Structured Planning of Hardware and Software Co-simulation Testing of Smart Grids

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Abstract: The traditional electricity grid is ought to become a smart grid. One reason is the integration of volatile renewable energy generation, which poses the demand for advanced communication and control technology. This results in a change of the overall system dynamics, which in turn require testing to be done in early stages and with a more holistic approach. However, there is a gap in the transition from system specification and static analysis to an experimental setup validating these specification. This paper demonstrates first steps towards a structured methodology for deriving validation experiments for smart grids from initial system requirements. Our approach aims to fill the introduced gap by integrating Smart Grid Architecture Model (SGAM) for static analysis, Holistic Testing Description (HTD) for experimental analysis, and additional tools in a new workflow. Initial assessment of the workflow has been validated on its ability to select the most suitable components and test beds to perform an experiment. Therefore, two case studies were selected, one in the electricity power domain and another in the electricity market domain.

1 INTRODUCTION

The new power grid consists not only of physical electrical equipment (e.g., transformer, cables, etc.), but also Information and Communication Technology (ICT) and the automation of these equipment adds new domains and dimension to the complexity of this system. The main reason behind the integration of these technologies is the introduction of decentralised generation resources and renewable energy in the efforts to dramatically reduce energy sector emission levels. These new concepts of energy generation require constant monitoring and prediction, as they are intermittent, weather dependent, and have limited storage capacity. Due to their flexibility and the dynamic of the grid, communication and control systems as well as new electricity market options need to be tested at earlier stages.

This evolution transforms the traditional electrical grid to a smart grid. This grid has physical devices transferring power and software administrating the interaction between them. The emerging Cyber Physical Energy System (CPES) in hand comprises of different disciplines and mixed technologies. A complex configuration, as described, demands testing the integration of its constituents on a system level, not only testing of certain aspects of it, addressing all relevant domains. Moreover, the testing procedure is required to follow a multi stage process alongside development, and before roll out (Van Der Meer et al., 2017). A well established approach for the analysis of smart grids and the development of its components is the use of simulations (Hartmann, 2009). These simulations may be purely software based (Schloegl et al., 2015) or can contain a real hardware setup (Nguyen et al., 2017).

Despite the readily available tools for testing and validation, developing a test for this complex system is an issue of forming a clear test objective, besides a specific and relevant multi domain test environment (Blank et al., 2016). Test standards usually developed within specific context of a scientific or technical application. For example, organisations within automotive, thermal systems or electric power domains each identify and maintain their specific standards, test requirements, protocols, and test environments (Heussen et al., 2019). However, multi domain testing requires integration of a more fragmented knowledge, which has been addressed in the context of the Eu-

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ropean ERIGrid project (Mäki et al., 2016; Heussen et al., 2019; Van Der Meer et al., 2017). Thus, the disciplinary and methodological framing of experiments is becoming a challenge itself, especially when forming a ”holistic” test objective and designing experiments for this objective.

The aim of this paper is to propose a workflow for simulation experiments that reduces the gap in the transition between specification and static analysis of a complex system on one hand, and operational testing on the other hand (see section 3). This approach is built upon integrating wide range of tools and knowledge developed in the literature, taking into consideration the increased number of stakeholders involved and their business opportunities (see section 2). In section 4, two case studies are presented for evaluation of the workflow on experiments applied in different domains of the smart grid. Finally, the contribution is concluded and ideas for future work are elaborated in section 5.

2 FOUNDATIONS AND RELATED WORK

The approach presented in this paper bases on different tools and methods, which will be introduced in the following. We will give a brief introduction to the concept of co-simulation in section 2.1 and to the Holistic Testing Description (HTD) procedure in section 2.2. An overview of the Smart Grid Architecture Model (SGAM) and its corresponding utilisation from a use case description is given in section 2.3. Approaches for simulation planning are summarized in section 2.4. Finally, electricity market mechanisms testing is briefly discussed in section 2.5.

2.1 Co-simulation

As components in smart grid are highly interconnected, test cases quickly become too complex for pure analytical handling. Therefore, simulation based experiments are important intermediate step for the validation process (Steinbrink et al., 2018). As simulators have been developed to cover only one research area or domain, simplifying the effect of other connected domains, co-simulation has been developed, which consists of multiple simulators coupled together by a software interface. Each simulator may cover a different aspect of the smart grid. Together, the simulators allow researchers to analyze complex interactions and dynamics in more detail (Vogt et al., 2018).

Co-simulation consists of independently developed and implemented simulation models. Thus, each simulator has its own solver and works simultaneously and independently on its own model. The coupled simulators dynamically interact through their model’s input and output variables, so that the outputs of one simulator become the inputs of the other and vice versa (Palensky et al., 2017). The synchronisation and execution process is controlled during runtime by a master algorithm that orchestrate the simulation.

The concept of co-simulation does not only focus on pure software simulation. The setup might include hardware and software interaction as in Hardware-in-the-Loop (HIL) experiments. In this approach, a real hardware setup for a domain (or part of a domain) is coupled with a simulation tool to allow testing of hardware components under realistic conditions. The execution of the simulator in that case requires strictly small time steps in accordance to the real-time constraints of the physical target (Nguyen et al., 2017).

