Asynchronous Smart Grid Simulations

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Abstract. A shift from traditional power grids to future smart grids requires a different approach to the analysis of power grid systems. In the smart grid conception, the system is analysed in a dis-aggregated manner through simulations. Many objects and relationships must be considered for a complex system to be eventually modelled and simulated. Usually, the simulation is performed by synchronising calculations associated with objects. The main problem of this approach is that every calculation has to be executed at the same speed in spite of objects not requiring an update with the same frequency. So, lots of unnecessary calculations are done, making performance worse. With the objective of improving the simulation performance, in this paper a new approach for simulating power grids based on asynchronous timing is presented. This approach is orientated towards allowing calculations to be executed at their own pace.

Keywords: agent based model, power grid system, asynchronous simulation, simulation framework, complex system, power grid, demand side management, smart grid

1 Introduction

The climate change and liberalisation of markets are pushing the energy sector towards a new paradigm known as the smart grid. This paradigm is characterised by the introduction in the power grids of renewable energy sources (RES), new technologies such as storage mechanisms, massive integration of sensors and decision makers distributed along the grid. There is also a trend towards the introduction of a communication layer for the management and control of these technologies. The smart grid paradigm is also based on the use of the Demand Side Management (DSM) whose objectives include the minimisation of the peak demand and the system operation and planning improvement [10]. The system complexity is therefore increased and new tools are needed for the analysis and design of smart grids.

Traditionally, simulators have been an essential tool for analysing and designing power grid systems. Many simulation tools have been developed for this

purpose: UWPFLOW [8], TEFTS [6], MatPower [18], VST [15], PSAT [13], InterPSS [17], AMES [1], DCOPFJ [2], Pylon [4], and OpenDSS [3]. However, these tools are limited to simulating smart grids specific issues, like a communication system integrated in a large-scale simulation. GridSim [7] was developed to deal with these problems. GridSim is a modified version of TSAT [5] (an industry-proven transient stability simulator) which addresses the electro-mechanic working mode of the power grid system. GridSim is a real-time simulator adapted to integrate sensing with a high data rate. The modelling approach of these tools manage the production and demand in an aggregated manner.

However, smart grid simulations require the representation of both demand and production in a dis-aggregated manner. Tafat is a tool able to simulate smart grids that enables a bottom-up representation which includes, not only a technical system description, but also a sociological description of people interacting with the system [9]. With this representation, it is possible to design, implement and test smart grid simulations. All these tools execute the simulation with a synchronised approach. Synchronous simulations have the advantage of simple time management as all objects of the modelled system are running in the same time instant. It forces objects to always perform calculations, in every time step. Sometimes these calculations are unnecessary due to the fact they cannot provide new results. For example, a washing machine is usually waiting for an agent to be turned on, considering this as an event. Later on, it develops some washing cycles where the power may vary along the time. Whenever the washing machine state does not change, calculations could be avoided.

In this paper, it is proposed that an asynchronous simulation approach is included in Tafat which would allow objects to develop their own time as desired. They could behave both event and time-based according to their nature. Furthermore, they could use variable steps from one calculation to another. For example, in an asynchronous simulation where the power consumption of a washing machine is analysed, calculations would be done only when the washing machine state changes. The advantage with respect to a synchronous simulation is clear since in the synchronised case, calculations are done every time step.

In the context of discrete event simulation the asynchronous concept has dual connotation. One of them consists in variable time-increment procedures as opposed to a ″synchronous″ or fixed time-increment procedures for simulation control. This connotation is related to the known concept Distributed Discrete Event Simulations (DDES) [12, 14]. For instance, Simula [16], a simulation-oriented programming language, is based on this asynchrony concept where the time-management is mainly event-based. This kind of asynchrony was already considered in Tafat through using different time steps for each mode of behaviour [9]. On the other hand, the asynchrony can be understood as a non-sequential processing where simulation parts may not be executed in the proper temporal order. That is to say, later parts of the simulation may be executed before previous ones [11]. The last connotation is the one to which we subscribe in this paper. The objective is to apply the time-management to each model element allowing them to be in different time instants.

