computers MDPI

*Supplementary Materials*

**File S1 The ODD reporting framework**

## 1. Overview

### *1.1. Purpose*

This model is used to illustrate how digital twins that are endowed with cognitive intelligence can adopt collaborative mechanisms to enhance sustainable energy consump-tion in an energy ecosystem. The considered collaborative actions include (a) oppor-tunity seeking (b) invitation to the formation of Virtual Organizations (VO) (c) acceptance or decline of invitation based on (i) delegation (ii) value system compatibility (d) VO for-mation (e) Resource Sharing.

### *1.2. Entities, State Variables, and Scales*

#### 1.2.1. Entities, State Variables

Entity 1: The Community Manager
Entity 2: The Community Storage System
Entity 3: The global environment: This is the environment within which all the proposed agents reside and interact with one another. The environment is called the Collaborative Virtual Power plant Ecosystem (CVPP-E) The CVPP-E is a digital twin representation of a renewable energy community.
Community goal states:
Active community goals: Goals that the community is currently pursuing (active goals)
Inactive community goals: Goals that are currently not being pursued by the community (redundant goals)
Entity 4: Households States: This represents the constituent households within the community.

Types of households:

- Households with single pensioners.
- Household with single non-pensioner.
- Household with multiple pensioners.
- Households with children.
- Households with multiple persons with no dependent children.

Each household can further exist in one of two states. These are (a) prosumer household state and (b) consumer household state

Characteristics of prosumer households: Households in the prosumer state have four (4) embedded PV systems represented by four different states. Only one of these states can be active at a time.

- BainSystem state represents a PV with a capacity of 6.930kW.
- BrainSystem state represents a PV with a capacity of 1.950 KW.
- Helius state represents a PV with a capacity of 3.99kW.
- DaSS state represents a PV with a capacity of 3.22kW.

Characteristics of consumer households: Households in the consumer state have the embedded PV and local storage system to be in the inactive state.

**Embedded household appliances:** Both prosumer and consumer households have nine (9) embedded household appliances. The appliances and their related variables are described in Table 1.

**Table S1.** Type of Appliance.

| | Duration of Use (*hrs*) | | Appliance power ratings (kW) | | Frequency of use per week | | |
|---|---|---|---|---|---|---|---|
| | ***Minimum*** | ***Maximum*** | ***Minimum*** | ***Maximum*** | ***Minimum*** | ***Average*** | ***Maximum*** |
| 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 |

**Delegated state**: Represent the condition that an agent delegated

**Undelegated states**: Represent the condition that an agent is undelegated

**Active Value System State**: Represent the condition that the value system corresponding to a particular preference of the agent is active

**Inactive Value System State:** Represent the condition that the value system corresponding to a particular preference of the agent is inactive.

**Active influencer state**: Represent the condition that the agent can convey influence on other agents in the environment

**Active influencee state**: Represent the condition that the agent can receive influence from other agents in the environment

PV availability state:

PV unavailability state:

Local storage availability state:

Local storage unavailability state:

1.2.2. Scale: One time step of the model represents one hour in real-time. The model starts from 0H0 and ends at any defined time which can be days, weeks, months or years.

## 2. Process overview and scheduling

### *2.1. Process for the creation of agents*

If an agent is a prosumer, randomly assign one of four PV systems and a local storage system

For prosumers and consumers agents randomly assign value systems

For prosumers and consumers, agents assign a random number between the minimum and maximum power rating data provided

### *2.2. Processes of energy generation*

In Figure S1, the "flow" element is used to simulate the rate of flow of any quantity (the flow of electrical energy in the case of this model). The flow rate is determined by "Param-eter A". This parameter could be a variable or a constant. In this model, this parameter represents 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 "accu-mulator" that accumulates or aggregates the amount of flow that enters the stock block. 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. Mathematically, the rate of flow from an infinite source (the cloud) into stock-1 (Figure S1) is given by equation (S1).

$$\frac{d(Flow)}{dt} = Parameter\ A \tag{S1}$$

The rate at which stock _1 is accumulated is given by equation (S2)

$$\frac{d(stock\_1)}{dt} = \frac{d(Flow)}{dt} \tag{S2}$$

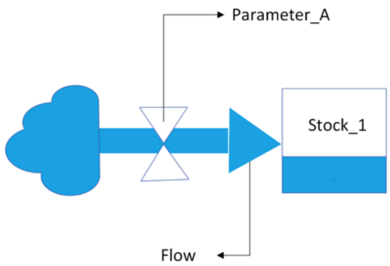



**Figure S1.** Example of stock and flow diagram representing generation and storage.

*2.3. Process for energy consumption and storage*

Figure 13 depicts a flow from "Stock-2" to "Stock-3." The element Stock-2 can represent a finite supply of energy sources, 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”. Concerning Figure S2, the rate of flow is given by equation (S3). Similarly, the rate at which stock_2 depreciates is given by equation (S4). Finally, the rate at which stock_3 is accumulated or is given by equation (S5)