2.2 Holistic Testing Description (HTD)

The project ERIGrid proposed a methodology, that can be used to plan experiments in smart grid context to account for multi domain systems and varied experimental platforms, nonetheless improving reproducibility of experiment results. This method is called Holistic Testing Description (HTD) (Heussen et al., 2019). The template-based approach consists of three main documents that abstract the test objective from the testbed. Each document gives a different view of the system, filling these documents in order gradually gives a more concrete view of this System Configuration (SC). These documents are as follows (Heussen et al., 2017; Van Der Meer et al., 2017):

1. Test Case (TC)
   The starting point of HTD procedure is defining a test case. The inputs are the Generic System Configuration ((G)SC) and its corresponding System under Test (SuT), which describes the system boundary in which the Object under Investigation (OuI) lies, a list of use cases that could be realised by this test object, and finally the test objective, which declares the Purpose of Investigation (PoI). From this, the Domain under Investigation (DuI) could be defined, additionally the use case description would help define the Functions under Test (FuT) and choose the Function under Investigation (FuI).
2. Test Specification (TS)
   After identifying the SuT and the OuI, the test specification template is of help in identifying

the concrete Test Specification System Configuration (TS-SC) which is more granular in respect of equipment number and specific connections. The test design and the input/output parameters are also identified in this stage.

3. Experiment Specification (ES)

   The final stage is to map the testing requirement and the SC to a testbed or collection of testbeds in an integrated experiment, describing its configuration. It is important to be noted, that the test system is separated from the experiment realization, which could allow the test system to be realized on separate testbeds.

The mapping procedure, that realizes the test description on a testbed, can be semi-automated as suggested by (Heussen et al., 2019). This can be achieved by developing a database that stores information objects about test laboratories and co-simulation software as assets, and a method for selecting the appropriate tesbed and its integrated component for test realization according to the test objective and test developer requirements.

The database will give information on the available testbed components and their connection possibilities. The selection method describes a two-stage process for deriving an experiment implementation from a given test specification. During the process the test developers are asked to assess the degree of precision to which the experimental setup needs to replicate various aspects of the test specification (e.g., grid topology, communication system, static and dynamic parameters), by examining each aspect (component or sub-system) of the test system and assigning one of four different precision levels to it:

Precise. The respective component has to be matched 1:1 (real hardware).

Equivalent. The respective component has to be matched equivalently in a dedicated software simulation tool (e.g., grid topology modelled in PowerFactory), or emulation based manner (e.g., communication network emulator, real time electric grid simulator, etc.)

Nominal. The respective component can be matched in a software based manner with some deviations, but they should only lead to marginal influences on objective and results (e.g., CSV file time series of a household load, storage module that can be used as heat or electricity storage)

Irrelevant. The respective system aspect does not influence the test objective and results.

The result of the assessment phase is pairing each system aspect with a precision category. The assessment can be used to communicate the fixed implementation requirements of a test and to prioritize the rest of the system aspects. These constraints, together with the prioritization, enable an iterative search of the database. Consequently, the above mentioned suggestion is applied in our approach as the core of our assisted testbed mapping procedure.

2.3 SGAM

In order to enable the seamless interaction between automation components across all sectors of the new smart grid the Gridwise Architecture Council (GWAC) introduced the concept *interoperability* to the electric power infrastructure (GridWise Architectural Council, 2008) by defining a framework consisting of eight interoperability categories. This will result in a more cost effective integration of new components, easier system update and replacement (CEN-CENELEC-ETSI Smart Grid Coordination Group, 2014).

According to the GWAC, architecture is the next category after a framework, ”architectures are the blueprints for solutions addressing the issues identified in the framework”. It is the right path towards more specific solution but also neutral regarding technology (CEN-CENELEC-ETSI Smart Grid Coordination Group, 2012b). Accordingly, the Smart Grid Architecture Model (SGAM) condensed the eight interoperability categories into five layers. Each layer is applied on the power grid, which has a hierarchy of automation functionality (Neureiter et al., 2016).

2.3.1 Interoperability Layers

The five SGAM layers represent the first dimension of this three dimensional architecture model, and are described as follows (CEN-CENELEC-ETSI Smart Grid Coordination Group, 2012b):

Business. The business layer represents the business view on the information exchange related to smart grids. Regulatory and economic structures can be mapped on this layer. It supports business executives in decision making related to business models and specific business cases.

Function. The function layer describes functions and services including their relationships from an architectural viewpoint. The functions are derived by extracting the use case functionality, which is independent from actors.

Information. The information layer represents the information models, that are used to exchange information between functions. It contains information objects and the underlying canonical data models. These represent the common semantics for functions and services in order to allow an interoperable information exchange via communication means.

Communication. The communication layer is to describe protocols and mechanisms for the interoperable exchange of information between components in the context of the underlying use case.

Component. The component layer is the physical distribution of all participating components in the smart grid context. This includes system actors, applications, power system equipment, protection and telemetry devices, network infrastructure, and any kind of computers.

The other two dimensions reside on the smart grid plane as value creations chain (Domains) and automation pyramid (Zones) (Uslar et al., 2019) controlling the energy supply chain. The SGAM primarily provides a general reference in how to architect smart grids.

2.3.2 Mapping of Use Cases to SGAM

As software development is becoming an integral part of a smart grid architecture, methods from this discipline has been adopted for modelling smart grids; such as utilization of use cases for requirement engineering. Today, the *IEC 62559-2* Use Case Template is a broadly accepted structure for describing smart grid related use cases (Binder et al., 2019). A method for use case mapping to an SGAM framework is introduced in (CEN-CENELEC-ETSI Smart Grid Coordination Group, 2012b; Neureiter et al., 2016) and described in the following paragraphs.

The initial step is extracting information such as name, scope and objective, use case diagram, actor names, use case steps, information which is exchanged among actors, and functional and non-functional requirements. This information are ensured to be provided, if the use case template *IEC 62559-2* is used. Actors can be of type devices, applications, persons, and organizations. These can be associated to domains relevant for the underlying use case and mapped to the component layer. The business layer is intended to host the business processes, services and organizations which are linked to the use case to be mapped.

