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## JRC TECHNICAL REPORTS

# Smart grid interoperability testing methodology

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2018

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**EU Science Hub**

<https://ec.europa.eu/jrc>

JRC110455

EUR 29416 EN

PDF ISBN 978-92-79-96855-6 ISSN 1831-9424 doi:10.2760/08049

Luxembourg: Publications Office of the European Union, 2018

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How to cite this report: Papaioannou I., Tarantola S., Lucas A., Kotsakis E., Marinopoulos A., Ginocchi M., Olariaga Guardiola M., Masera M., *Smart grid interoperability testing methodology*, EUR 29416 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-96855-6, doi:10.2760/08049, JRC110455

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## **Acknowledgements**

The authors would like to acknowledge the contributions from the participants to the dedicated workshop on Methodology of Design and Analysis of Experiments for interoperability testing, held at the JRC – Ispra on May 7th, 2018 (in alphabetical order):

- Dr. Abouzar Estebarsari (Polytechnic of Turin, Italy)
- Dr. Sergei Kucherenko (Imperial College, London)
- Dr. Van Hoa Nguyen (G2Elab INP, Grenoble)
- Prof. Ferdinanda Ponci (Institute for Automation of Complex Power Systems, RWTH Aachen University)
- Dr. Abbass Raad (G2Elab, INP, Grenoble)
- Prof. Andrea Saltelli (University of Bergen - Norway)
- Prof. Bruno Sudret (ETH, Zurich)

and the European Commission's Joint Research Centre's staff from Units:

C.3 - Energy Security, Distribution and Markets

C.4 – Sustainable Transport

and I.1 - Modelling, Indicators & Impact Evaluation

The discussions with the participants during the workshop, and their written comments provided after the event, contributed instrumentally to the finalization of this report.

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## **Abstract**

Smart grid interoperability is an important enabling aspect of electricity technology deployments. It involves all parts of the smart grid from generation to transmission and from distribution to consumption. Testing interoperability requires producing detailed test cases describing how smart grid components are intended to interact with each other. A systematic approach for developing smart grid interoperability tests may facilitate the dissemination of innovative solutions, the stability and resilience of the smart grid. This report provides an analysis of the methods applicable to smart grid interoperability tests. It comprises the body of methods and principles associated with smart grid interoperability and it proposes a methodology offering theoretical underpinning to the necessary set of methods and best practices for developing successfully smart grid interoperability testing specifications.

## Introduction

The Smart Grid exhibits a high complexity regarding organizational and technological aspects. Key challenge of the Smart Grid is integration, affecting components, information, systems and applications. Functionalities and interfaces should ensure interworks in order to enable high level processes. Connecting all of the pieces in a power grid gives rise to an interconnected network in which information flow and analysis will take place in real time. Information and Communication Technologies (ICT) like Machine to Machine Communicators, Agent technology and Internet of Things will enable the migration of the classical power system towards the modernisation of the grid.

Interoperability is an essential requirement for this migration process and should be carefully considered since any operational, architectural and functional failure will have high cost due to the scale of the power system and its economy. Moreover, interoperability is crucial for deploying Smart Grids open to all vendors and integrators, where the operators can concentrate on the top level functions, independent from proprietary solutions. Hence, interoperability is at the same time a technical imperative, and the enabler of an open market where innovation can flourish.

The digital transformation of the energy sector is already changing the way energy is produced, distributed and consumed, affecting not just industry but also consumers and local communities. This revolution is characterized by the conjunction of renewable sources, smart grids, smart houses, and electric vehicles, and is enabled by the massive application of information and communication technologies.

A key challenge for digital energy, especially relevant from the consumer standpoint, is the interoperability of all the components, systems, applications and information involved. Interoperability is the ability of two or more items to work together, and it is central for the creation of a single digital energy ecosystem. But interoperability is at stake for the fact that digital energy emerges from the convergence of many industrial sectors, with different standards, culture and technical background (e.g. electricity, power electronics, home appliances, telecoms, internet/web, etc.). A clear consequence of the manifold players is that interoperability will not happen spontaneously, but it will have to be supported with dedicated policy, standardisation and technical instruments.

Interoperability enables the coordination and optimization of the electricity system's operations in all domains - from the generation down to the customer's premises - by ensuring the exchange of meaningful and understandable information. But even if interoperability has been recognised as a foundational component for the modernisation of the grid, testing interoperability of smart grid standards is still far from being commonly specified.

*"The absence of answers to the above expectations (i.e. offer profile testing means and procedures) mostly means additional complexity for setting up and maintaining Smart Grids systems" [1].*

*"Testing and certification is taking on increased urgency driven by the fact that while there are many smart grid standards, there remains a large gap in the availability of test programs corresponding to these standards" [2].*

Testing interoperability requires producing detailed test cases describing how smart grid components are intended to interact with each other. A systematic approach for developing smart grid interoperability tests will facilitate the dissemination of innovative solutions, and the stability and resilience of the smart grid.

The Smart Grid Interoperability Laboratory (SGILab) at the Joint Research Centre (JRC) of the European Commission proposes in this document a unified approach towards a European framework for developing interoperability testing specifications. A successful development and deployment of the future smart grid requires a better understanding of how components interoperate and how the proposed standards ensure interoperability among those components. Towards this objective a methodology serves as a systematic

way to evaluate the interoperability of different subsystems or electric grid components and methodically verify the ability of given equipment under test to communicate effectively with other components. The use of a methodology provides a systematic means to analyse any interoperation flaw against business and user requirements. Further analysis could then be utilised to assess the impact of any inconsistency and propose potential solutions.

Designing interoperability tests is not straight forward. The testing specifications should be carefully defined in a way to maximise the possibilities of finding potential inconsistencies, shortcomings or errors. The proposed interoperability testing methodology guides the specification developer on how to build a successful interoperability testing exercise. The methodology facilitates the developer in including all the necessary steps while insuring reliable results. The success of a smart grid interoperability test depends on how well this is achieved.

The methodology summarises a set of best practices the developer could follow to complete in a smooth way a smart grid interoperability test. Ad-hoc developments without the use of any methodology could potentially lead to lack of reproducibility and benchmarking, bad quality, longer development time and higher cost. Moreover, the methodology helps the user through a step by step process to create smart grid interoperability testing Use Cases, Basic Application Profiles (BAP) and Basic Application Interoperability Profiles (BAIOP) [3]-[6]. It keeps track of the testing specifications along the development of the testing process from conception to realization.

The methodology is used mainly as a common framework for interoperability testing and consist of five stages; Use Case creation, Basic Application Profile (BAP) creation, Basic Application Interoperability profile (BAIOP) creation, Design of Experiments (DoE), Testing and Analysis of Experiments (AE). Each stage allows the developer to select certain features then used in the subsequent stage. During the completion of all stages, the developer can select relevant standards, their options, test beds with all qualified and test equipment as well their attributes or functions used during the testing.

The SGILab will implement the proposed methodology by performing interoperability testing in the two laboratories that have been constructed for this purpose in Ispra (Italy) and Petten (the Netherlands).

The two labs allow interoperability testing of smart grid components following experimental procedures, simulations and emulations and utilising accepted standards [7]. The assessment of interoperability is done with reference to use cases and quantitative assumptions stipulated by industry and standardization bodies. The focus is extended in identifying also the factors that could potentially compromise interoperability.

The SGILab is dedicated to the assessment of interoperability aspects between Smart Grids and Electric Vehicles (EV) as well as to the study of component integration in micro-grid environments. It is also used to assess the interoperability between smart grids and smart homes, including the crucial role played by consumers/prosumers as specified in the Energy Union and Climate strategy [8]. A real time system to simulate the electricity distribution grid and to test hardware devices is also available in order to study the integration of distributed electricity generation into the power grid.