$$\frac{d(Flow)}{dt} = Parameter\ B \tag{S3}$$

$$\frac{d(stock\_2)}{dt} = -\frac{d(Flow)}{dt} \tag{S4}$$

$$\frac{d(stock\_3)}{dt} = \frac{d(Flow)}{dt} \tag{S5}$$

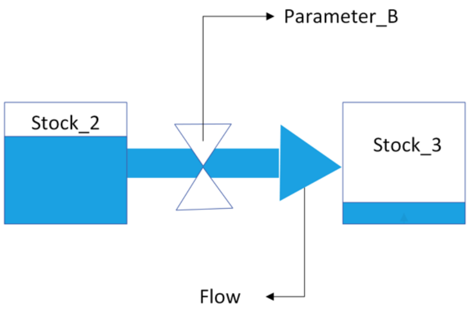



**Figure S2.** Example of a stock and flow diagram of consumption.

*2.4. Opportunity seeking process*

The community manager determines if the condition for the formation of a goal is met.

Once conditions are met, the manager formulates the corresponding goal(s).

The manager proposes the goal(s) to goal to the community in the form of invitations.

*2.5. Invitation to the formation of a VO*

The invitation is communicated by the CVPP-E manager

The invitation is communicated to the agents within the environment in the form of messages

All agents will receive copies of the invitation (messages)

*2.6. Responding to Invitations*

After receiving the invitation agents will first check their "delegated" status

- If undelegated, the agent will decline the invitation
- If delegated the agent will proceed to check its assigned value system
- If value system compatibility is not found the agent will decline the invitation-based value system. Non-compatibility.
- If value system compatibility is found, the agent will accept the invitation.

*2.7. Process for the determination of the prospects of a VO*

The CVPP-E manager aggregates all the received responses.

The CVPP-E manager checks the condition for the formation of a VO.

Several conditions can be used for the formation of a VO. However, in this model, the VO threshold is the adopted condition. The VO threshold is the minimum number of accepted invitations.

Once this threshold is reached or exceeded, the VO will be formed.

If otherwise, the VO will not be formed.

*2.8. Process for scheduling a VO*

Process for executing a scheduled VO/Goal

## 3. Design Concepts

*3.1. Basic Principles*

This aspect of the design concept addresses general concepts, theories, hypotheses, or modelling approaches underlying the model's design, at both the system and agent levels. In this case, the general concepts include

- The concept of Business Ecosystems
- The concept of collaborations

- Common goal
- Resource Sharing
- Communication and information exchange
- Collective actions
- Collaborative Network concepts
- The concept of a Virtual Breeding Environment
- The concepts of Virtual Organizations formation and dissolution
- Ad-hoc/goal-oriented networks

### *3.2. Emergence*

Describes the key model results or outputs that are modelled as emerging from the adaptive decisions and behaviours of agents. The emergence behaviours in the model include:

- Virtual Organization formations. This emergent behaviour is a result of the collective decision of all the agents in the environment. It is nondeterministic and highly stochastic.

- The rationale for deciding the level of emergence is the use of the concept of thresholds. The adopted threshold namely the VO formation threshold is used to determine if the condition for the formation of a VO has been met. The formation of a VO is judged a successful emergent behaviour.

**Adaptations**

CVPP-E manager adaptation behaviours

a) Opportunity seeking
b) Formulation of community goals.

Prosumer and consumer adaptation behaviours

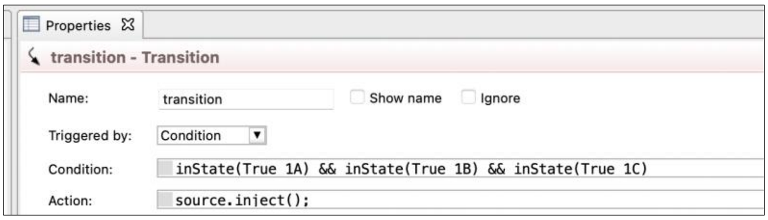
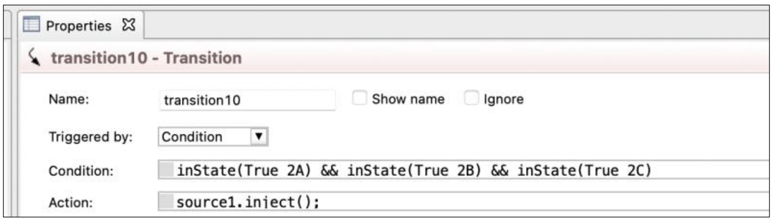
Agent's decisions that result in adaptive behaviours are based on these principles.

a) Values system: Agents make decisions based on their assigned value system. If the Value system is compatible agents accept invitations otherwise the agent declines the invitation to the formation of VOs.
b) Delegation: Agents make decisions based on delegation.
c) Delegated autonomy: Agents make decisions based on their assigned delegated autonomy. If the agent is delegated and they have a compatible values system, they accept invitations to participate in the formation of VOs
d) Resource Sharing: Prosumer agents also make resource-sharing decisions based on the availability of surplus energy and zero local demand.
e) Consumption priority for prosumers: Energy consumption priority of prosumers agents are in this order: (a) Directly from the Photovoltaic source (b) local storage source (c) community storage source (d) grid.
f) Consumption priority for consumers: The consumption priority of consumers is as follows (a) Community storage (b) grid.