A use case consists of several sub use cases with specific relationships, these sub use case can be transformed to functions when formulating them in an abstract and actor independent way. The information layer consists of objects which are exchanged between actors and derived from the use case description in form of use case steps and sequence diagrams. The communication layer contains protocols and mechanisms for the interoperable exchange of information between the components.

2.4 Simulation Planning

While co-simulation and hardware experiments can be used for testing the dynamic behavior of the smart grid and the SGAM can be used for the static planning and evaluation of the smart grid, an integrated process combining these approaches would be beneficial. Based on the more abstract planning in the SGAM, concrete simulation scenarios should be developed, which allow more detailed testing.

Binder et al. have already worked on this challenge (Binder et al., 2019). The purpose of their contribution is to allow a quick repetition between the problem definition and the generation of code using specific toolchain methodology. The method adopted Model Driven Engineering (MDE) for automated and rapid code generation for simulation components. However, their approach focuses on the generation of code based on activity diagrams and does not support the integration of already existing simulation components.

In their publication (Uslar et al., 2019), the authors suggested that the SGAM view on the system could be considered as input information for the specification of HTD test cases. Thus, a new workflow could be realized that starts with an SGAM model and use case based representation of a desired smart grid setup and has test developers derive TCs from it, following the HTD until the experiment implementation, resulting in the validation of all crucial parts of the system.

A process for the simulation planning based on an information model and catalogs with available co-simulation components is described in (Schwarz et al., 2019). The information model describes the data structure for the modeling of a co-simulation scenario. The co-simulation components available for coupling in a scenario are collected in a catalog. This approach is implemented based on Semantic Web technologies. The information model is modeled as an ontology and the catalogs are realized in a Semantic Media Wiki (SMW). With the Page Forms extension for the SMW a form for the definition of components is build, which provides a questionnaire for new components. With the catalogs of simulation components, the development of co-simulation scenarios can be assisted, as described in (Schwarz and Lehnhoff, 2019).

2.5 Electricity Market Testing

Electricity market plays a crucial role for the future development of electricity grid. Thus, its testing is of high importance for the development and implementation of future technologies. But, electricity markets are different from place to place and even in the same region, it is possible to find different market approaches. (Barroso et al., 2005) provided an overview of electricity markets in 23 different countries, and despite its differences, they classified it considering:

Market Clearing Process: in power pool, bilateral contract or a mix of them.

Pricing Scheme: like single market price, nodal pricing or zonal pricing.

But a wide variety of market models and arrangements can be found. Therefore, to derive a market experiment, a proper definition of the roles of the players involved as well as the specific market type has to be defined. This section will provide some hints about how SGAM and HTD methodologies can be used to perform different electricity market tests.

According to the Smart Grid Reference Architecture technical report the interoperability between different actors in the electricity system, is essential to facilitate a smart market (CEN-CENELEC-ETSI Smart Grid Coordination Group, 2012b). They define a smart market as the environment in which energy products and services are freely traded by many market actors.

SGAM uses actors, which represents trading platforms, for electricity and other electricity products like grid capacity or ancillary services, to defined market testing. SGAM is also partitioned into hierarchical zones, that model the information management of the electrical process. The operation zone in SGAM, coordinates the activities in the market zone to ensure the safety and stability of the grid. Three areas for energy services are considered: Energy Market (Commodity), Grid Capacity Market, and Flexibility Market (Imbalance). (CEN-CENELEC-ETSI Smart Grid Coordination Group, 2012b).

On the other hand, HTD clustered markets in two areas: Energy Markets and Ancillary Services. The components are actors with particular roles like: BRPs, market operators, retailers, aggregators, among others. The business models, market structures, and rules are considered as domain related constraints. In addition, a purely market perspective as OuI is not the main focus of HTD.

Markets (including the stakeholders role) and enterprise zones in HTD, are more related to the ICT domain, in particular consider Information Technology (IT), in which the components are functions aimed at guaranteeing power system stability or energy balance according to the SuT.

Therefore, to test markets, the roles and system actors need to be inline for a common understanding of all parties. The Harmonized electricity market Role Model (HRM) was chosen for most of the cases (also referenced in SGAM) performed by ENTSO-E (ENTSO-E, 2019a), in which an actor represents a party that participates in a business transaction, and a role is considered as the behavior of an actor or the activities of the actors. This definition was also followed for the market testing presented in this paper.

Finally, both methodologies can be used to describe an electricity market test, but so far they have been focusing more on IT (communication devices and control components) than electricity transactions like bidding process or marginal cost calculations. (Do Prado et al., 2019), highlighted the necessity of new business models to ensure operation optimization, flexibility, customer integration, and sustainability to promote markets liberalization. For this reason, we propose a way of mapping the electricity market test as part of the structured planning of a co-simulation.

3 APPROACH

The identification of suitable model and components for a co-simulation setup is still a challenge for experiments in co–simulation testbeds. The possibilities to re-use components or models, or even to reproduce the same experiments when sometimes models differ on their abstraction level increase this challenge (Heussen et al., 2019). Our approach implements a simulation planning mechanism using the concepts summarised in section 2, that can help in the identification of the most suitable components or models to run the desired experiment. Additionally, it suggests a workflow that can lead to seamless transition between modelling of a system specification and the simulation setup validating this system. This flow is semi-automized in order to assist the test developer in building the most suitable validation experiment, enhancing the practicality and reducing the time required in filling the HTD template based documents.

The proposed process is described in detail in section 3.1, while its technical integration is shown in section 3.2.