One of the substantial impacts of the JRC SGILab is the creation of a Repository collecting the intermediate and final outcomes of the testing process in a consistent framework, which should be open to vendors, users and practitioners as a common reference source. The resulting final database would be the most updated and comprehensive inventory of key elements and software tools for the design and analysis of experiments to streamline testing efforts and of final test and analysis results to be used as a knowledge centre. The objective of the repository is to create a collaborative dynamic platform bringing together interested parties under a cooperation perspective for future interoperable energy system and subsystems.



A dedicated workshop on Methodology of Design and Analysis of Experiments for interoperability testing was held at the JRC – Ispra on May 7th, 2018, with the participation of experts in design of experiments, modelling, sensitivity analysis, smart grids and interoperability testing. The discussions with the participants during the workshop, and their written comments provided after the event, contributed to the completion of this report. Some concluding remarks are presented in Annex 4.

# 1 Interoperability

## 1.1 Definition and best practices

Interoperability refers to the ability of two or more devices from the same vendor, or different vendors, to exchange information and use that information for correct co-operation [9]. As stated by CEN-CENELEC-ETSI Smart Grid Coordination Group (SG-CG) [10], this definition is extended to "The ability of two or more networks, systems, devices, applications, or components to interwork, to exchange and use information in order to perform required functions." In addition, "Interoperability between systems in a smart grid must be considered and well specified in use cases, in order to develop interoperable Smart Grid systems by design. Use cases provide a basis for the specification of functional requirements, non-functional requirements, test cases and test profiles".

The CEN-CENELEC-ETSI group has also stated in [3] that "If two or more systems are capable of communicating and exchanging data, they are exhibiting syntactic interoperability. Specified data formats (e.g. XML) and communication protocols (TCP/IP) are fundamental tools of syntactic interoperability". To ensure interoperability, a semantic model which specifies the structural elements to process the information is needed. While the development of communication protocols have greatly progressed in the last decades, facilitating the syntactic interoperability, semantic interoperability is much more challenging as it requires the definition of common languages.

According to the GridWise Architecture Council [11] interoperability for the electric power system can be defined as "the seamless, end-to-end connectivity of hardware and software from the customers' appliances all the way through the distribution & transmission systems to the power source, enhancing the coordination of energy flows with real-time flow of information and analysis". It is a fundamental component of the electric grid modernisation concept implying a "smart grid", which is a large, complex "system of systems" with many stakeholders each one having diverse needs that must be met.

This literally means as derived from the GridWise Architecture Council (GWAC) work [1] that the smart grid should facilitate:

- The exchange of meaningful information
- A shared understanding of the exchanged information
- A consistent behaviour complying with system rules and
- A requisite quality of service such as reliability, time performance, privacy, and security.

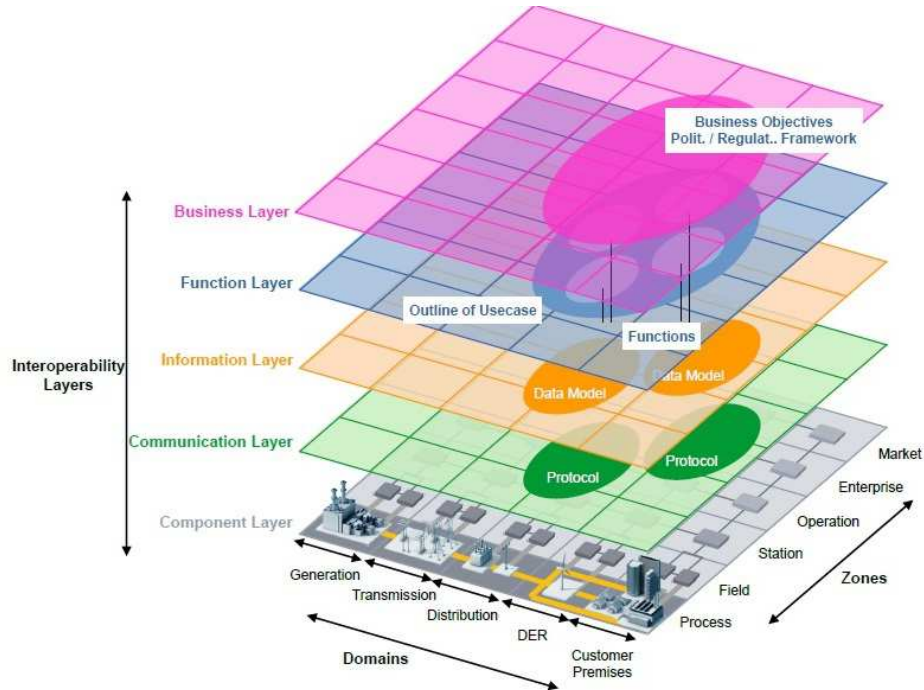
Based on the Smart Grid Architecture Model (SGAM) Framework [12], there are five different layers of interoperability:

- Component layer which is the hardware to connect systems or devices such as power cables
- Communication layer which is the communication technology (e.g. PLC or Ethernet) and the communication protocol for data transmission
- Information layer which is the data model to be used to ensure a common understanding of the data exchanged
- Functional layer specifying the functions and interactions
- Business layer specifying economic, regulatory and business interoperability objectives

This means that all interactions (i.e. physical, information-based and process-based) should satisfy the interoperability principle. This includes the field level (e.g. substation

automation, distribution automation, distributed energy resources), to remote operations (e.g. remote grids management), market management, service management, customer management, etc. A major challenge for interoperability is the integration across domains.

**Figure 1** SGAM framework



Source: [12] CEN-CENELEC-ETSI Smart Grid Coordination Group Smart Grid Reference Architecture, 11-2012

While standards promote interoperability, they do not guarantee interoperability [2]. Smart Grid equipment is designed based on international or national standards but this does not guarantee interoperability. That is because such standards are intended to be used in various architectures [13], or have to be interpreted with respect to new emerging standards. Thus, they often contain a wide range of functions, options and free data fields. The causes for non-interoperable standards could be the following:

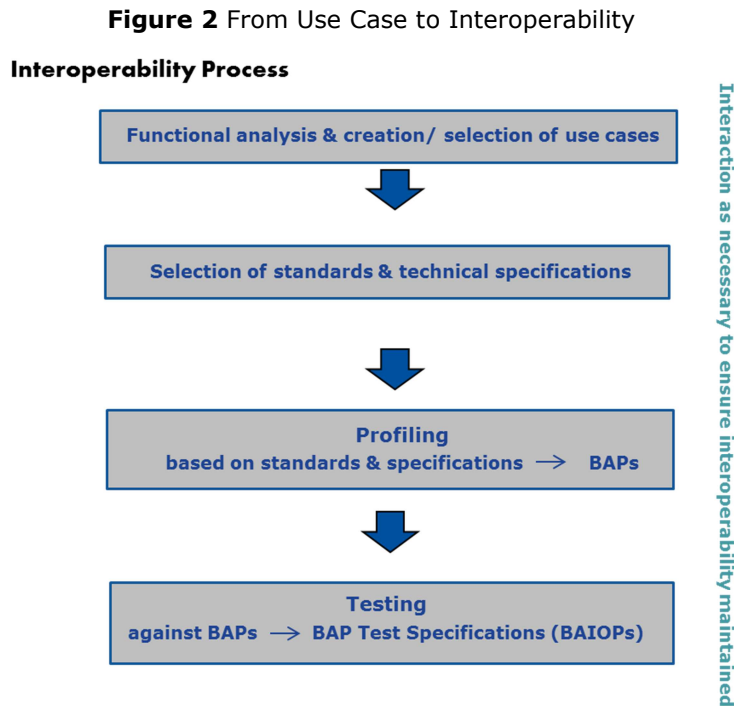
- Ambiguous requirements
- Incompatible standards (standards with different Quality of Services (QoS), traffic priorities etc.)
- Different standards with overlapping or interrelated requirements
- Requirements not well identified or missing
- Inadequate handling of options
- Lack of clear system overview
- Loose definition of interfaces (reference points)
- Poor maintenance
- Using standards beyond their original purpose
- External events/ conditions that might deteriorate interoperability

Interoperability testing is a key factor with increased urgency based on the fact that many smart grid standards have been identified but very few of them have been really tested against interoperability. For example, in the IOP (interoperability) excel tool provided by CEN-CENELEC-ETSI [14] more than 500 standards have been listed as SG

standards but (by filtering the standards based on IOP testing) less than 20 appear to be tested.