2 Tafat asynchronous simulation

In initial Tafat framework releases, the simulation of power grids was done following a synchronous timing approach. This paper examines a new approach to achieve asynchronous simulations with Tafat. This section introduces the concepts and constructions that Tafat architecture includes to model power grids. Theses constructions are focused on dependencies between objects that are massive and very relevant in a complex system simulation. In order to properly handle an asynchronous simulation, it is important to understand the dynamics of coupled objects. For the sake of clarity, a traced execution of objects interaction during an asynchronous simulation is demonstrated.

2.1 Tafat system modelling

Modelling in Tafat is done by developing two views: an object oriented description of the scenario, and a behavioural specification of these objects. The first view is the static representation of the real world objects, where each single object is described with features (static attributes) and variables (dynamic attributes). This representation also includes the specification of object relations. The second view focuses on objects' dynamic : that is, how objects should behave, emulating the way they act in the real world (behaviour). A single object can be associated with several behaviours. These associated behaviours are responsible for modifying the model object variables along the time. Object variables are encapsulated and can be only accessed and modified by their associated behaviours.

The solution of separating objects from their behaviours, makes it straightforward to change the method for calculating variables. In this way, it is possible to simulate different behavioural aspects with the same representation.

For example, a washing machine representation contains:

1. Static View
   - The description of their features such as capacity, installed power and energy labelling, and their variables such as mode (on, off), active programme (temperature, cycle, timeout...), and active power.
   - The topological relation to the electrical installation in a household
2. Dynamic View
   - The specification of the washing machine-operating mode. The behaviour is then associated with this model object.

Normally, a behaviour is coupled with other objects, both for querying their states or sending messages in order to change their states. In the Tafat model representation, defining behaviour which interacts with other objects is allowed.

This representation approach consists of interfaces that should be defined in the object which could be externally accessed. In Tafat, there are two types of interfaces:

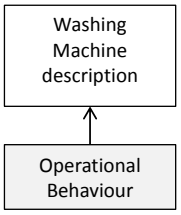

Fig. 1. The operational behaviour of a Washing Machine is associated with the Washing Machine object description

1. event interfaces that handle messages and are responsible for modifying the object internal variables as requested, and
2. data interfaces that handle queries and provide the value of requested attributes

An example of these types of interfaces is shown in the figure 2. On the one hand, the thermal behaviour within a household has a data dependence with the temperature of the surrounding Outdoor. In this case, the Outdoor temperature data is requested by the associated object through the outdoor data interface. On the other hand, an agent sociological behaviour wants to turn on the washing machine. Then, this sociological agent must use the washing machine event interface to achieve this task. The washing machine event interface would change the washing machine mode to "ON". The washing machine operational behaviour would calculate the proper power consumption based on this mode. Later on, when the cycles end, the operational behaviour turns off the washing machine.

2.2 A power grid simulation case

In order to consider the main issues that involve asynchronous simulation a simulation case is proposed to show how objects interact when working in different times (Figure: 3).

The objects within this simulation case are an Outdoor, a Household, a Washing Machine and a Radiator.

- The Outdoor is the object that represents environmental conditions, in this case, the temperature. The Outdoor temperature behaviour is responsible for setting the temperature which can be loaded from an external database.
- The Household works as a container of the appliances of a household, a Washing Machine and Radiator in this case. The Household Behaviour is concerned with the thermal dynamics inside the household.
- The Electrical devices inside the Household are a Radiator and a Washing Machine. These devices are handled by an Agent.
- Finally, the Agent represents the people living in the Household and the associated behaviour defines the actions that these people are performing. For example: a person turning on the Washing Machine.

