# Composition of Simulations for the Analysis of Smart Grid Scenarios

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**Abstract:** In this paper the need for a modular Smart Grid simulation framework is motivated. This framework has to allow the automatic composition of existing simulation models for the evaluation of control strategies. Domain specific requirements for this approach are discussed. Based on reference models from literature, a layered approach for solving the composition problem is presented. It breaks down the problem into a syntactical, semantical and a scenario layer, for each of which basic concepts for solving the problem are presented.

## 1 Introduction

Nowadays the electricity grid undergoes a large structural change towards a so-called Smart Grid, among other reasons, triggered by the increased integration of renewable energy sources. In the future, the power grid will no longer be dominated by a relatively small number of large coal and nuclear power plants but rather by a large number of dispersed, renewable energy sources (DER). The major problem thereby is the coordination of this large number of DER such that generation and demand are balanced at any time. This is a challenging task due to the number and restrictions of the involved components. Control strategies for this complex and new task still need to be developed and in particular evaluated and tested, for example with respect to grid stability or other scenario specific objectives.
To ensure that this transition process can be done as economically as possible and especially without losing the reliability of today's grid, these control strategies need to be tested in simulated Smart Grid scenarios first. A simulation concept to enable an easy and straight forward creation of such virtual Smart Grid scenarios shall be developed in the work presented here. This work contributes to the efforts for creating the *mosaik* Smart Grid simulation framework that is currently being developed at the OFFIS.

## 2 Motivation

In the past few years, different control strategies for DER have been developed by a number of institutes and companies. Also at the OFFIS and the University of Oldenburg, control strategies and simulation models for evaluating these strategies, have been developed. The models have been implemented independently of each other and without interoperability in mind. As the very first control strategies have focused on the control of homogeneous classes of DER, such as solar-panels or electric vehicles (EVs), this approach was sufficient to evaluate the strategies. Since then, the focus has moved to the development of control strategies that can manage heterogeneous DER and loads, as well as to a more grid centric view, using a topological grid model and keeping an eye on the assets operation limits. All of this imposes new challenges on the control strategies making an evaluation insufficient that is using homogeneous types of DER only. To allow the evaluation of these next generation control strategies, this work will provide an easy to use and straight forward concept for building a virtual testbed based on modeling and simulation technology that allows to combine existing and validated as well as new DER, load and power grid models that still have to be developed. Currently this is not easily possible, since:

- different simulation platforms are used
- the simulation models do not have interfaces that allow combination with other models (control- and data-flow is not accessible from outside the simulation platform)
- the simulations may have different resolutions and fidelity (e.g. 1-phase, 3-phases)
- the simulations include different, tightly coupled control strategies

To create such a virtual testbed for simulating Smart Grid scenarios different simulation models have to be composed to a single, executable simulation. Simulation composition according to [PW03] is the "capability to select and assemble simulation components in various combinations into valid simulation systems to satisfy specific user requirements". For Smart Grid simulation and control strategy evaluation the specific user requirements include the topology of the power grid to be used and the position and type of DER and loads in this topology. A concept that allows the specification of these requirements as well as the automatic composition of simulation models will be the main contribution of this work. This is an alternative approach to monolithic tools developed by [CW09] or [KH09] which are not designed to compose existing, heterogeneous simulation models to form a complex Smart Grid simulation. The latter, however, offers benefits as each model can be implemented using the best platform for it's purpose, existing, well-known and validated models can easily be reused and also third-party models can be considered.

The research questions that are to be answered within this work are as follows:

1. What abstraction level and semantic information is required for the simulation models to facilitate automatic composition?
2. How can Smart Grid scenarios be described in a formal way that allows to compose the scenario automatically using available simulation models?
3. How can control strategies be evaluated using the simulated Smart Grid scenario (technically)?