In order to make two implementations interoperable, several steps should be taken, such as: the definition of functionalities, the selection of standards, and creation of profiles and of course the testing which includes both the conformance and the interoperability testing [15]-[16].

The need for a common framework of testing interoperability has been recognised. The main work regarding interoperability testing has been presented by CEN-CENELEC-ETSI mainly in [3] and the SG Task Force (Expert Group1- Standards and Interoperability) [17]. The suggested process for testing is presented by CEN-CENELEC in Figure 2.



Source: [3] CEN-CENELEC-ETSI Smart Grid Coordination. SG-CG/M490/I\_Smart Grid Interoperability Methodologies to facilitate Smart Grid system interoperability through standardization, system design and testing. 2014

The European Smart Grid Task Force EG1 [17] adopted a similar approach for testing interoperability of specific interfaces of the flexible demand architecture. Thus a unified process to test interoperability should follow a similar approach:

- Use case creation
- Function analysis
- Standards selection
- Profiling based on standards and specifications
- Test Case creation
- Testing

## 1.2 SGILab proposed Interoperability Testing Methodology

The focus of the JRC Smart Grid Interoperability Lab is on testing the ability to exchange and use information in heterogeneous electric power grids. The work will be more on the interoperability of technological (hardware/software) implementations according to

proposed standards used in conjunction with applicable reference architectures. The emphasis will be on the implementation of devices or protocols directly supported by the standards and on the ability to perform an effective and efficient exchange of information between heterogeneous smart grid components. Finally, the goal is to assess the ability to automatically interpret the information exchanged meaningfully and accurately in order to produce useful results. SGILab will perform interoperability testing using and extending best practices.

The block diagram of the JRC Interoperability Methodology (including, inputs, activities, outputs and data storage) is depicted below in Figure 3. The activities of the process are defined as explicit Steps that have to be followed to execute the Methodology:

Step 1: Use Case Elaboration

Step 2: Basic Application Profiles (BAP) creation

Step 3: Basic Application Interoperability Profiles (BAIOP) creation

Step 4: Statistical Design of experiments (DoE)

Step 5: Testing

Step 6: Statistical Analysis of experiments

For each Step there are inputs which will be elaborated by the laboratory staff by using and updating existing data, e.g. Use Cases from existing repositories or creating new data in case that there is no data available. In any case, within each process the outcome will be formulated in specific templates (for UC, for BAP, BAIOP and DoE) suggested and created by JRC and uploaded in the SGILab repository.

The added value in the suggested methodology is that JRC has compiled best practices in a unified approach which considers a wide range of smart grid implementations.

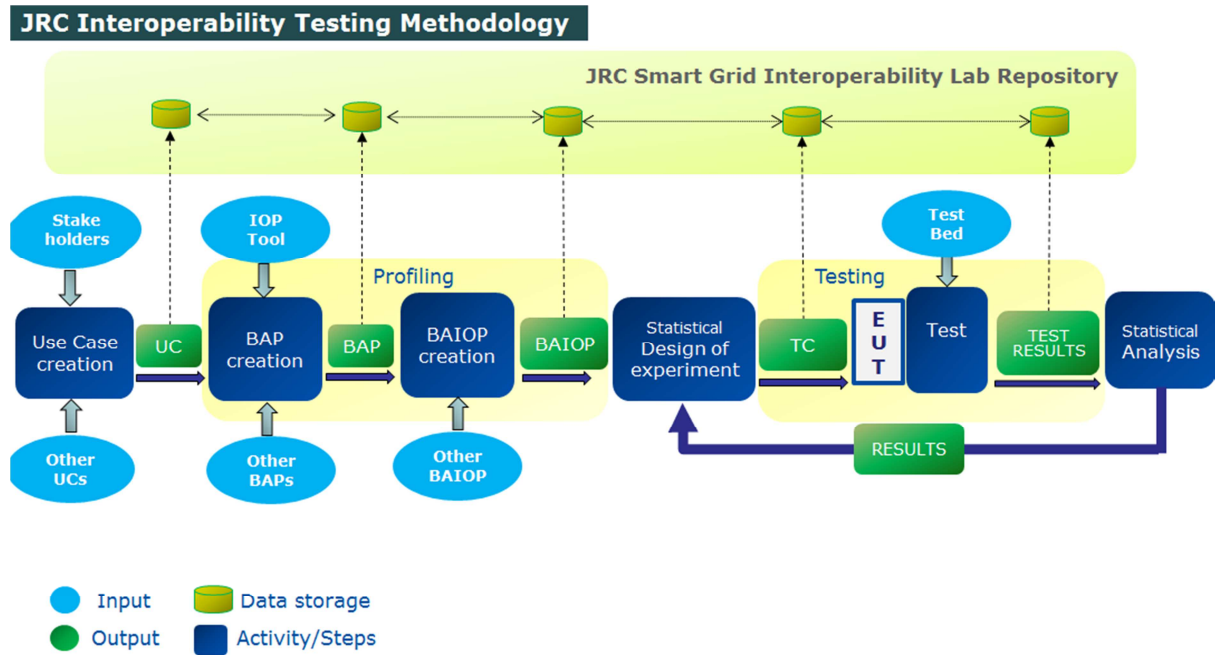
Use Cases and Basic Application Profiles are elements of the methodology which have already been proposed by CENELEC and the Smart Grid Task force; nonetheless the detailed test specifications were missing or have been suggested only for specific interfaces of the AMI [17].

JRC proposes a detailed test set up, by designing a detailed template for the Basic Application Interoperability profile to be used as a testing protocol. The BAIOP is detailing the testing process by specifying the evaluation criteria, the criteria under which the EUT will receive a pass or a fail mark in the interoperability test. Furthermore, the Statistical Design of Experiment specifies the parameters to be tested which then in the 5th Step will define the test cases (where a step by step analysis is created). The tested functionality is broken down into sub-functions which are then tested in separate test cases. In this way test cases are simpler to be followed and executed, which in turns means that the criteria are better monitored. The verdict then can be clearly concluded with no space of ambiguity. Furthermore, when the interoperability test has a fail verdict is easier to track where is the failure which may lead to a recommendation towards standardisation organisations (in case of a gap or incompatibility of the standard) or towards the manufacturer (in case of a wrong interpretation of the standard in the design phase of the product), or towards the involved parties (in case of a gap in the business model) etc.

The methodology will be utmost automated (with less possible human intervention) so that it can be replicated and under the same conditions and testing environment to provide the same evidence. The JRC Smart Grid Interoperability Lab Repository will be used to store the intermediate and final products of the process but also to automate

some of the activities (this shall be explained in a follow up report). The system will be available to be used by laboratories.

**Figure 3** SGILab IOP Testing Methodology



## 2 Use Case (Step 1)

### 2.1 Best practices

Interoperability between actors, systems, subsystems and components in a Smart Grid must be considered and well specified in Use Cases (UC). UC provides the basis for the specification of functional requirements, non-functional requirements, test cases and test profiles, for conformance testing and interoperability testing. Furthermore, it also serves as the basis for the design of the testing experiment and the test bed configuration. The UC enables a common understanding between different sectors, committees or stakeholders in complex systems as the Smart Grid.

The concept of UC and in general the project planning, requirements definition, architecture development, technology selection and deployment as a way to handle Smart Grid requirements, was introduced by the IntelliGrid Consortium with EPRI in IEC PAS 62559 in Guidelines for Systems Development Using the IntelliGrid Methodology [18].