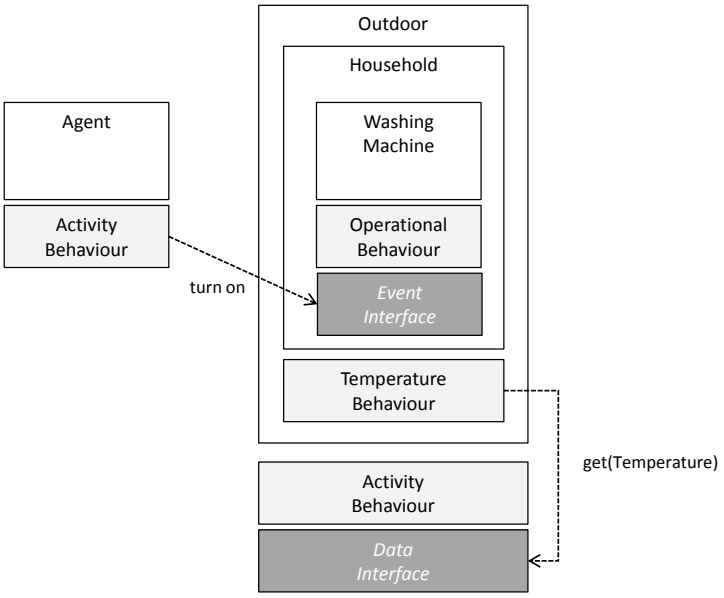

Fig. 2. Dependencies examples between objects

The coupling in this model is represented by the dotted lines in the figure 3. This coupling is always defined from behaviours to interfaces. The Agent depends on the Washing Machine to change the operation mode of this device. The Radiator depends on the Household temperature, since the heat radiation is calculated based on the gap between the Radiator reference temperature and the Household temperature. The Household has two dependencies: with the Outdoor temperature and with the Radiator power, since the Household temperature is calculated by a numerical solution of a differential equation which includes these two variables. Note that, in this case, there is a cyclic dependence between the Household and the Radiator.

2.3 Asynchronous simulation dynamics

A system simulation requires time-management to ensure that temporal aspects are correctly represented and emulated. This temporal representation only exists during the simulation process and is referred to as ˝Simulation Time˝. Simulation Time is represented as a timestamp, a long integer where a unit corresponds to a millisecond of real time.

The time-management in a synchronous simulation is centralised while the time-management in an asynchronous simulation is distributed. That is, an asynchronous simulation involves that every object manages its time, so they could have different timestamps (Figure: 4).