## 3 Related Work

In literature different approaches are described for simulating complex Smart Grid scenarios. However, these are based on a single simulation platform making the integration of existing, validated and well-known simulation models difficult or may even require an error prone and time consuming reimplementation. Further, these approaches do not provide a standard compliant interface to the simulated DER, making it impossible to analyze the data-volume for communication or migrating control strategies to a production environment. HOMER is a tool for evaluating different designs of off-grid and grid-connected power systems [Lab11b, p.3] that has been developed by the US National Renewable Energy Laboratory. The user can add different power resources (e.g. wind turbines, CHP plants, diesel generators) to the grid and provide a range of parameters for these resources. HOMER then simulates the behavior of these resources for all hours in a year and for the different parameter combinations that are valid to explore the configuration space. The control strategies used by HOMER cannot be set by the user and it is not possible to integrate different models of power resources available in other simulation frameworks/packages into HOMER. Furthermore, as HOMER is an economic model, the electrical grid is not modeled in detail. [BGL$^+$04, p.2]
[KH09] have "analyzed, designed, and built a simulator based on software agents that attempts to create the dynamic behavior of a smart city." This simulation shall serve as a basis for further testing of DER management algorithms, business models and behavior analysis. The advantages are the possibility to observe and manipulate the behavior of single entities (opposed to simulations that only operate on static load profiles) and as such the evaluation of a broad range of control strategies. As the simulation platform is based on the JADE agent framework [Lab11a] and the Smart Grid, due to its dispersed and large-scale nature, promotes the use of agent based control strategies, these can be directly implemented with the same technology and thus tightly integrate with the simulator. However, the approach does not consider the integration of existing models but rather requires to model all entities of a Smart Grid scenario as JADE agents. Also, [KH09] do not mention any standard compliant interface to access the simulated devices. Furthermore, they do not mention how the scenarios are configured which in turn is a major part of this work.
GridLAB-D [CW09] is a powerful simulation tool for power systems developed by the Pacific Northwest National Laboratory (PNNL) in cooperation with industrial partners. It allows the specification of a wide range of scenarios. Besides evaluated models and algorithms for load flow analysis, GridLAB-D contains models of different resources such as transformers, household appliances or solar-panels as well as the possibility to add external models using sockets. However, compared to GridLAB-D, the concept presented here is designed explicitly for the composition of different, heterogeneous simulation models by using formal, semantically enriched descriptions of the models and a powerful scenario specification formalism, allowing to specify large scenarios with little code. Also, it will be explicitly designed to serve as testbed for control strategies by offering a standard compliant API (e.g. IEC61850, CIM) for these.

As a conclusion it can be said that no Smart Grid domain specific approach is known that allows the simulation of a Smart Grid scenario based on the composition of existing simulation models implemented on different platforms. Related work regarding simulation composition from other domains will be referenced in the chapters dealing with specific aspects due to the complexity of the topic.

# 4 Approach

[Tol10] gives an overview of different layered models for the simulation composability problem. The idea is to break down the problem into different, distinct layers to better deal with the challenge [Tol10, p.407]. [ZKP00] present a layered model for defining the architecture of a system which is comprised of six layers. The work presented in this paper is structured according to an adapted version of this model. The first two layers called *network* and *execution layer* contain the communication infrastructure and the communication protocols. As well-established solutions for the communication infrastructure exist, this layer has been left out. Layer 3, called *modeling layer*, describes the modeling formalism and the semantics of the models as well as their data. All models discussed by [Tol10] contain such a semantic layer as this information is essential to enable the automatic composition of the simulations. The Levels of Conceptual Interoperability Model (LCIM), also introduced by [ZKP00] can provide further structuring for this level. However, it has not been analyzed in detail, yet. The 4th layer introduces architectural constraints for the overall system. As an architectural discussion is not within the scope of this work, this layer is left out. The 5th layer, called *decision layer*, applies the capability to select and execute model sets to support what-if analyses. For control strategy evaluation, the scenarios define such a what-if case and therefore, this layer is seen as the scenario specification layer. Finally, the top most *collaboration layer* shall allow experts - or intelligent agents in support of experts - to introduce viewpoints and individual perspectives on the system [Tol10, p.410]. In this work this layer is seen as the API for the control strategies as these analyze and manipulate the system at runtime. Figure 1 shows the original and the adapted model used in this work as well as the related research questions. The current findings for the concept, structured according to these layers, will be presented in section 4.2 after the domain specific requirements have been presented in the next section.