3.1 Process

An overview of the proposed process is depicted in figure 1. It shows the integration of HTD and SGAM

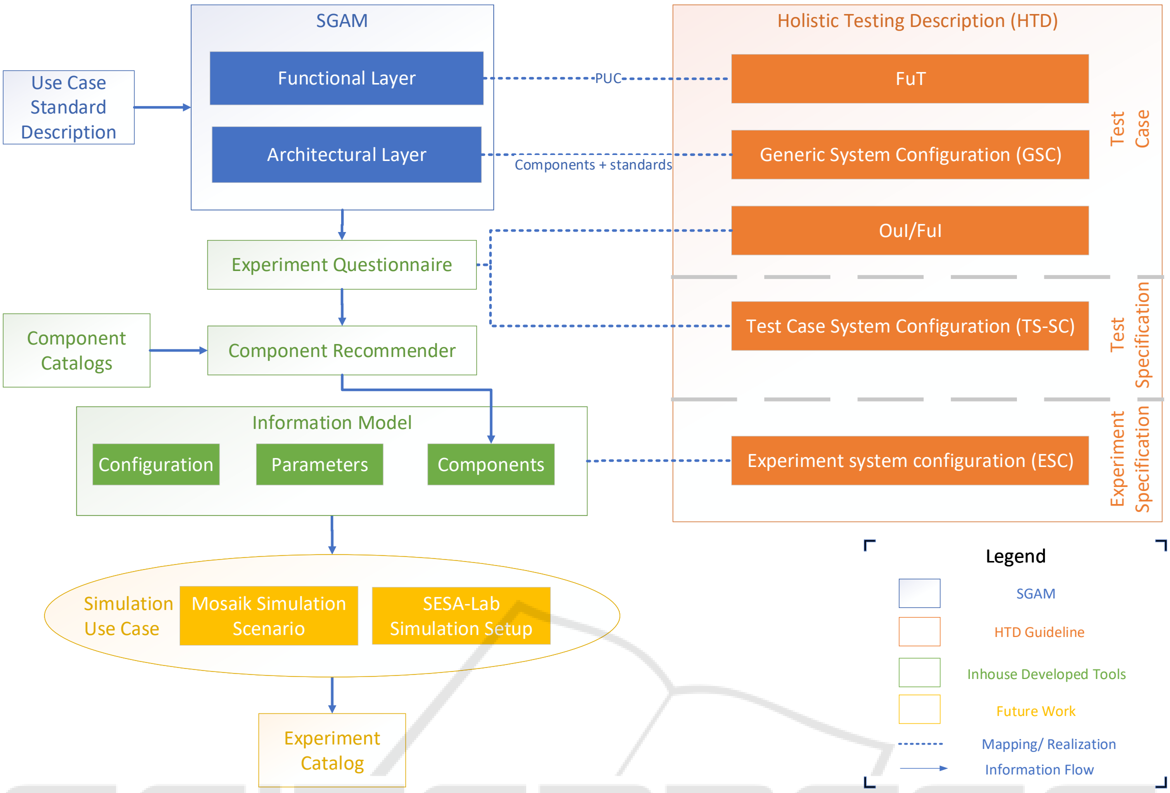


Figure 1: Overview over the process and its alignment with the HTD.

(*blue and orange boxes*), which is described in section 3.1.1. How this integration can be assisted by questionnaires and catalogs (*green boxes*) is introduced in section 3.1.2 to 3.1.3. Finally, the modeling of a concrete experiment (*green boxes*) is described in section 3.1.4 and the execution in 3.1.5 (*yellow boxes*).

3.1.1 Integration of HTD Test Case and SGAM

The key aspect of this workflow is the HTD methodology. The workflow is aligned with the methodology and uses it as a guideline in its three stages described in section 2.2. Following the procedure described in section 2.3.2, use case description and its corresponding mapping to the SGAM plan is the initial step towards modeling of a certain smart grid architecture according to the requirements imposed by the use case description. From an HTD point of view, this system architecture can be considered as GSC.

Generally a use case description that describe the system's main functionality could be decomposed into several sub use cases as mentioned in section 2.3.2. These granular Primary Use Cases (PUC) (Neureiter et al., 2016) are transformed to functions and a collection of them can be selected from HTD prospective as FuT. Accordingly, the initial steps of developing the first stage of test case is achieved by modelling of a system in SGAM and extracting PUC as FuT.

3.1.2 Experiment Questionnaire

To document the system configuration as well as the system specification, an experiment questionnaire has been developed. This questionnaire is subdivided in a part with general questions and different subsections for specific domains (e.g., elecricity grid, control, market, thermal, and ICT). Thus, it can be used flexibly depending on the domains to be considered. The questionnaire helps also in selection of suitable components to run a test.

The system has been described in its generic form, the test developer has to define the SuT. This is realized by the questionnaire the user has to go through in order to give a closer look at the boundary of the SuT with its constituent components and numbers, especially the OuI. The questionnaire helps to define test case and test specification terms such as DuI, OuI and its corresponding FuI, a concrete PoI, and temporal resolution. The output of the questionnaire represents the domain independent TS-SC.

Domain Specific Questionnaire for the Eletricity Grid. The supply of electricity is done through multiple stages and different voltage levels. It is important when developing a test on an electrical equipment, to know its position in the supply system and the working voltage level. The questionnaire is dividing the grid to areas such as generation, transmission and distribution. Some tests also need grid data that simulates realistic grids, but data from real grids is usually not public. Therefore, benchmark grids exist in order to test certain developed methodologies and the questionnaire contains a database of these benchmark grids to choose from.