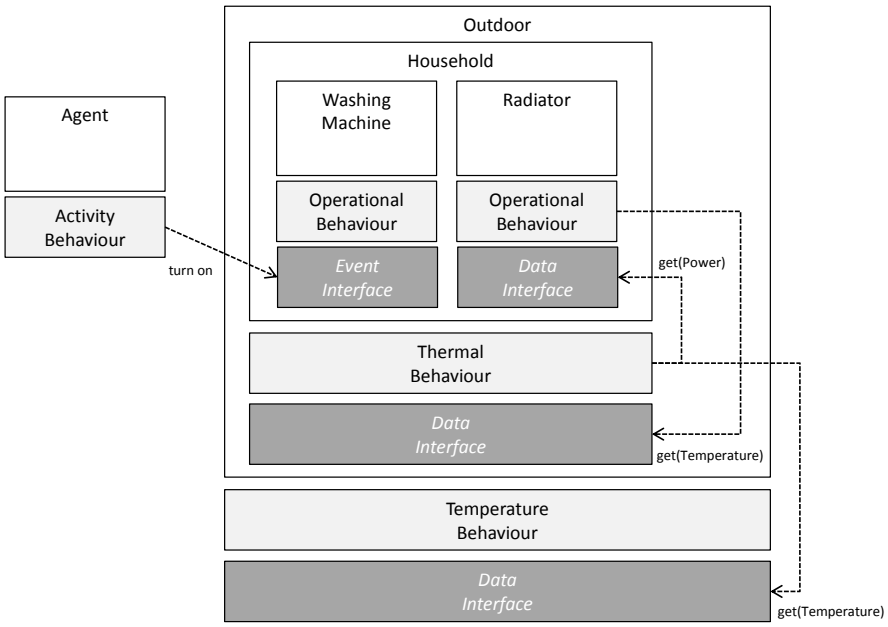

Fig. 3. Model composition

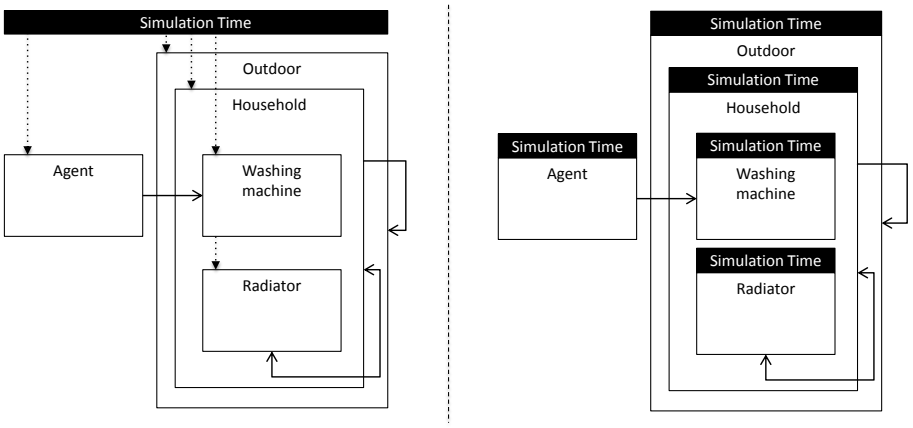

Fig. 4. Synchronous vs Asynchronous simulation

In this simulation paradigm, when an object is not coupled with other objects, its Simulation Time develops without considering other object Simulation Times. In this simulation case, the Outdoor is completely independent of other objects.

However, when objects are coupled, the challenge consists of correctly reproducing temporal relationships. The identified temporal relationships are as follows:

1. Coupling with a data interface
2. Cyclic coupling with data interfaces
3. Coupling with an event interface

In the following sections these relationships are discussed.

Coupling with a data interface Since an object could access a variable of an external object which may be in a different time instant, every object must keep the different states that have been calculated during the simulation execution. So, when a variable is modified, a state snapshot is created in order to keep the object state in this time instant.

If an object is querying for a variable value in a time instant t_i, there are two cases: the object Simulation Time is delayed or ahead with respect to the external object Simulation Time. In the first case, the external object is able to provide the value by retrieving the last snapshot previous to this time instant (t_i). I n the second case, the dependent object must wait until the external object reaches this time instant (t_i).

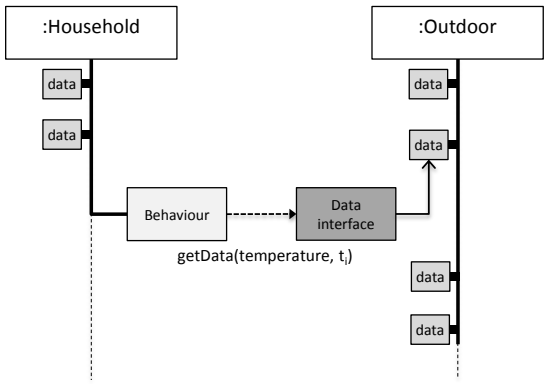

Fig. 5. Household requires the external variable temperature from the Outdoor. Note that the time is vertically represented

In the figure 5, the first case is shown. The Household Simulation Time is t_i and the Outdoor Simulation Time is t_j. Whenever t_i is lesser or equal than t_j, the requested data can be delivered since the data has already been calculated and stored.

However, when the Household Simulation Time (t_i) is greater than the Outdoor Simulation Time (t_j), the Household behaviour is blocked (Figure: 6) until

t_j is greater or equal than t_i (Figure: 7) delivering the last Outdoor Temperature value stored in the last calculated snapshot.

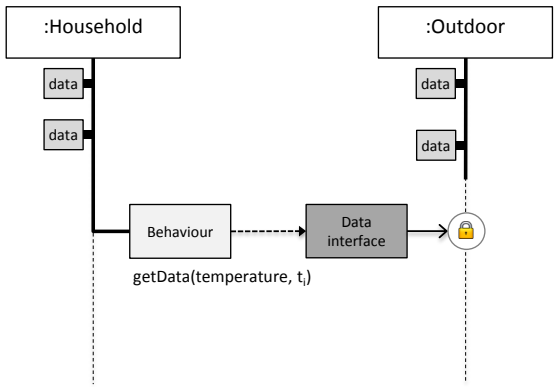

Fig. 6. The Household behaviour request is blocked since the Outdoor Simulation Time is delayed with respect to the Household one