## 4.1 Requirements

The requirements analysis can be divided into 3 steps focusing on the Smart Grid scenarios and their building blocks. First, the analysis of existing models (4.1.1) will provide input for determining the required abstraction level and semantical information of the models (input for syntactical and semantical level). Next, the analysis of current and planned simulation scenarios (4.1.2) will provide the major input for the creation of a metamodel that allows to define the scenarios that are to be simulated (input for semantical and scenario level). Finally, an analysis of the control strategies that are to be evaluated allows

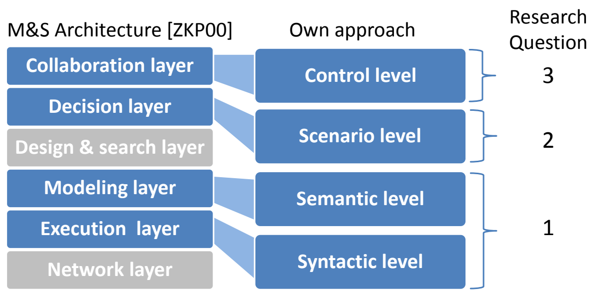


Figure 1: Adapted layer model according to [ZKP00]

the extension of the concept so that the controls strategies can be integrated as easily as possible. In the following, due to the scope of this paper, only the key aspects of the requirements are presented.

#### 4.1.1 Simulation Models

Currently, at the authors institute different DER models are available. They differ in resolution (different step sizes from 1 to 15 minutes), fidelity (e.g. simplified or regular 3-phase power flow), paradigm (continuous and discrete-event) as well as their implementation (Matlab, SimPy, Python). From this very first analysis of available and used simulation models different requirements can be identified that a simulation composition approach needs to offer. First of all simulations with different paradigms need to be integrated. However, as shown by [ZKP00, p.185] continuous simulation models can be integrated into a coupled simulator by wrapping them as discrete-event simulations. Thus, in the remainder of the work the focus is on the discrete-event paradigm, assuming the simulation models advance in predefined time steps. Taking a look at the heterogeneous simulation frameworks used, it becomes clear that a coupling/composition of models implemented on different simulation platforms must be possible. While these heterogeneity can easily be dealt with using available communication frameworks (may it be web services or other remoting frameworks), the different levels of fidelity are a substantial challenge for achieving an automatic composition as the fidelity information must (a) be available and (b) be interpreted correctly by the composition engine. A semantic annotation of the different models making the simulation engine aware of these differences in resolution and fidelity during composition is to be developed (see chapter 4.2.2).

#### 4.1.2 Scenarios

The models analyzed in the last section are the building blocks for the Smart Grid scenarios. The scenarios themselves need to be analyzed also, to find out how these blocks need to be combined. Here, determining the differences and similarities of the scenarios is essential to keep the concept for scenario specification as simple as possible while at the same time being complex enough to allow for the specification of a broad range of scenarios. Therefore, a number of scenarios from current and planned research projects have been analyzed. Figure 2 shows an example of such a scenario from a topological perspective.