CEN/CENELEC/ETSI in [4] collected several modifications and tailored the UC template for its purpose. Based on these outcomes, IEC Technical Committee TC 8 decided to transform IEC/PAS 62559 into a new IEC 62559 with three sub parts:

- IEC 62559-1 describes UC based approach for standardisation
- IEC 62559-2 specifies templates for UCs, actor list and requirement list
- IEC 62559-3 provides the definition of UC template artefacts into an XML serialised format in order to exchange UCs between different UC repositories or with UML engineering tools

In order to support the UC development process the use of a tool, namely a Use Case Management Repository (UCMR), is introduced in SG-CG. There is also a repository of UCs available from IEC and EPRI (<http://smartgridstandardsmap.com/> and <http://smartgrid.epri.com/Repository/Repository.aspx> respectively).

There is a vast collection of UCs readily available online. There are different sources:

- CEN/CENELEC/ETSI provides a large number of them on different documents, mainly in Sustainable Process Report [4] and through working groups e.g. the Smart Meter Coordination Group (SM-CG) has defined a common set of Smart Metering Use Cases as a part of its work under the M441 mandate.
- ENTSO-E <https://www.entsoe.eu/>
- COTEVOS project: <http://cotevos.eu>
- DISCERN project: [http://discern.eu/project\\_output/tools.html](http://discern.eu/project_output/tools.html)
- GRIDINNOVATION project [www.gridinnovation-online.eu/tag.aspx?tag=4337](http://www.gridinnovation-online.eu/tag.aspx?tag=4337)

The UC driven development is a good practice to define system requirements. When the requirements of a system are analysed the functionalities are captured in UCs. UCs are used to capture the actors (internal/external applications or human users) interacting with the system. UC diagrams are used to form the system boundaries and specify potential interactions among actors or between actors and UC and to define relationships among similar UCs

The presentation of UCs may be informal, using a text document supported by drawings, or more formal using Use Case Diagrams as specified in the Unified Modeling Language (UML), which is the preferred option.

Depending on the nature, UCs can be classified as:

- Business UC. Business UCs describe business processes that the system's actors should perform. It is the description of the UC on the Business layer of the SGAM.

- Technical or system UC. System UCs describe SG functions to be executed in the Business UCs. Their purpose is to detail the execution of those processes on the Function Layer of SGAM.

## 2.2 SGILab UC template

One of the first activities of JRC SGILab would be to specify the initial set of UCs that can be carried out in the laboratory, based on the availability of test beds and on the interoperability testing methodology. Then the existing repositories should be explored and existing UCs would be selected. In this stage, inputs from Smart Grid stakeholders and UC repositories as presented above will be utilised.

In order to generate new UCs or adapt existing ones, JRC has developed a UC template based on the available ones:

- PAS 62559, an example of which can be found in Appendix C of the book 'Standardisation in Smart Grids' [19]
- DISCERN's Use Case Template\_v2.1.doc that provides and XML export functionality based IEC 62559-3 meta-model. This would facilitate the maintenance and management of the Use Case Repository. Deliverable D2-3.2 'Tool support for managing Use Cases and SGAM models' of the project presents a very pragmatic approach.
- EPRI and IEC Intelligrid template which can be found at:

<http://smartgrid.epri.com/Repository/Repository.aspx>

SGILab UC template comprises the following parts:

- The name, identifier (ID) version and sources (literature), maturity of UC, keywords etc
- Scope and objectives of the UC function along with a short and a complete description
- The actors: an actor is an entity in the system that communicates and interacts. It may be a person, a device, a piece of software, an organisation, or an entity that can act on its own and can have goals and responsibilities, e.g. a "customer" or a "meter". A list of actors provided by CEN-CENELEC-ETSI SG-CG in the Sustainable Processes report [4] may here be used
- Constrains, legal issues, preconditions and assumptions for each actor or system
- Reference standards and Standardisation committees. The IOP tool provided by CEN/CENELEC/ETSI [14] and the Smart Grid Standards map by IEC (<http://smartgridstandardsmap.com/>) can be used here. The objective of this information is mainly to collect all the relevant to the UC standards which then can be used for the profiling stage. Thus in the IOP tool the filters that should be generally used are the Information and the Communication in the SGAM layer columns. This will facilitate further to map the UC on the Communication and Information layer
- Drawing of the UC. It is the visualisation of the UC on the function layer of the SGAM. The Visio tool recommended by the Discern project can be used ([https://www.discern.eu/project\\_output/tools.html](https://www.discern.eu/project_output/tools.html)). This will facilitate further the mapping of the UC on the Communication and the Information layer of the SGAM
- A step by step analysis of the UC: organised in three tables:
  1. The 1st table includes the triggering event, the pre and post condition that enable the Primary Actor to produce a message.
  2. Normal sequence: the function of the UC is step by step presented in this table including the actors that participate in the exchange of information and the technical requirements to achieve this interaction. Here a normal operation of the system is considered.



3. Alternative, Error Management and/or Maintenance/Back up scenario: alternative steps compared to the previous table are considered under special occasions, situations and abnormal conditions (e.g. violation of power regulations etc.). The UC is a very descriptive document which has to include all the possible interactions among the actors and all the possible conditions should be taken into account. Thus here, errors, violation of regulations, back up and maintenance scenarios have to be included.

JRC SGILab UC template is presented in the Annex I.

### 3 Profiling

An interoperability profile should describe:

- How a standard/ specification can be used to support the requirements of a specific function
- The way the standard will be used and its options fixed
- All information that is required for a producer to create payload instances, for a consumer to interpret payload instances, and for an impartial party to judge compliance of a payload instances

Thus after selecting the standards applicable to the specific profile, an additional specification has to be made. Since there are standards covering a high number of functionalities that not all have to be implemented and they contain options that have to be further detailed, further definitions have to be made. Such definitions describe the way a standard is used and locks the options considered. These definitions are fixed in the "interoperability profile", through the Basic Application Profile (BAP), the Basic Application Interoperability Profile (BAIOP) and they will define the evaluation criteria in the BAIOP.

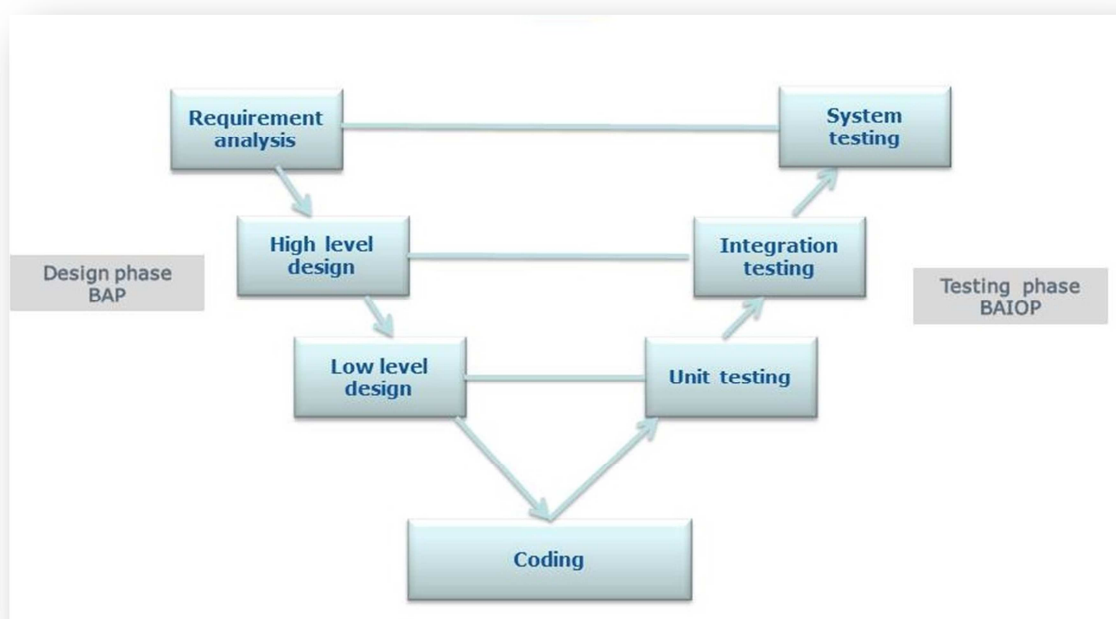
Two models are required for the profiling process:

- A profile semantic model which specifies the structural elements which will process the information. This includes the names of data items and the relationship between named data items that make up the payload
- The syntactic model which specifies how the semantic model is serialised (sequence of inputs and output that is represented by a particular grammar) so that it can be transferred from producer to consumer (e.g. in different computing environments)

One of the most important purposes of a profile is to help ensure interoperability between systems. Adopting a profile increases the possibilities for seamless information exchange and interoperability between systems, since a profile enforces one possible interpretation and limits the ambiguity of an open standard.