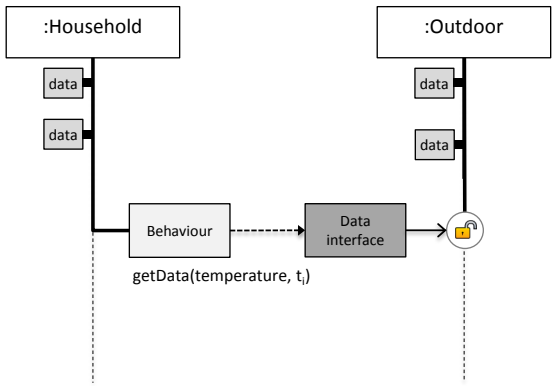

Fig. 7. When the Outdoor Simulation Time reaches the Household one the data is delivered.

Cyclic coupling with data interfaces The cyclic dependence is a concrete case of the data dependence. Two objects depending on each other whose Simulation Times are different, is handled with the following rules: the most delayed one will always retrieve the required data while the most advanced will be blocked until the delayed reaches its Simulation Time (Figure: 8). The mutual blocking

is not possible since objects retrieve the value for the current Simulation Time to calculate the next Simulation Time value.

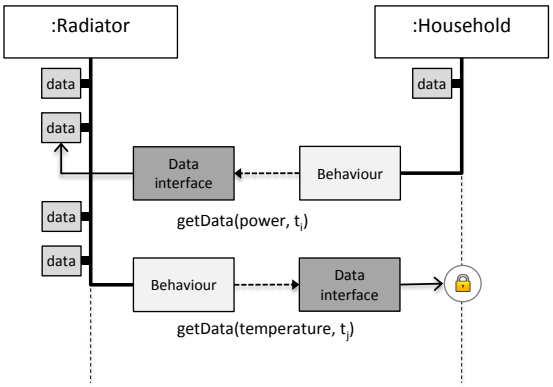

Fig. 8. Radiator and Household cyclic dependence resolution

In the example shown in the figure 8, the Household requires the power consumption of the Radiator in order to calculate the new temperature value. On the other hand, the Radiator behaviour needs the Household temperature value to modify the Radiator state, since the reference temperature at the Radiator thermostat serves as a control mechanism.

Coupling with an event interface The event coupling means that an object receives external messages that contain orders for changing its internal variables. This is the case of objects which are managed by people that are represented as Agents in the model. The Agent interacts with these objects by sending a message using the object event interface. When the message is received by the object interface, the object Simulation Time is developed and then, a new snapshot state is created.

It could happen that the agent develops its simulation time without the intention of sending an order to any object. In this case, the agent behaviour must send a "Notification Time Message"to the object. In fact, when the agent simulation time develops, the agent behaviour must send a Notification Time Message to all objects the agent is controlling. This notification determines how long an object can develop its Simulation Time. This type of relationship means that object's Simulation Time that is controlled by an agent, will never exceed the agent Simulation Time.

Figures 9-12 show an event relationship between a social Agent that turns on the Washing Machine. In this example, the Washing Machine Simulation Time is always behind the Agent Simulation Time. In other words, the Agent Simulation Time sets a restriction for the Washing Machine Simulation Time.