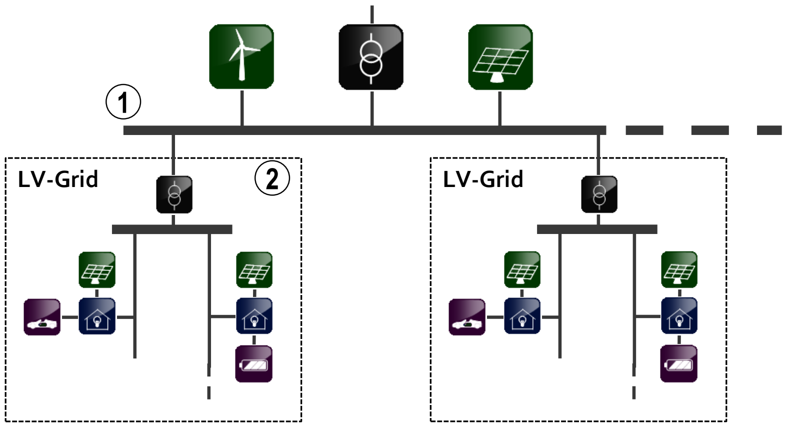


Figure 2: Example of a Smart Grid scenario

It shows a medium voltage grid (1) to which different renewable energy sources are connected. Furthermore, a number of low voltage grids (2) that are comprised of residential loads, solar panels and EVs are connected to the medium voltage grid. Different basic requirements can be derived from this scenario. First of all, models of consumers and producers (resources) are the building blocks of the scenario, which need to be connected to different nodes of the grid topology. Some resources (EVs) move through the grid. This means that the connection point of these resources depends on some of their attributes (e.g. the EV location). It also has to be considered that some resources may only occur in groups, for example solar-panels may only be mounted on top of a house. Further requirements are related to the size of the scenarios that need to be specified. To handle this, a random distribution of the resources within a grid topology needs to be possible. Also certain patterns occur often in larger scenarios (e.g. use lv-grids to build a mv-grid scenario). For such cases it shall be possible to capture these patterns as scenarios and (re)use these hierarchically, i.e. as building-blocks for larger scenarios.

#### 4.1.3 Control Strategy Integration

The scenario shown above only focused on the physical structure of the Smart Grid. However, control strategies for all kinds of power grid resources starting from a circuit breaker up to a pool of several thousand electric vehicles are the major components that distinguish the vision of the Smart Grid from today's less controlled power grid. Therefore, the Smart Grid simulation framework needs to offer a corresponding API that allows to use it as testbed for the control strategies. The control strategies themselves will not be part of the framework, as these strategies will differ strongly regarding technology and structure. The same is true for the metrics used to evaluate such a strategy. These will have to be specified by the user and calculated using logged simulation data once the simulation has finished. Figure 3 depicts this separation between the simulated Smart Grid components (physical topology) and the control strategies (information topology). As the current research at the OFFIS focuses on agent based control strategies, the requirements for integrating these are to be considered in particular. Different organization forms for agent based systems exits [HL04]. The information topology in figure 3 shows an agent based control strategy using a hierarchical organization form. The question here is how do the agents find the resources they are related to? Therefore, the agents need to query the physical topology which can be split into two parts: The relation between entities of a simulation model (e.g. between a bus and a branch in a power grid model) are defined within the model, the relations created by composing the models into a scenario are established during the composition (see 4.2.3) and thus outside the models. The framework shall offer an interface that abstracts from these differences and offer a homogeneous view for the agents. Finally, the API shall offer a standardized way for the agents to communicating with the simulated resources, e.g. based on the OPC Unified Architecture [Roh10, p.24] and the Common Information Model [Usl09, p.43]. Such an approach will facilitate migration and interchange/comparison of control strategies. The idea is to build a standard specific mapping upon the semantic information of the models so that an automatic generation of standard conform interfaces is possible.

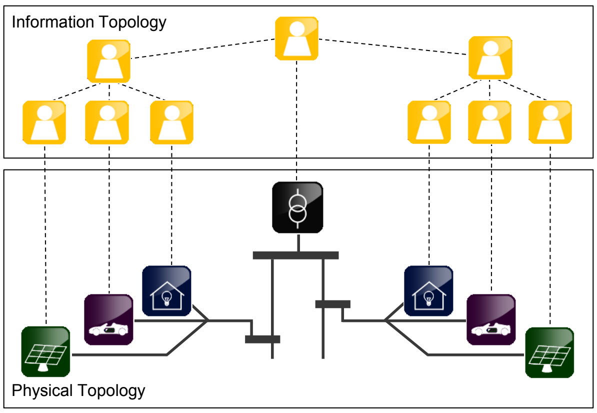


Figure 3: Smart Grid simulation as testbed for agent-based control strategies

### 4.2 Simulation Composition

In the following sections current ideas for a composition concept, structured according to the different levels introduced in the beginning of this chapter (see figure 1), are presented. The control level has not been analyzed yet and will therefore not be part of this paper.