Domain Specific Questionnaire for the Electricity Market. Considering that markets can create opportunities for innovative business or solve grid problems, electricity markets can be designed as engineering tools, based on simulations (Ringler et al., 2016). Therefore, a section in the experiment questionnaire deals with the electricity market to determine the current regulatory framework, based on the following attributes:

Market Organization. It considers how the electricity market is organized like: Power pools, bilateral contracts, or a mix of them. In addition, it asks for the type of scheduling (central or self) and the contract's capability to influence price formation (physical market contract or only financial market contract).

Pricing Structure. Considers if the market model, for the particular study calculates nodal prices or zonal prices

Trading Time Frame. Scheduling, like day ahead, intraday and real-time market. But depending on the simulation, there are some models that focus more on long-term (one to several years ahead), medium-term (a week ahead up to two years) and short-term (a week to a day ahead), for the market planning or expansion analysis.

Capacity Allocation. Considers how much space can market participants use on cross border lines by keeping into consideration the grid topology. Considers if the regulation asks or not for a congestion management.

Actors Involved. Allowing the selection of the actors in the current regulation, based on the HRM (ENTSO-E, 2019a).

The Focal Use Case Collection. (Rossi et al., 2016) and the challenges for the retail market according to (Do Prado et al., 2019).

This categorization was elaborated to fit the different markets types and use cases found in the literature (CEN-CENELEC-ETSI Smart Grid Coordination Group, 2012b; Uslar et al., 2019; Mäki et al., 2016; CEN-CENELEC-ETSI Smart Grid Coordination Group, 2012a; Rossi et al., 2016). Considering that a market test requires knowledge of the condition of the electrical grid, when a market test is planned, the questions regarding the required precision of the grid components for the models as well as the grid topology are asked.

3.1.3 Component Catalogs

Up to this stage, the developed system is independent from any testbed environment. In theory, it could be realized on any test environment. This separation of test description and its realization on testbed aligns with the HTD methodology. In order to realize the test system on a test environment, component catalogs for hardware and software objects have been developed to give an overview of the availability of components on certain testbed. In our case, these are the in house environments such as co-simulation framework mosaik (Steinbrink et al., 2019), or SESA-Lab (Büscher et al., 2015). The catalog collects many different categorizations of the components, as described in (Schwarz et al., 2019). The type of components were defined based on the documentation from ERIGrid (Mäki et al., 2016, p.32ff.), which contains a list of different domains, areas, levels, components, and attributes.

The recommendation process of the components is conducted using the assessment criteria presented in section 2.2 and a component recommender querying the suitable components according to their precision level, accordingly the testbed environment is chosen that contains components fulfilling the requirements presented in the assessment phase. Examples of this are given in section 4.

3.1.4 Information Model

The ESC has to describe the detailed system configuration for a test. To do this in a structured and machine readable way, an information model (Schwarz et al., 2019) is used, which allows to model data flows and parameters of simulation components. Due to its ontological implementation the content of the information model is available for querying, which can also be used for validation of a scenario (Schwarz and Lehnhoff, 2019). For the modeling of hardware components the information models was extended with additional modeling options for the inputs and outputs and the topology of the power system.

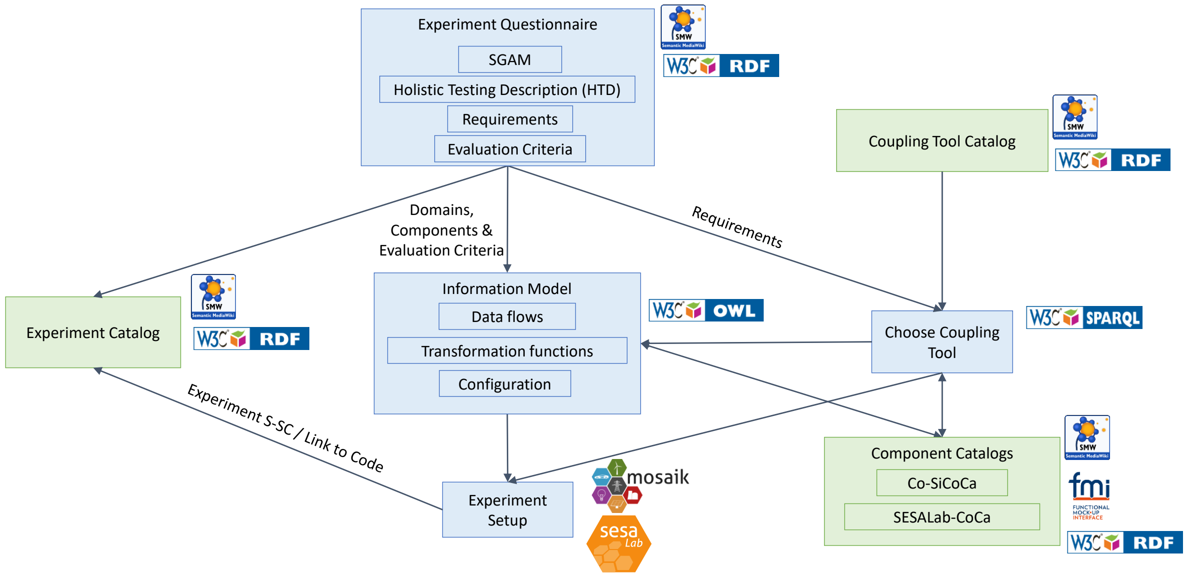


Figure 2: Technical Integration Diagram.

3.1.5 Simulation Execution

The development of an executable co-simulation scenario is usually done manually. But based on the described previous steps with a formal modeled scenario based on the information model, the automatic generation of the executable software co-simulation scenario would be possible and will be future work. For the execution of a hardware co-simulation the information model and the filled out experiment questionnaire could provide a setup for the manual implementation of the experiment.