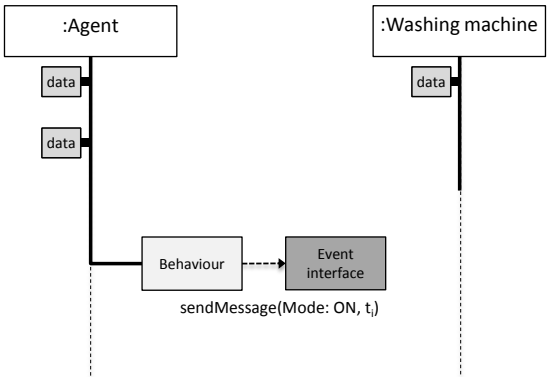

Fig. 9. The Agent sends a message to turn on the Washing Machine

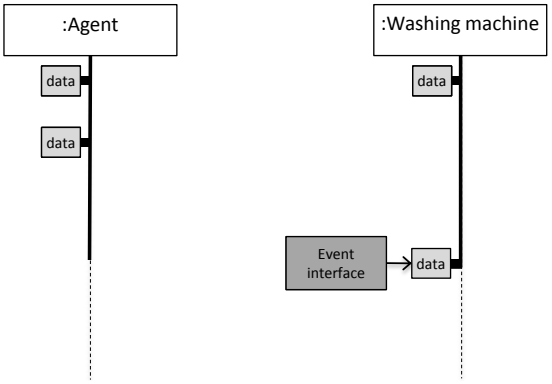

Fig. 10. The Washing Machine event interface changes the object mode to on

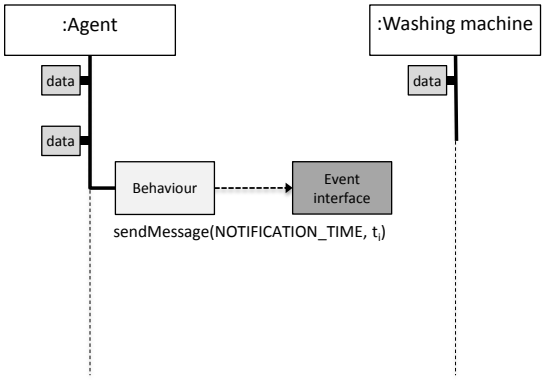

Fig. 11. The Agent indicates the Simulation Time in which it is to its controlled objects

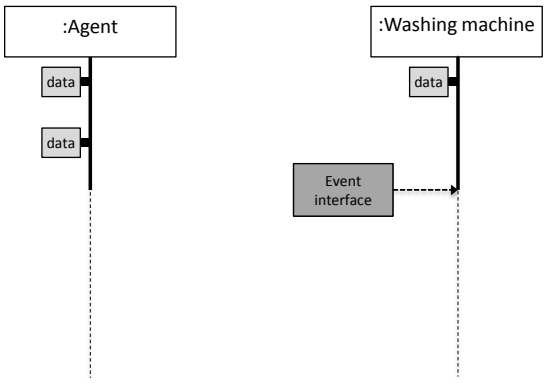

Fig. 12. The washing machine receives the message. Now the washing machine can develop its time until the temporal point indicated in the message

In the case of the Washing Machine, its power consumption would be 0 at the beginning of the simulation as it's off. Therefore, a new snapshot is created when the Agent turns on the Washing Machine. From that moment, the Washing Machine behaviour will calculate the new power consumption with the restriction that the calculations development should not exceed the Agent Simulation Time, in case the agent turns off the Washing Machine.

Scales The dependencies explanation has been focused on the low scale level. This is due to the fact more complex interactions take place at this level in the demand simulation of the power grids. Scaling up from the presented case to power grid levels demonstrates how the time would be developed following a bottom-up approach. In the figure 13, information flows are shown which indicate how the demand power is aggregated from the lowest levels to the highest ones at a concrete time slice. This aggregation is required to calculate the demand at every scale. Assuming that every element of a level makes the same calculations, it could be observed that each level may be delayed with respect to the lower one. This is the typical case since the upper elements are waiting for the information coming from the lower elements. However, it is possible for all of them are in the same time instant. It is not possible for upper levels to be ahead of the lower ones.

2.4 Object time management

In the previous cases, the discussion was focused on objects with a single type of behaviour. However the time-management of an object with several behaviours or/and several event interfaces must be dealt with. Every time a type of behaviour is executed, it registers the Next Time Execution, that represents when it should be executed. The object time-manager selects the behaviour with the