The same rule for interoperability must be considered from the design phase to testing and profiling. The V-Model [20], which was original used to represent the software development process, is used here to capture the process steps for developing IOP testing. The advantage of the V-model is its ability to demonstrate the relationships between each phase of the development life cycle (on the left) and its associated phase of testing (on the right). In the following Sections the creation of BAP and BAIOP is further analysed.

**Figure 4** The V-Model



### **3.1 Basic Application Profiles (Step 2)**

#### **3.1.1 Definition of BAP**

The user (utility, grid operator, energy services provider, user group etc.) will typically need to specify in detail how a specific standard (or set of standards) will be used and which options from the standards are used in what way in order to achieve the desired functionality as described in the UC. This stage of profiling is the so-called BAP. As mentioned before a UC shows the interactions between components and is the basis for the selection of the appropriate standards. Hence, in the UC creation phase of the IOP methodology, a list of standards relevant to the UC and the actors' interactions is created.

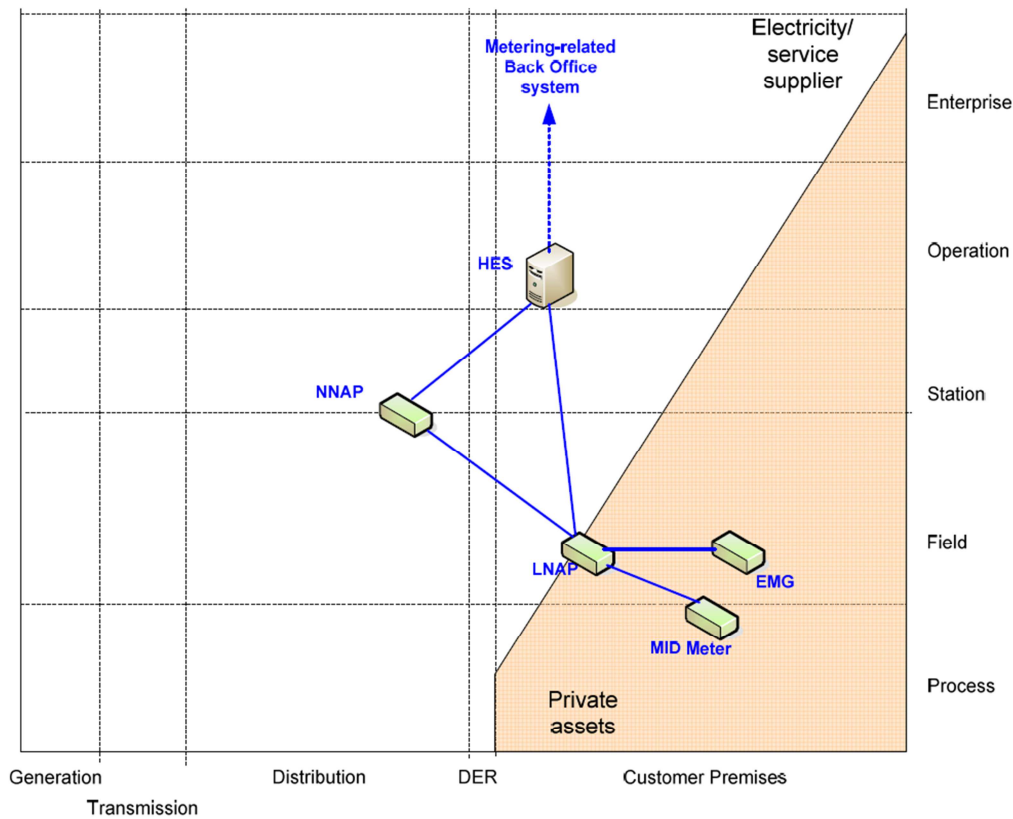
Initially and in order to define the BAP of the UC, information flows between the actors should be considered. These flows are the exchange of information between two actors. Two actors are interacting if they exchange information at least once in the UC. From the creation of the UC (UC template, Annex I) tables 3.1 and 3.2 of the proposed UC template show which actors exchange information (this suggests an information flow). With the aid again of the Visio tool, the communication layer can be created for the UC (the component layer has been created along with the UC creation).

For each of the information flows, the possibility of an alternative way for the two actors to interact need to be checked. Alternative way means that the two actors exchange information through another actor (or actors). Thus it is very important that the description of the UC is thorough and it includes all the possible actors and interactions and their alternative way of communication. A UC which is carefully and completely described facilitates the profiling and decreases the possibility of omitting interactions which in the end might jeopardise the interoperability of the system.

If variants of BAPs for an application function are needed, different BAPs for the same application function have to be defined and created. For example, we assume the Advance Metering Infrastructure as described in the following picture of the component layer (Figure 5). The Head End System (HES) communicates with both in-home gateway

(Local Network Access Point –LNAP) and the meter data concentrator (Neighbourhood Network Access Point – NNAP). The data exchange between HES and the LNAP can be done with a direct communication or through the NNAP. Thus both information flows should be considered (direct or indirect through NNAP) and this will affect the definition of the respective BAPs.

**Figure 5** AMI in component layer



Source: [1] CEN-CENELEC-ETSI Smart Grid Coordination Group, SEGCG/M490/G Smart Grid Set of Standards, Version 4.1 draft v0, 06-01-2017

At this stage, in order now to create the BAPs, all the relevant standards and protocols that specify the information flows should be determined. A preliminary work has been already done by filling Table 1.10 of the SGILab UC template. The following table is used to create the BAPs taking into account the following:

- BAPs have no alternatives. Options are fixed
- In case of different options within the same standard, additional BAPs should be defined
- In case that an interaction between two actors is realised through intermediate actor/actors then the BAP contains each standard/ protocol for the intermediate communication to achieve the exchange of the specific information. Again here options should be fixed

For defining the BAPs and fixing the options, Table 1 is proposed.