3.2 Technical Integration

The technical implementation of the proposed process is shown in figure 2 with the used technologies. The starting point is the experiment questionnaire in a SMW, which represents the SGAM and HTD and also asks for requirements and evaluation criteria of the experiment. The filled out questionnaire is stored in an experiment catalog in the SMW to make it available for reuse or comparison of experiments. The domains, components, and evaluation criteria identified in the experiment questionnaire can be exported as RDF from the SMW, so that a direct integration in the information model is possible.

Based on the requirements, which can be deduced from the experiment definition, the user could also be assisted in choosing a suitable coupling tool, e.g., mosaik or the SESA-Lab. For this purpose, a questionnaire for coupling tools has been developed in the SMW, which makes the characteristics available for querying with the Semantic Web query language SPARQL. Especially, the decision between a pure software co-simulation or an integration of hardware, can be assisted based on the chosen precision levels of the components.

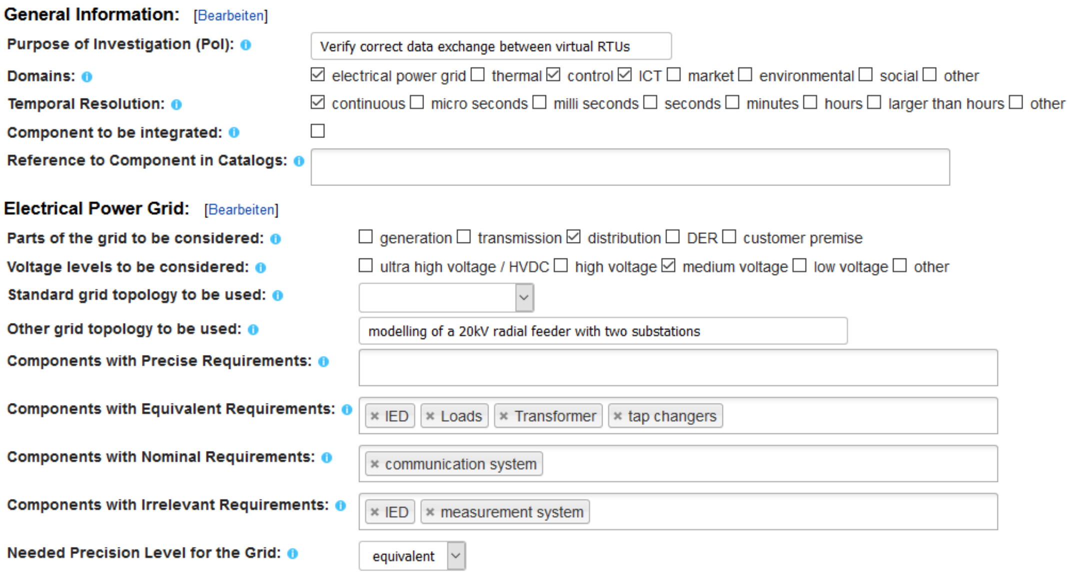
Based on the information model, the chosen coupling tool, and the component catalogs in the SMW the user can get recommendations of suitable simulation components for his experiment and an executable software or hardware co-simulation scenario can be build. In the future, the automation of this process step will be further investigated.

4 EXAMPLES

To evaluate the applicability of our proposed approach, suitable case studies representing a typical energy system example have been created. The first case is to test a new tool, that emulates the behavior of a real component in the distribution grid. The second case study presents a market model simulating a trading platform for energy flexibility.

4.1 Voltage Regulation on a Distribution Feeder

In the document (CEN-CENELEC-ETSI Smart Grid Coordination Group, 2012a) a list of systems that may form a smart grid has been presented. The aim of the document is to model smart grid systems or subsystems and investigate the missing standardization in information and communication interoperability. This



General Information: [Bearbeiten]
Purpose of Investigation (PoI): Verify correct data exchange between virtual RTUs
Domains: ☑ electrical power grid ☐ thermal ☑ control ☑ ICT ☐ market ☐ environmental ☐ social ☐ other
Temporal Resolution: ☑ continuous ☐ micro seconds ☐ milli seconds ☐ seconds ☐ minutes ☐ hours ☐ larger than hours ☐ other
Component to be integrated: ☐
Reference to Component in Catalogs:

Electrical Power Grid: [Bearbeiten]
Parts of the grid to be considered: ☐ generation ☐ transmission ☑ distribution ☐ DER ☐ customer premise
Voltage levels to be considered: ☐ ultra high voltage / HVDC ☐ high voltage ☑ medium voltage ☐ low voltage ☐ other
Standard grid topology to be used:
Other grid topology to be used: modelling of a 20kV radial feeder with two substations
Components with Precise Requirements:
Components with Equivalent Requirements: IED, Loads, Transformer, tap changers
Components with Nominal Requirements: communication system
Components with Irrelevant Requirements: IED, measurement system
Needed Precision Level for the Grid: equivalent

Figure 3: Experiment questionnaire for case study 1.

list is well exhaustive and contains three types of systems that exists in modern day electricity grid:

Domain specific systems: generation, transmission, distribution, distributed energy resources, customer premises (CEN-CENELEC-ETSI Smart Grid Coordination Group, 2012b)

Function specific systems: E.g., marketplace systems, demand flexibility systems, smart metering systems, weather observation and forecast systems

Systems that usually focus on administration features: E.g., asset management, clock reference, communication management, device management

For the evaluation of the presented process, a system configuration for automation of the functions on a feeder line in the electrical distribution grid has been chosen. This system is generic enough to contain a cluster of use cases that could be evaluated separately, additionally an already in-house publication (Ansari et al., 2019) that implemented a Test Case in this system's context has been developed. This makes the feeder automation system an ideal case for the evaluation of the suggested process. The developed in house test system investigates power quality regulation by applying this system's architecture.