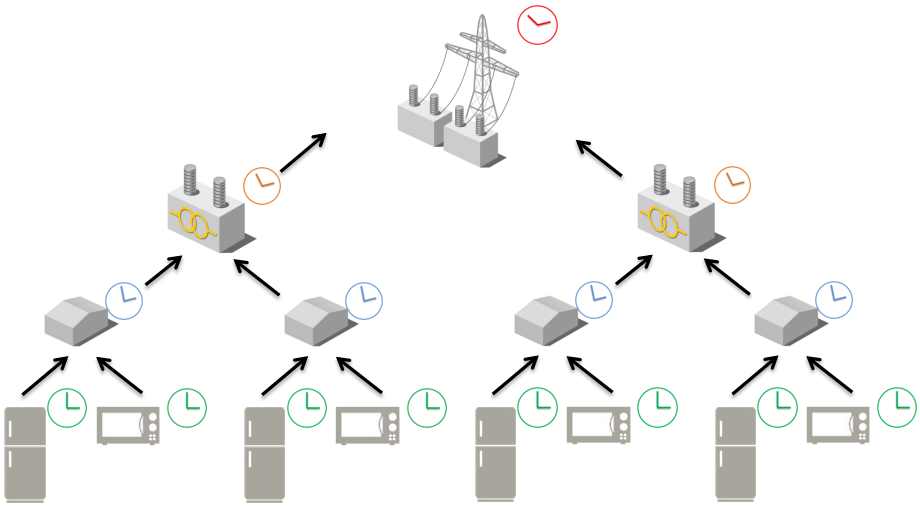

Fig. 13. Demand simulation in a higher scale

nearest Next Time execution to the current Simulation time. The event interfaces are dealt with in the same way, so that the Interface Next Time Execution corresponds with the time defined in the last message received. Whenever a received message concerns a variable value modification, the object behaviours will be executed afterwards allowing a change in their Next Time Execution, according to the new state. Therefore, objects can dynamically develop their Simulation Times : that is, their Pace could vary from one Simulation Time to the next one. To illustrate the internal time-management, the photovoltaic cell behaviour is studied. This behaviour calculates the generated power, based on the environmental solar radiation. Therefore, the generation power variable will vary along the day until the sunset when the production will become 0. Then, this variable will not change until sunrise. According to this behaviour, three solutions can be proposed to avoid systematic calculus along the night:

1. When the sunset is reached the behaviour registers the Next Time Execution in the sunrise time, whenever this data is available.
2. When the sunset is reached the behaviour registers the Next Time Execution of the previous known sunrise time. This temporal jump may avoid the first solar radiation when the sunrise time is before the already known one. Therefore, the Next Time Execution could be the previous known sunrise time minus ten minutes.
3. The photovoltaic cell outdoors could send messages to the photovoltaic cell event interface whenever solar radiation changes. Following this, the photovoltaic behaviour could register its Next Time Execution to infinite (sleep mode). Therefore, solar radiation changes are received by the photovoltaic cell event interface-allowing mode of behaviour to access this information.

2.5 Implementation

In this section, architectural methods to implement this approach are presented. This architectural proposal takes into account the previously described requirements for simulating a power grid, using an asynchronous approach.

A Tafat Thread represents the execution of a single Model Object and from this point of view describes the execution state, awake or sleeping, and the simulation time in which it is (Figure: 14). During the execution of the whole simulation, Tafat Core request awake Tafat Threads to be executed. After this execution, a Model Object will have changed its simulation time and/or its state. In order to improve the performance, Tafat Core keeps a list of the awake threads and it is listening for state changes in threads to update this list.

A single Model Object has many controllers that can modify the Simulation Time. A controller factor could be either Behaviour or an Event Interface. These controllers, that implement the Develop Time interface, participate in the Model Object simulation, each of them proposing different Next Simulation times. When the Next Simulation Time of any of these controllers is undefined, the Tafat Thread that represents the Model Object turns into a sleeping mode. Once, the Next Simulation Time of all the Model Object controllers are defined, the thread will wake up. Next Simulation Time of Develop Time Controllers could be set to undefined or a value that should be greater than the current Model Object Simulation Time. A feasible value for a Next Simulation Time could be infinite, meaning that Behaviour is suspended, pending an external event.