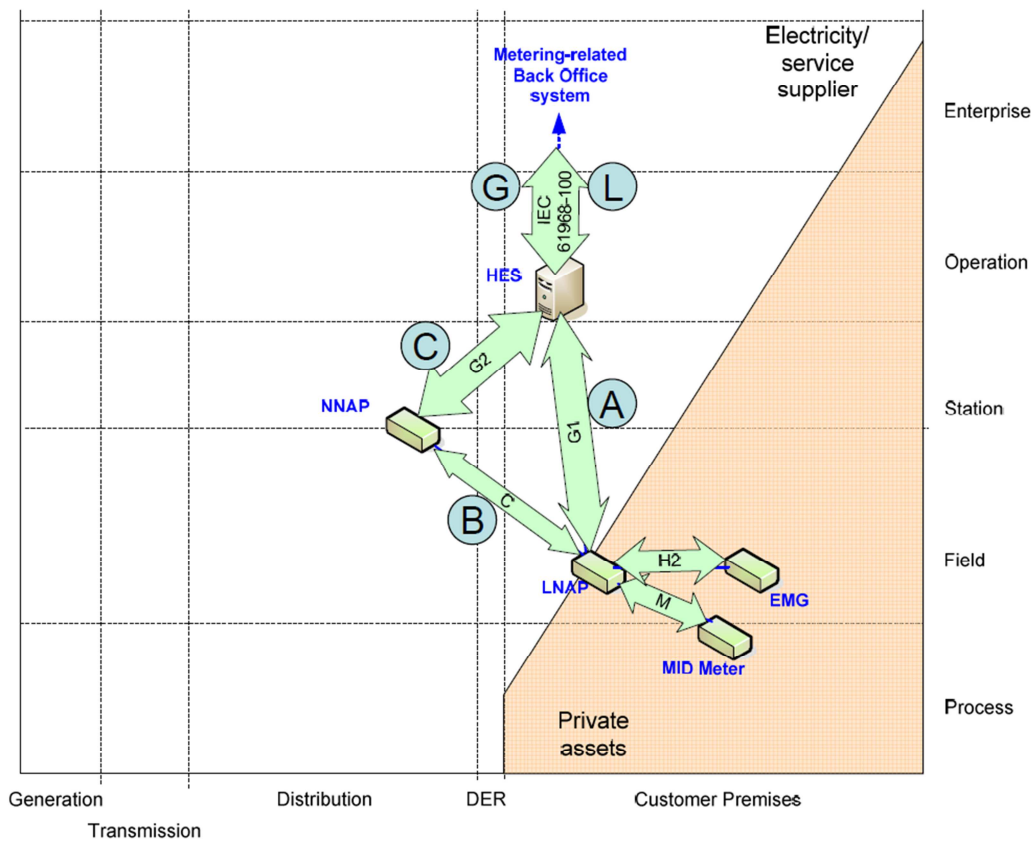
**Table 1** Definition of BAPs

Information exchange between actors	Type of information	BAP	Protocol/ Standard (or option of Protocol/ Standard)

Assuming the AMI architecture, the communication layer is shown in Figure 6.

The standards for the communication between the actors have been defined by the SGCG. Hypothetically and for the sake of simplicity, we assume that for the communication between LNAP and NNAP (C) only standards CLC/TS 50568-4 and CLC/TS 50590 exist with fixed options; for the communication between NNAP and HES (G2) there is only the standard CEN-CLC-ETSI/TR 50572 with fixed options; and for the respective communication between LNAP and HES (G1) there are two only standards with fixed options, the CEN-CLC-ETSI/TR50572 and the IEC 62056-1-0. For the definition of BAP the indirect communication between LNAP and HES through NNAP should be also considered, as shown in Figure 6.

**Figure 6** AMI in communication layer



Source: [1] CEN-CENELEC-ETSI Smart Grid Coordination Group, SEGCG/M490/G Smart Grid Set of Standards, Version 4.1 draft v0, 06-01-2017

**Table 2** BAPs definition- Example

<i>Information exchange between actors</i>		<i>Type of information</i>	<i>BAP</i>	<i>Protocol/ Standard (or option of Protocol/ Standard)</i>
LNAP	NNAP	Data	BAP1.1	CLC/TS 50568-4
LNAP	NNAP	Data	BAP1.2	CLC/TS 50590
HES	NNAP	Data	BAP2	CEN-CLC-ETSI/TR 50572
LNAP	HES	Data	BAP3.1	CEN-CLC-ETSI/TR50572
LNAP	HES	Data	BAP3.2	IEC 62056-1-0
LNAP	HES (through NNAP)	Data	BAP3.3	CLC/TS 50568-4 and CEN-CLC-ETSI/TR50572
LNAP	HES (through NNAP)	Data	BAP3.4	CLC/TS 50590and CEN-CLC-ETSI/TR50572

### 3.1.2 BAP template description

Once the standards/protocols have been defined and their options are fixed then the BAPs can be created. A BAP is actually an extensive document which according to SGCG Smart Grid Set of Standards document may comprise:

- An introduction including purpose of the BAP
- Scope
- Terms, definitions & abbreviations
- Referenced documents, e.g. to other companion documents
- System architecture
- Use case definitions for different interoperability layers, starting with the functional layer, including standards and implementation details i.e.
- Security

For the SGILab the creation of the BAP serves as a way to lead to the BAIOP, which is the test specification to be carried out in the laboratory. For the SGCG the BAPs and BAIOPs are the results of the standardisation process to serve different Generic UCs (Figure 5 in [1]). For the SGILab the BAP is defined for one specific UC (it may of course be used in other UCs too), thus for the JRC IOP methodology what the BAP will comprise is suggested to be a bit different from the SGCG suggestion:

- BAP Identifier, UC Identifier, Standard (or set of Standards)
- Version
- Referenced documents, e.g. to other companion documents
- Terms, definitions & abbreviations

- Functionality which is covered with the BAP/ Scope
- Description of how the specific standard (or set of standards) will be used and which options from the standards are used in what way in order to achieve the desired function. The aim of the description is to fix the options, to reduce the complexity of the standard and to define the criteria to be used later in the BAIOP.

This means that the BAP is actually an in-depth analysis of the standard (or set of standards) in order to specify the way it is going to be used thus:

- Only existing standards should be referred
- Only testable statements should be stated
- Specifications should be precise enough that its implementation can be tested with a unique verdict: "passed" or "not passed"
- Data models and services should be defined
- Instances (e.g. specific device types) and procedures (e.g. programmable logics, message sequences etc) should be also defined

The BAP template is presented in the Annex I.

## 3.2 Basic Application Interoperability Profile (Step 3)

### 3.2.1 Definition of BAIOP

While the BAP is created during the design phase, the Basic Application Interoperability Profile (BAIOP) [17] is created in the testing phase and it is an expansion of the BAP. The European Smart Grids Task Force Expert Group 1 suggests that BAIOP is a BAP Test Specification which defines the detailed set-up to test the individual technical requirements of a BAP.

This extension means, in practical terms and according to the European Smart Grid Task Force EG1, to add:

- Device configuration
- Test configuration with communication infrastructure (topology)
- BAP related test cases
- Specific capability descriptions (e.g. PICS, PIXIT, MICS in case of IEC 61850)
- Engineering framework for data modelling (instances) and communication infrastructure (topology, communication service mapping)

Table 3 is proposed to be used for defining the number of BAIOPs to be produced for the tests to be carried out. Initially, it should be noted that what is going to be tested is that an actor communicates with another actor or actors in order to perform a specific functionality, thus all the possible ways and combinations of communication should be taken into account to define the number of BAIOPs.

**Table 3** Definition of number of BAIOPs based on BAPs possible combinations

<i>Information exchange between actors</i>	<i>BAP</i>	<i>BAIOP1</i>	<i>BAIOP2</i>	<i>BAIOP3</i>							<i>BAIOP X</i>

Assuming again the AMI example where the definition of the BAIOP should be made for testing the LNAP which should retrieve data both from the NNAP and the HES and perform a functionality. The possible combinations of BAIOPs are showed in Table 4.

**Table 4** Definition of number of BAIOP for the AMI example (Figure 5 and 6)

<i>Information exchange between actors</i>		<i>BAP</i>	<i>BAIOP1</i>	<i>BAIOP2</i>	<i>BAIOP3</i>	<i>BAIOP 4</i>	<i>BAIOP5</i>	<i>BAIOP 6</i>
LNAP	NNAP	BAP1.1	X		X			
LNAP	NNAP	BAP1.2		X		X		
HES	NNAP	BAP 2						
LNAP	HES	BAP3.1	X			X		
LNAP	HES	BAP3.2		X	X			
LNAP	HES (through NNAP)	BAP3.3					X	
LNAP	HES (through NNAP)	BAP3.4						X

Based on Table 4, there are 6 different ways for the LNAP to retrieve the data, thus 6 BAIOPs.