## 4. Objectives

### *4.1. The objective of the CVPP-E Manager*

| Index | Adaptive behaviour (Direct objective-seeking) | Characteristics of agent success |
|---|---|---|
| 1 | Opportunity seeking | The measure of success is when three external conditions are simultaneously true. The true condition is determined using state charts that alternate between the true and false states. The true state represents the prevailing condition and the false state represents a dormant condition. |

| | | |
|---|---|---|
| 2 | Formulation of community goals. | The measure of success is when three conditions are true.<br>1. If condition 1A is true, condition 1B is true, and condition 1C is true, formulate community goal 1.<br>Codes:<br><br><br>2. If condition 2A is true, condition 2B is true, and condition 2C is true, formulate community goal 2.<br>Codes:<br><br> |

*4.2. The objective for Prosumer and Consumer Agents*

| Index | Adaptive behaviour (Direct objective-seeking) | Characteristics of agent success |
|---|---|---|
| 1 | Value system compatibility | The measure of success is the condition of "states matching"<br>For instance, if value system 1 of agent "X" corresponds or matches with community goal 1, compatibility with community goal 1 is achieved.<br>Two states are considered to correspond or match if both states are in the true states.<br>On the contrary, If value system 1 of agent "X" **does not** correspond or does not match with community goal 1, compatibility with community goal 1 **is not** achieved.<br>Two states are considered not to match when either one or both states are in the false state. |
| | Delegation | The measure of success is when the agent recognizes their delegated state |
| 2 | Delegated autonomy | The measure of success is the level of autonomy. Three levels are defined in the model. These are<br>1. Full delegation: Autonomy to delegate all appliances.<br>2. Partial delegation single appliance: Autonomy to delegate on one appliance<br>3. Partial delegation double appliance: Autonomy to delegate two appliances<br>A total of three appliances can be delegated in the model. These are (a) washing machine (b) dishwasher (c) tumble dryer. |
| 3 | Resource sharing | The measure of susses depends on the following conditions<br><br>**Level 1 resource sharing.**<br>If photovoltaic is available and local storage is full and local demand is zero, share surplus generation from photovoltaic with community storage |

| | | |
|---|---|---|
| | | **Level 2 Resource sharing.**<br>If community storage is full and there is demand from prosumers/consumers agents, share stored energy with prosumers/consumers agents |
| 4 | Prosumer consumption priority | Priority 1: Consume from PV source. If unavailable check priority 2.<br>Priority 2: Consume from local storage. If available check priority 3.<br>Priority 3: Consume from community storage. If unavailable check priority 4<br>Priority 4: Consume from the grid. |
| 5 | Consumer consumption priority | Priority 1: Consume from community storage.<br>Priority 2: Consume from the grid. |

## 5. Adaptive Behaviour

When an agent accepts an invitation, it adapts its behaviour in line with the goal for which it accepted the invitation. Adaptive behaviour may include participating in the VO or goal activity when the scheduled time is due.

Consumers adapt their consumption behaviours to minimize consumption from the grid by maximising consumption from the community storage.

Prosumers adapt their consumption behaviours by minimizing their consumption from the grid and maximizing consumption from renewable sources namely photovoltaics systems, local storage and community storage.

Community/local storage system adapt their behaviours by enabling the system to charge when their contents drop below a threshold. Furthermore, they enable discharging when their contents appreciate beyond a certain threshold.

### *5.1. Cognition*

Agents in the model have cognitive capabilities. Cognition is achieved through the use of state charts. Agents in the model are cognitive of the following

- Delegated state
- Undelegated states
- Active value System State
- Inactive value System State
- Active influencer state
- Active influencee state
- PV availability state
- PV unavailability state
- PV capacity state
- Local storage availability state:
- Local storage unavailability state
- Local storage capacity state
- Community Storage availability state
- Community Storage unavailability state
- Community storage capacity state

### *5.2. Stochasticity*

Stochasticity or non-deterministic processes are modelled using a built-in probability distribution. The uniform distribution is mostly used to model these stochastic processes

The following parameters are modelled as non-deterministic processes.

- Appliance power ratings. Modelled as a *uniform distribution (x,y)*, where x is the possible minimum power rating and y is the possible maximum power rating.

- Duration of use. Modelled as a *uniform distribution (x,y),* where x is the possible minimum usage time and y is the possible maximum usage time in hours.
- Frequency of use. Modelled as a *uniform distribution (x,y),* where x is the possible minimum frequency and y is the possible maximum frequency per week.
- Request to use an appliance. Modelled as a *uniform distribution (x,y),* where x is the possible minimum number of requests and y is the possible maximum of requests per day.
- The capacity of the installed PV system.
- Value systems
- Community goal