### 4.2.1 Simulation & Model Interoperability (Syntactical Level)

The syntactical level is the lowest layer, determining the possible interactions with the simulation models. Therefore, a suitable abstraction level has to be chosen that allows the integration of a broad range of simulation models as well as sufficient flexibility and detail for using these in different scenarios, while at the same time being as simple as possible to minimize integration effort. For discrete event simulation models, which we focus on in this paper (see 4.1.1), the lowest reasonable abstraction level would be the DEVS formalism introduced by [Zei76]. Although such a low-level abstraction provides maximum flexibility it has several disadvantages:

- Model integration is difficult and error prone
- For the identified Smart Grid scenarios such a low abstraction level may not be required (see related works below)
- Integration of models implemented with COTS simulation packages is a requirement, however, such simulation packages are usually not "open" (i.e. not allowing to apply the DEVS level of detail)

Regarding the last point, [Boe05, pp.151] did extensive research upon distributed simulation in industry and defines three different levels of "openness" of COTS simulation packages "fully open", "partly open" and "fully closed". A fully open simulation package is a simulation package that allows access to all entities and their attributes at every step in time. [Boe05] states that according to this definition most of the available simulation packages are only partly open. [Boe05] therefore also uses a higher abstraction than the DEVS formalism, leaving out elements such as the event calendar and only focuses on the entities and their attributes. [ZPO$^{+}$05, p.3] use the same abstraction level since their approach for oil reservoir performance forecasting is also based on existing software and thus is "not concerned with modeling the internal structures or implementation of the building software components." Instead they "only capture the interfaces [of the components] each of which can be characterized with a set of input signals and a set of output signals". For the concept that is to be developed such an abstraction level will be used. Thus, for being integratable into the concept a simulation must simply offer an interface that allows to set and get model data for the current time step. For keeping the simulations synchronized they have to offer a *step* method, causing the simulation to advance a predefined timespan. By taking this black.box perspective, the composition concept can abstract from the internal simulation paradigm of each model. Interactions between the simulated entities will be implemented within the control strategies (see 4.1.3). For the current and anticipated scenarios analyzed during requirements this approach seems sufficient.

### 4.2.2 Semantic Description of Simulations and Models (Semantic Level)

On the semantical level, information about the structure (contained models and their entities) and characteristics (possible step sizes, available configuration parameters, etc.) of a simulation as well as the in- and outputs of the simulated entities will be formally described. Sufficient information about the latter will be key for enabling an automatic composition based on the scenario description presented in the next section. Required semantic information for this problem can be derived from the analysis of existing approaches such as [GG05], [Mor08], [Org06] and [BAV07]. These semantics are related to the simulation-domain in general and describe aspects such as the update interval (when is an output updated), the availability of output data (every step or only when the update occurs), the time dimension (for what timepoint/-span the data is valid) and information about units and data types. However, before this semantic information can be applied, mappings between in- and outputs must be established. This shall be made possible by using a common, domain-specific reference model containing possible dataflow types such as powerflow, sun radiation and so on, which have to be used for describing an entity's in- and outputs. Furthermore, the annotation of domain-specific attributes for each in- and output of a certain dataflow type will allow to specify invariants, i.e. conditions that in- and outputs must meet to be connectable. This way, for example, it can be prevented that a DER for the low-voltage level is connected to the medium-voltage grid or that a DER having a 1-phased powerflow is connected to a grid using a simplified 3-phased powerflow although the latter could have the same syntactical structure (e.g. a float indicating the powerflow in Watts).

#### 4.2.3 Scenario Definition (Scenario Level)

In literature, most approaches dealing with simulation composition only touch the scenario definition mechanism [BAV07][KH09], use very complex [Mor08] or invasive approaches where the scenario specification impacts all simulation components [TO10, p.9]. The scenario specification concept developed in this work shall be non-invasive and thus located outside the simulation models that are to be composed. This will be achieved by using a formal scenario description (in the following called scenario metamodel) that, in combination with the semantic information about the simulations and their models, can be interpreted by a central composition engine to instantiate and execute the models so that the overall scenario is being executed.

In [Sch11] a first prototype for scenario metamodel, implemented using a domain specific language (DSL), has been presented. Although it could be successfully applied in a current project and already supported the definition of resource groups (see 4.1.2) and large scenarios by allowing random distributions of resources in the power grid topology, it had several drawbacks. For example, the dataflow was limited to the powerflow between nodes in the power grid and the connected resources. Other model relations were not possible as this dataflow was hard coded in the simulation engine based on a very simple semantic annotation of the in- and output data. Another disadvantage was a missing lack of detail in the model description. A model represented a single, real life entity. However, a power grid model may contain a number of different entities such as cables, transformers and so on. Nonetheless, it could be shown that the use of a DSL for implementing the scenario metamodel as well as the semantic annotations of the models is easy to understand and to apply. Also, the implementation was straight forward using the Xtext [BCE$^+$10] framework.