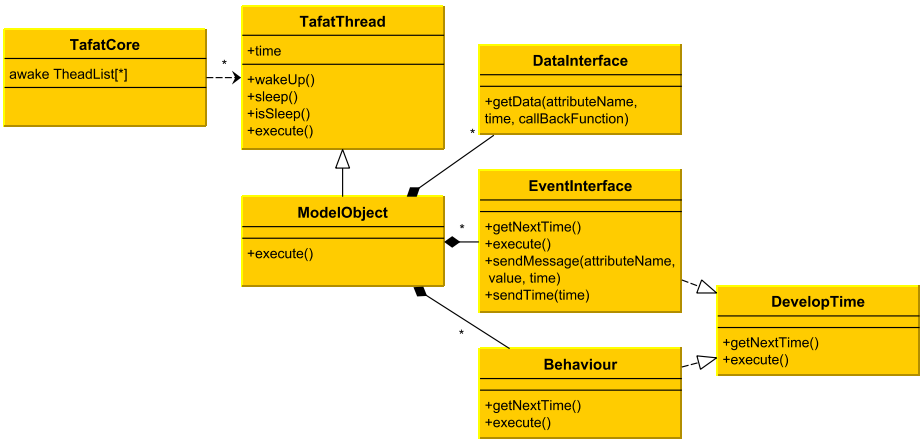

Fig. 14. Tafat asynchronous simulation architecture

For example, the Next Simulation Time of a Washing Machine Behaviour can be infinite, so that the washing machine is off and therefore, it is waiting to be turned on (Figure: 15). On the other hand, the Next Simulation Time

of this Washing Machine Event Interface is undefined until other Model Object Behaviours that use it, set the Next Time Simulation. Since the Washing Machine depends on the Social Agent to be modified, the Social Agent must inform this device of this. This Current Time is transmitted through a message which arrives at the Washing Machine Event Interface. When the Social Agent Current Time arrives, the Washing Machine Event Interface will modify its Next Simulation Time from an undefined value to the one which has arrived in the message. Whenever an event for modifying the state of the Washing Machine arrives, the Washing Machine behaviour will be executed once, allowing to it to calculate its Next Simulation Time based on this new state.

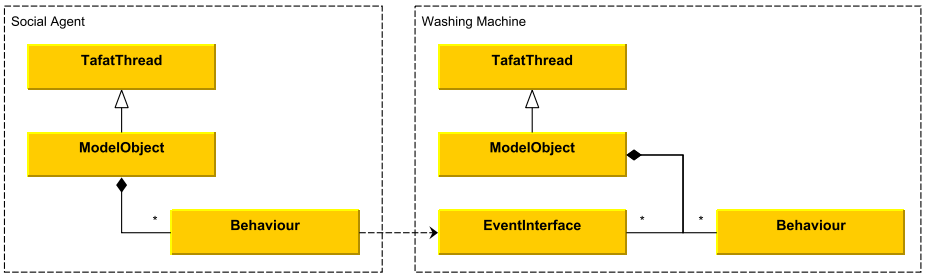

Fig. 15. The Washing Machine Event Interface Next Simulation Time turns from undefined to a defined value when the behaviour of the Social Agent sends its Current Time. On the other hand, the Washing Machine behaviour Nex t Simulation Time turns from infinite to a reachable time when its state is changed to ON by the Agent

Another improvement from the performance point of view is based on the Snapshots removing. A concrete Model Object may have dependences for requesting data or set values in external Model Objects. Similarly, other Model Objects could require this one to be accessed. For this reason, the Model Object must keep the snapshots for all the Model Objects which request data. As this Model Object knows the data requesters, it is able to find out the time in which the requesters are and, therefore, it could delete the Snapshots which are previous to the Current Time of the most underdeveloped Model Object requester.

3 Conclusions and outlook

Going towards asynchronous complex system simulations involves a re-conceptualisation. This re-conceptualisation affords objects interaction issues which could come from both data and event dependencies. In a synchronised execution environment, every object of the system is in the same time slice and the time-management is usually handled using a single clock. The main advantage of this approach is, among others, the simplicity when accessing or modifying an object since all of

them are in the same time slice. However, the main disadvantage of the execution of object calculations, is that some of them are unnecessary because the execution is not going to produce any different output.

The use of an asynchronous approach for simulating complex systems provides flexibility in the object evolution. Objects can freely develop as far as their dependencies are satisfied. Furthermore, object behaviours can be both event and time-based which provides the possibility of having sleeping behaviours. This sleeping behaviour could change their status to active by receiving external events. The behaviour step may vary from one execution to the next at a dynamic speed. Both sleep mode and dynamic speed are important features to avoid the systematic calculations at fixed steps which produce the same values. Finally, we think this approach may facilitate the parallel complex simulation execution.

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