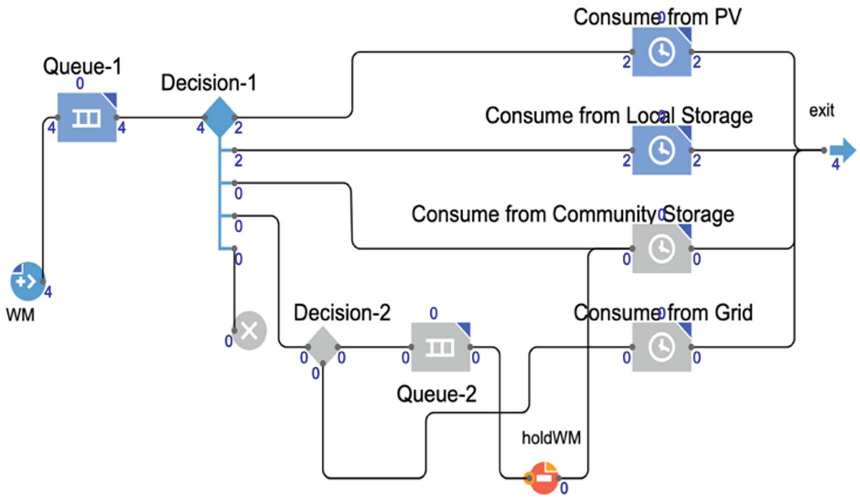

Fig. 8. A discrete event model of consumption priority

on their behalf. In this particular example, the goal was to minimize community consumption within a certain period namely the "vending window" (Fig. 9) 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 1. In Fig. 9 we show the outcome of one scenario, thus, scenario 1 (Table 2). The outcome shows that, within the vending window, the use of all three appliances was suspended resulting in zero consumption (Fig. 9).

Table 1. Distribution of CHDT population from the various category of HH in sample scenario

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 2. Population size of the various HH in ample 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

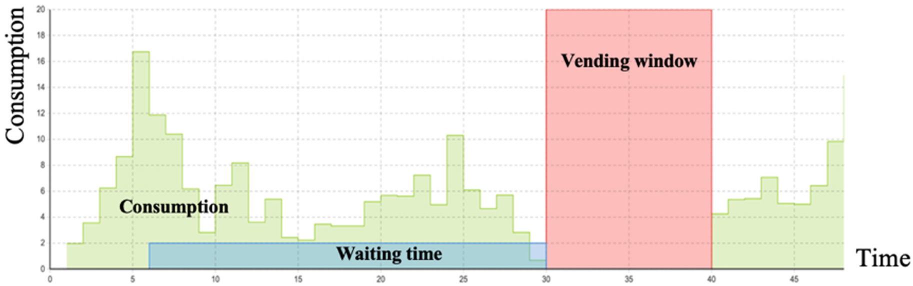

Fig. 9. The outcome of a collective action behaviour for scenario 1 (Table 2)

5 Prerequisite for Implementation and Limitations of the Study

Data from these HH appliances may be collected using IoT sensors, and this data could be transmitted using normal IoT protocols to the cloud where the digital twin may be hosted. In terms of appliance control, IoT actuators could be integrated into the appliances to carry out switching commands of the CHDTs, such as turning the appliances on and off. These commands could also be transmitted using IoT protocols. On the other hand, appliances are becoming more intelligent, embedding computational power. Scheduling and monitoring of these appliances could be done in the cloud by the CHDT. As suggested by [17], a Digital Twin Environment (DTE) is a logical environment in which software and sometimes hardware components interact to simulate an entire digital twin system or subsystem. To help reduce implementation costs, the services of a third-party service provider who provides DTE Platform as a Service could be procured to provide the DTE for the proposed CHDTs. Although this approach may raise some security concerns, a less expensive but effective way could be by embedding a layer of security at the gateway interface between the IoT devices and the DTE.

Limitations. Theoretically, the presented framework only considers four collaborative behaviours although in practice, there could be more. The framework is exemplified with only three deferrable loads. These are washing machines, dish washers, and tumble dryers. In practice, many other appliances could also be used to help achieve similar results. Appliances such as air conditioners, refrigerators, and water heaters, also known as interruptible loads, could be used to achieve similar results.

Prototype. The prototype model was developed using a multimethod simulation approach which involves the integration of multiple simulation paradigms such as System Dynamics, Agent-Based, and Discrete Event simulation techniques in a single simulation environment. The Anylogic [18] simulation platform was adopted for this purpose.

6 Conclusion and Future Work

This work is part of an ongoing research that seeks to integrate collaborative behaviours into the domain of RECs to facilitate sustainable energy consumption and exchange. The main objective of this study, as stated in the RQ, was to determine a suitable framework that could support the modelling of the collaborative behaviours of CHDTs within a CVPP-E environment. By adopting the BPMN modelling language, several frameworks have been developed that clearly and systematically outline the collaborative behaviours, key features, collaboration steps, and key roles of the collaborating entities. As discussed, three key collaborative behaviours were identified and modelled: (a) common goals, (b) resource sharing, and (c) collective actions. Demonstration of some partial outcomes for the developed prototype model contribute to point the suitability of the proposed framework.

In future works, other collaborative behaviours like value co-creation (tangible and intangible value) as well as some key performance indicators will be explored further to help access the performance of the model. Other collaborative scenarios such as the case where members could drop in and out of the collaborative, depending on their own strategies, will also be considered.

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