Following the above suggested process, the system has been already modeled in SGAM as in (CEN-CENELEC-ETSI Smart Grid Coordination Group, 2012a) where the use case is chosen to be voltage regulation of the feeder. A list of PUCs is defined that collectively achieve this use case. From HTD perspective, SGAM modelling defines the generic system configuration GSC and FuT, a PoI is defined to verify the in-house developed virtual Operation Technologies (OT) such as virtual Remote Terminal Unit (vRTU) ability to emulate real RTU device functionality. The developed questionnaire helps define the SuT and give a TS-SC as shown in figure 3, additionally the selected components precision level will determine the experiment setup and the simulation environment suitable to fulfill the test requirements.

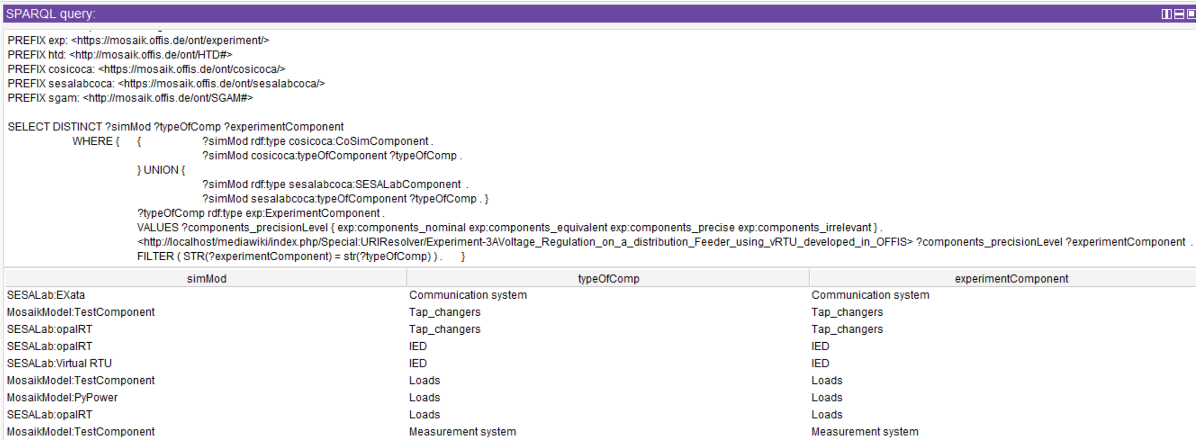
In this case, SESA-Lab was the suitable testbed for this experiment. The lab contains real time simulator (opalRT) of the electricity grid which aligns with the selected precision level requirements imposed by the test developer, as shown in figure 4.

4.2 Market Model Testing

Today's electricity market design requires evolution to fit new actors and new technologies (ENTSO-E, 2019b). Some solutions will need to evaluate the congestion management, inclusion of locational signals, visibility of the resources, trades close to real time, flexibility markets, among others.

For our market testing use case an active power flexibility trades scenario was created, in which the European electricity market was characterized (power pool price based). This use case idea was based on (Meibner et al., 2019) and (Uslar et al., 2019).

A generic market trading platform was created in our component catalog. This platform simulates local energy exchange to enable energy flexibility, that can significantly reduce network expansion costs. The SuT was modeled in SGAM. Only the market, enter-

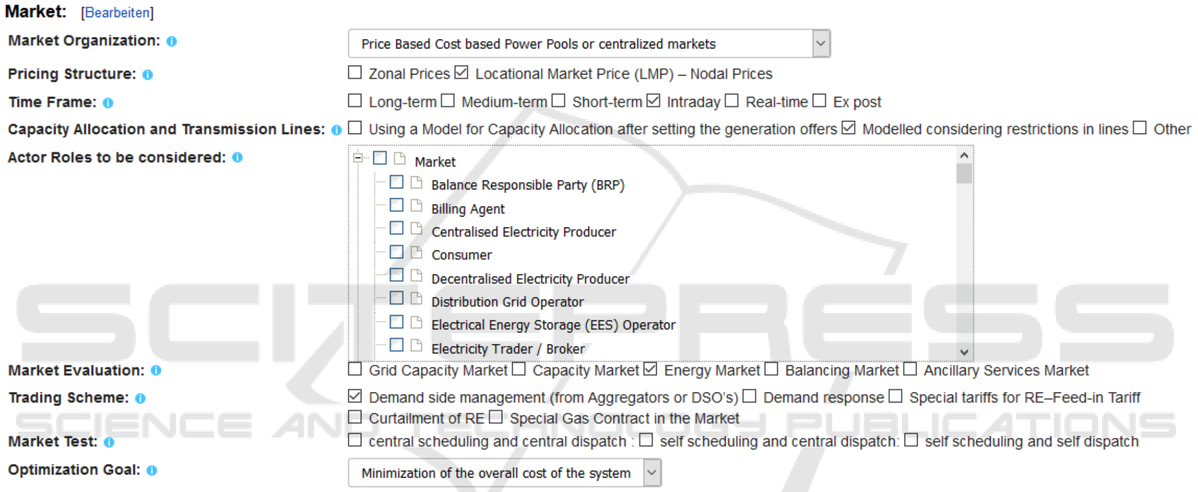


```
PREFIX exp: <https://mosaik.offis.de/ont/experiment/>
PREFIX htd: <http://mosaik.offis.de/ont/HTD#>
PREFIX cosicoca: <https://mosaik.offis.de/ont/cosicoca/>
PREFIX sesalabcoca: <https://mosaik.offis.de/ont/sesalabcoca/>
PREFIX sgam: <http://mosaik.offis.de/ont/SGAM#>

SELECT DISTINCT ?simMod ?typeOfComp ?experimentComponent
          WHERE {   {           ?simMod rdf:type cosicoca:CoSimComponent .
                                ?simMod cosicoca:typeOfComponent ?typeOfComp .
                    } UNION {
                                ?simMod rdf:type sesalabcoca:SESALabComponent .
                                ?simMod sesalabcoca:typeOfComponent ?typeOfComp . }
                    ?typeOfComp rdf:type exp:ExperimentComponent .
                    VALUES ?components_precisionLevel { exp:components_nominal exp:components_equivalent exp:components_precise exp:components_irrelevant } .
                    <http://localhost/mediawiki/index.php/Special:URIResolver/Experiment-3AVoltage_Regulation_on_a_distribution_Feeder_using_vRTU_developed_in_OFFIS> ?components_precisionLevel ?experimentComponent .
                    FILTER ( STR(?experimentComponent) = str(?typeOfComp) ) .     }
```