- BAIOP1: the LNAP receives data from NNAP (BAP1.1) and from the HES (BAP3.1)
- BAIOP2: the LNAP receives data from NNAP (BAP1.2) and from the HES (BAP3.2)
- BAIOP3: the LNAP receives data from NNAP (BAP1.1) and from the HES (BAP3.2)
- BAIOP4: the LNAP receives data from NNAP (BAP1.2) and from the HES (BAP3.1)
- BAIOP5: the LNAP receives data from HES (BAP3.3) through the NNAP thus it receives also the data from the NNAP
- BAIOP6: the LNAP receives data from HES (BAP3.4) through the NNAP thus it receives also the data from the NNAP

Each BAIOP defines a set of test cases to be carried out in order to check that the actor under test (in this case LNAP):

- communicates properly (based on the respective BAPs) and according to the UC with the other actors (in this case NNAP and HES)
- performs the specific functionality according to the UC

Thus, the first actor (LNAP) comprises the Equipment under Test (EUT) while the other actors (NNAP and HES), with which the EUT communicates, comprise the System under Test (SUT). The SUT can be a whole or a part of the Test Bed (the SUT here is the NNAP and the HES, whereas the Test Bed can be the AMI system).

This is the reason why the BAP2 from the example above does not appear in any of the BAIOPs: it is the communication between the HES and the NNAP, the two actors of the SUT which communication should be established properly before the testing.



The SUT should be well defined and soundly operating, thus the actors of the system should communicate and execute their functions regardless the EUT. Of course it can be that the function of the EUT to be tested is a part of a chain of actions which cannot be executed without the sound operation of the whole system (including the EUT). In these cases we shall assure before that the whole SUT works by simulating/replacing the EUT, assure that the system operates well and as described in the UC. Then the EUT should be placed in the loop.

### **3.2.2 BAIOP template description**

BAIOPs should specify the detailed setup to test the individual technical requirements of a BAP (or BAPs). It should be clarified at this point that the BAIOP is not device specific but rather implementation specific based on the standard. That is because the objective is to test the execution of a specific functionality as specified in the BAP (which derives from the analysis of the standard). This functionality is closely related with the surrounded system and thus the test will check that the integration and the role of the EUT in the system is properly defined according to the specifications of the BAP.

The European Smart Grids Task Force Expert Group 1 suggests the content of a BAIOP for the H1/H2 interfaces [17]. Based on this, SGILab proposes the following structure for the BAIOP extending thus its context to include more SG functionalities:

1. Identifier/ Description
2. BAPs' Identifiers
3. UC Identifier
4. Referenced documents
5. Terms, definitions & abbreviations
6. Functionality/ Scope
7. Testing process description: This shall describe the basic testing process and clarify overall testing requirements.

Section 7 will consist of four parts describing all the setting up of the test before running the test (any Test Case that falls under the same BAIOP). It will give a thorough description of the EUT but also of the equipment to be used in the system under test (SUT). It should be noted that the SUT can be a part or a whole Test Bed (the Test Bed is a broader system). The configurations of the EUT, the SUT and the Test Bed will be given in this part. The four parts are described here:

Evaluation criteria: in this point a thorough analysis of the objective of the test should be done. Here some important issues should be clarified such as: which are the interoperability criteria and if the test process is appropriate to fully assess the interoperability requirements. In this point it should be clear what is expected from the EUT to do (action, function, reaction, response, change of settings, cybersecurity aspects etc.) so that it can be characterised as interoperable within the system as described in the BAP. The criteria derive from the fixed option of the specific BAP and they should be clear leaving no space for unambiguity, leading to a unique verdict: "passed" or "not passed".

Specification of the EUT: it should be noted here that the description of the EUT should NOT be device specific.

- Technical specifications: definition of the minimum technical requirements that the EUT should have to support the function (e.g. display, sensor, recorder, operating system etc.)
- Operational specifications: definition of the minimum operational requirements that EUT should have to support the function (e.g. operational voltage, frequency, protection, connectors etc.)

- Initial criteria for the EUT, e.g.
  - unambiguous identification to ensure that the EUT is correct
  - safety requirements to avoid hazard during testing
  - further passed tests as precondition for the interoperability test

Description of the SUT:

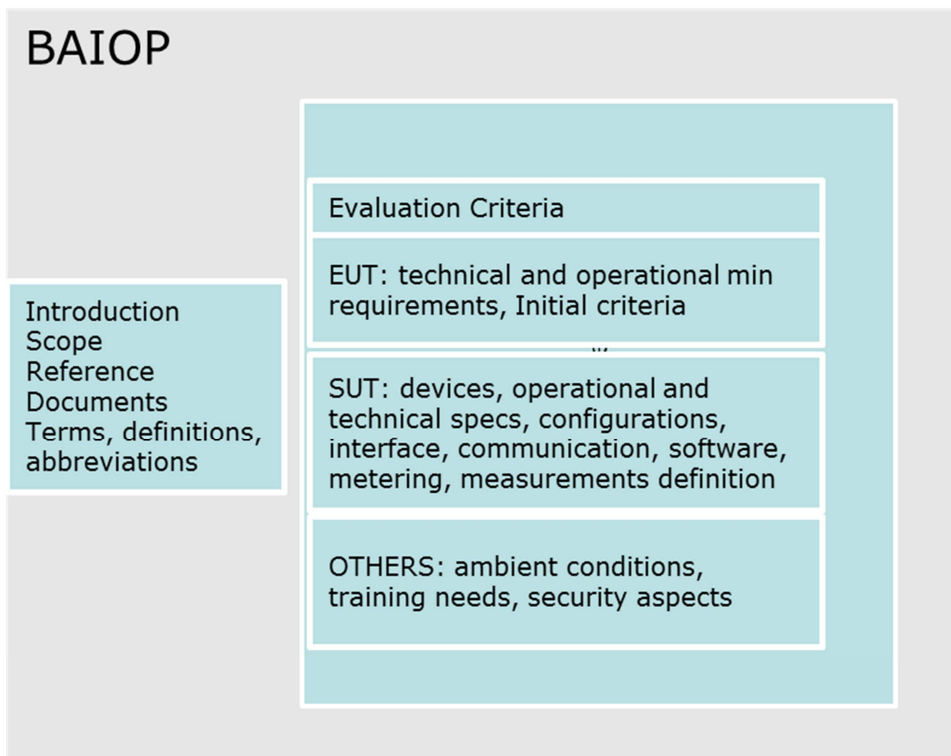
- Test Bed (of which the SUT is part)
- Devices/equipment that comprises the SUT
- Technical specifications
- Operational specifications
- Configuration of the SUT
- Any interfaces connecting the EUT(e.g. realised by Upper Tester and Lower Tester)
- Communication infrastructure
- Service access point to initiate the test and to evaluate the behaviour
- Special equipment to create appropriate conditions for the test (e.g. harmonic generator)
- Software (simulating hardware) that needs to be connected (e.g. energy market functions)
- Metering and control infrastructure that needs to be connected (where, why and how) and specifications of metering devices (frequency of sampling, operational conditions, range of fault etc.)
- Definition of values to be measured (voltage, current, harmonics, message stacks etc.). The points to be measured and the way to be measured (sampling, time resolutions etc.). The way to store and retrieve the measured data.

Others:

- Ambient conditions (temperature, humidity, pressure, noise, etc.)
- Human intervention (e.g. random usage of loads etc.)
- Staffing and training needs to carry out the tests
- Security aspects

A diagram of the BAIOP is shown in Figure 7.

**Figure 7** Diagram of the BAIOP



The BAIOP template is presented in Annex I.

## **4 Statistical Design of Experiments (Step 4)**

### **4.1 Introduction**

The Statistical Design of Experiments (DoE) is the systematic method of laying out a detailed plan in advance of carrying out experiments. In an experiment, one deliberately changes one or more process variables (or input factors) in order to observe the effect that these changes have on one or more response variables [21]. The design of an experiment sets the conditions that may influence the system (i.e., sets the values of the input factors) most likely to determine effects on the response variables, establishes the presence and management of control variables, lays down the number of experiments to be implemented, and the observations to be made. When the experimenter wants to test for interoperability only one particular situation, i.e. for given fixed values of the process variables, the DoE, and the corresponding statistical analysis of experiments described in Chapter 6, are not necessary.