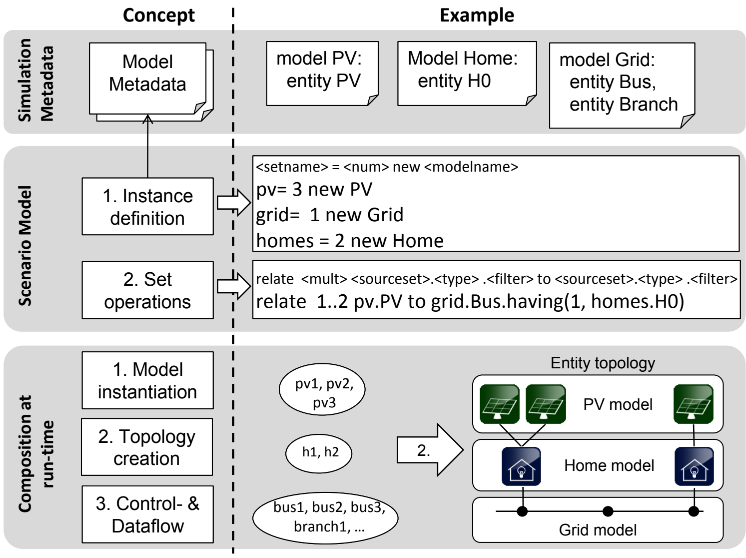


Figure 4: Set based approach to scenario definition

To overcome the limitations mentioned above, a new metamodel has been developed that uses a more generic approach based on set-theory. Figure 4 depicts this new approach showing the conceptual steps (left) and a concrete example (right). Based on the semantic description of the available simulation models the scenario consists of two basic sections. First, models are instantiated each resulting in a set of possibly heterogeneous entities (pv, grid, houses in the example). Each entity set contains all objects that are part of the instantiated model. For example, the set of the *Grid* model contains different *Bus* and *Branch* entities. Next, the scenario developer specifies relations that put certain entities of two sets into relation when the semantic information of the entity's in- and outputs allows this. The result is an entity topology as shown in the lower right part of figure 4. The key to allow the creation of complex scenarios is the combination of different subset operation for the relation operations. For each set the type of entities that is to be related can be selected by ID or indices (e.g. only the first 10 houses are used) and the existence of certain other relations can be checked. In the given example, for instance, the *PV* entities are only connected to those *Bus* entities of the grid which have a connection to a *H0* model. This implies that those connections that are a precondition for others are established first, creating and implicit order of the relation operations. However, this order shall be established by the simulation engine and not by the scenario developer. In addition, it is possible to specify an allowed multiplicity for the entities of the left hand set of the operation. So each relation operation leads to a n:1 relation between the entities. For each entity on the right set n entities are chosen randomly from the left hand set. However, by allowing to select entities with a certain ID specific relations can also be created. It is important to understand that the models will not be instantiated during scenario specification. But based on the semantic information about the models and their entities, the description of topological relations will be possible. As a consequence, when the ID based entity selection has to be performed, a predefined set of IDs will have to be provided, assuming that the IDs will either be given in an index based fashion (e.g. EV1..EVx) or be based on a model configuration (e.g. a power grid model may get the ids from a CIM topology definition so that the IDs are fixed for each entity, as described in [Sch11]). To enable hierarchical scenario definitions, scenarios can also be instantiated and their entity sets can be accessed from within the parent scenario. If the semantic information of the models indicate different resolutions the user will be forced to specify aggregation or extrapolation functions to overcome this mismatch.

## 5 Conclusion

In this paper the need for a Smart Grid simulation framework for the evaluation of control strategies, based on the composition of existing simulation models, has been motivated. The work presented here will not cover the complete development process of such a framework but rather focus on the development of a concept for the automatic composition of simulation models based on a formal scenario description. First requirements for such a concept as well as an approach for the scenario definition have been presented. These requirements will need to be elaborated in more detail and formal rules for data-matching and controlflow creation will be defined. A first prototype demonstrating that such an automatic composition is possible with this concept will have to be developed and evaluated.

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