simMod	typeOfComp	experimentComponent
SESALab:EXata	Communication system	Communication system
MosaikModel:TestComponent	Tap_changers	Tap_changers
SESALab:opalRT	Tap_changers	Tap_changers
SESALab:opalRT	IED	IED
SESALab:Virtual RTU	IED	IED
MosaikModel:TestComponent	Loads	Loads
MosaikModel:PyPower	Loads	Loads
SESALab:opalRT	Loads	Loads
MosaikModel:TestComponent	Measurement system	Measurement system

Figure 4: Query to find suitable components for case study 1.



Market: [Bearbeiten]

Market Organization: Price Based Cost based Power Pools or centralized markets

Pricing Structure: ☐ Zonal Prices ☑ Locational Market Price (LMP) – Nodal Prices

Time Frame: ☐ Long-term ☐ Medium-term ☐ Short-term ☑ Intraday ☐ Real-time ☐ Ex post

Capacity Allocation and Transmission Lines: ☐ Using a Model for Capacity Allocation after setting the generation offers ☑ Modelled considering restrictions in lines ☐ Other

Actor Roles to be considered:
- ☐ Market
  - ☐ Balance Responsible Party (BRP)
  - ☐ Billing Agent
  - ☐ Centralised Electricity Producer
  - ☐ Consumer
  - ☐ Decentralised Electricity Producer
  - ☐ Distribution Grid Operator
  - ☐ Electrical Energy Storage (EES) Operator
  - ☐ Electricity Trader / Broker

Market Evaluation: ☐ Grid Capacity Market ☐ Capacity Market ☑ Energy Market ☐ Balancing Market ☐ Ancillary Services Market

Trading Scheme: ☑ Demand side management (from Aggregators or DSO's) ☐ Demand response ☐ Special tariffs for RE–Feed-in Tariff ☐ Curtailment of RE ☐ Special Gas Contract in the Market

Market Test: ☐ central scheduling and central dispatch : ☐ self scheduling and central dispatch: ☐ self scheduling and self dispatch

Optimization Goal: Minimization of the overall cost of the system

Figure 5: Experiment questionnaire for market model testing (case study 2).

prise and operation zones of SGAM were deployed, in the distribution domain. The idea of this use case was to find the suitable components (market trading platform or markets models) to the performed the flexibility analysis modelled in SGAM.

The market trading platform will only match the bids and reported as a business connection to the trading partners. The trading partners were a Virtual Power Plant (VPP), that controls and loads with a flexibility potential, and a Distribution System Operator (DSO) as market agent, that tries to contract flexibility to avoid congestion.

The categorization helps to seek for a model that allows price based power pools with Locational Market Price (LMP), when the grid is modeled considering restrictions in lines. The precision level was selected to nominal. Figure 5, shows the market categorization in the experiment questionnaire expressing how the market model or platform should be to run the use case. These requirements will be used in a query to propose the better components that fit the needs. As a result, mosaik was suggested as testbed, and some other components already implemented in the catalog were also called for the VPP as well as loads, DER Units, and a market trading platform described for this purpose.

5 CONCLUSION AND FUTURE WORK

The concepts presented in this paper aim to enhance existing approaches of smart grid testing and validation. The proposed workflow draws the initial steps towards establishing a structured planning procedure for validation in the smart grid domain, by combining concepts of static smart grid planning using SGAM and a holistic test case description method for integrating multi-domain objectives using HTD. The workflow allows test developers to assess which tools are most suitable to handle their interdisciplinary validation challenges. Additionally, interdisciplinary testing in a smart grid context becomes more transparent and reproducible. The presented methodology is applied internally to include our institute testing infrastructures (mosaik and SESA-Lab), but it could be extended to include other labs and software co-simulation frameworks. Thus, test developers have the flexibility of developing for example, multi-platform tests. This can be facilitated by the use of the Research Infrastructure Database developed in ERIGrid (Kulmala et al., 2018).

As proof of concept we presented two relevant case studies. The market model case study is used to test the dynamics of a trading mechanism before applying it as regulation and could be sufficiently simulated in software based matter. The second case study of voltage regulation in the distribution network contains transient and dynamic behaviors that could be simulated properly using hardware components. The workflow was able to suggest the suitable testing framework following the requirements imposed by the assessment criteria.

The extension of the experiment questionnaire to add more detailed questions regarding other domains such as thermal, control, ICT, environmental and social domain as well as use cases to test its usability, is a matter of future work. Additionally, further elaboration of market models in the component catalog will provide models for specific market studies.

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