A key goal of the statistical design of experiments is the efficient production of experimental data, since data points always require a certain acquisition cost. For a given experimental budget, there is an efficient design of experiments (i.e. a given number of combinations of input factors for which the system will be tested) that can guarantee an acceptable level of accuracy in the subsequent analysis of the results.

The result of the interoperability test should be either pass or fail. The test should be executed leading to a clear verdict. Investigating interoperability means in practise identifying for which set of values of the input factors the verdict is "pass" and for which set of values the verdict is "fail". In other words, the final interest is in the boundaries between pass or fail.

The tests should be reproducible in time and, under the same conditions, should result in the same verdict and thus should be as much as possible automated with less human intervention. The tests should be described in such a detail that can be replicated in any laboratory having the same/similar equipment.

Any thorough experimental program will be accompanied by two dedicated analyses of experiments [22], the Sensitivity Analysis and the Failure Analysis which are the object of Chapter 6.

The design of experiments defines the Experiment to be carried out by breaking it down into a number of Test Cases (the experiments), which aim at testing the behaviour of specific sub-functions of the EUT with the objective to evaluate their effect in the normal operation of the system or execution of sub-functions of the EUT. The main objective is to test that the EUT is performing the specific function as described in the UC, following the specific options of the standard, as described in the BAP under the test specifications defined in the BAIOP.

### **4.2 The DoE procedure**

The DoE procedure is accomplished by following the subsequent tasks:

Step 4.1: Define the goals of the experiment

Step 4.2: Identify the system responses to be measured

Step 4.3: Identify the input factors

Step 4.4: Identify intervals of variation of the inputs

Step 4.5: Sample N values for the input factors within their intervals of variation

The execution of the N Test Cases follows (it is described in chapter 5).

The procedure is exemplified hereafter by means of the use case Remote Metering under Power Quality Stress Conditions, which is described in detail in Annex II of this methodology report.

In practice, the procedure is connected to the UC through the configuration of a specific BAP and a BAIOP, which define the equipment to be used and the details of the interoperability test. Both BAP and BAIOP are described in the templates provided in Annex I.

#### **4.2.1 Define the goals of the experiment (Step 4.1)**

Planning an experiment begins by carefully considering its objectives. The objectives have already been defined in the UC description and here are used again to explicitly define the experiment.

In the UC example the goal is to investigate the interoperability between a smart meter and a data concentrator, which are supposed to exchange metering data using power line communication (PLC), under grid disturbances of increasing intensity. In other words, the data concentrator is supposed to collect periodical meter data from the smart meter through the physical electrical infrastructure.

#### **4.2.2 Identify the response variables to be measured (Step 4.2)**

Here, in the context defined by the goals of the experiment, a set of measurable response variables is identified.

In the UC example, in order to fulfil the goal of the experiment, the response variable is defined as the success ratio  $\gamma = r/p$  between the number of packets successfully received by the concentrator ( $r$ ) and the total number of packets sent by the smart meter ( $p$ ).

In this example, the response variable is continuous between 0 (no packets received by the data concentrator) and 1 (all data correctly received). There might be cases where the response variable is discrete (for example according to the verdict "pass" or "fail"). Discrete response variables will be treated in the same way as continuous response variables in the subsequent analysis of experiments. The details are provided in Chapter 6.

#### **4.2.3 Identify the input factors (Step 4.3)**

The factors that are considered to potentially influence the response variable are identified and characterised. The factors can be independent or linked by dependencies (such as if-then-else conditions between the inputs or constraints among them). The methodology works in all its facets when the factors are independent.

In the considered UC, the input factors are those causing the disturbance in the power grid. The hypothesis is that the disturbance is due to the presence of harmonics that are multiple of the fundamental ( $\omega_0=50$  Hz) sinusoidal wave.

In the example, the input factors are specified as the amplitudes  $A_1$ ,  $A_2$  and  $A_3$  of voltage harmonics multiple of  $\omega_0$ , i.e. the third harmonic (150 Hz), the fifth (250 Hz) and the seventh (350 Hz).

At the discretion of the experimenter, and based on the goals of the experiment, additional factors, such as higher harmonics  $A_i$  or the phase angles of the (voltage/current) harmonics, could be considered in the set-up.

#### **4.2.4 Identify intervals of variation of the input factors (Step 4.4)**

The intervals of variation of the input factors are defined in the BAIOP, where the standards taken into consideration and their options are fixed. The space of variation of the factors should be set widely enough to be useful for the execution of the interoperability test cases.

Operational ranges for the input factors are defined taking into account the power quality standards. Power quality standards, such as IEC61000, should be examined in order to set-up a realistic test, particularly chapters IEC61000-3-12 and 61000-2-4. These

chapters of the standards refer to the admissible values of total and individual current harmonic distortion and admissible voltage harmonic distortion. The tables summarizing these values are presented in the BAP (see Annex II). Due to the nature of the PLC communication the aim will be to focus on the voltage harmonics.

Having considered standard IEC61000-2-4, the intervals for the factors  $A_k$  in the use case example have been selected as:

$$A_1 \sim U(0, 13.8 V); \quad A_2 \sim U(0, 11.8 V); \quad A_3 \sim U(0, 9.5 V);$$

#### **4.2.5 Sample N values for the input factors within their intervals of variation (Step 4.5)**

The factors are considered as if they were statistical variables. In the use case example, the sampling strategy relies on the use of *quasi-random sequences*, and in particular the Sobol'  $LP_\tau$  sequence [23], [24] which has remarkable low-discrepancy properties and allows the sample points to cover homogeneously the space of factors' uncertainty (an illustration of the advantages of quasi-random sequences with respect to other sampling strategies is provided in Annex III. Moreover, in order to have an uniform coverage of the space of factors when using Sobol'  $LP_\tau$  sequences, the theory suggests to use a sample size N equal to a power of two, i.e. either 8, 16, 32, etc.. The Matlab / Octave script for generating Sobol'  $LP_\tau$  quasi-random sequences is available at:

<https://ec.europa.eu/jrc/sites/jrcsh/files/LPTAU51.rar>

Other sampling strategies could likewise be used to generate the sample, such as Latin Hypercube sampling (LHS) or simple random sampling. Computer programs to generate both LHS and simple random samples are available everywhere. Neither LHS nor simple random sampling recommends the use of specific values of sample size N. However, they have less uniform coverage properties with respect to the Sobol'  $LP_\tau$  sequence using a sample size N equal to a power of two.

By using one of the sampling strategies proposed above, N values for each factor are sampled from the ranges and probability distributions defined in Step 4.4. The choice of N is made based on the experimental resources available. The N sampled values give rise to a numerical matrix (the 'sample matrix') with N rows and a number of columns equal to the number of input factors.

In the UC example, the sampling starts with  $N = 2^3$  values using quasi-random sequences within the ranges and from the probability distributions defined in Step 4.4, generating a sample matrix of size 8x3 as in Table 5.

**Table 5** Example of 8 x 3 sample matrix generated using quasi-random sequences

	$A_1$	$A_2$	$A_3$
<i>Exp. 1</i>	6.9000	5.9000	4.7500
<i>Exp. 2</i>	3.4500	8.8500	2.3750
<i>Exp. 3</i>	10.3500	2.9500	7.1250
<i>Exp. 4</i>	1.7250	7.3750	8.3125
<i>Exp. 5</i>	8.6250	1.4750	3.5625
<i>Exp. 6</i>	5.1750	4.4250	5.9375
<i>Exp. 7</i>	12.0750	10.3250	1.1875
<i>Exp. 8</i>	0.8625	11.0625	6.5313

Each row of the matrix corresponds to a Test Case to be executed. The  $i$ -th Test Case will use the values of the  $i$ -th row of the sample matrix as input factors. A template is proposed to summarise the the DoE procedure (Annex I). The next step is to execute the  $N$  Test Cases described in the next Section (Step 5).

## 5 Interoperability testing (Step 5)

Testing is the critical stage to verify interoperability. An important condition in achieving interoperability is the correct implementation of the standards and specifications. This can be verified by conformance testing: the concerning implementation/device is tested against a test tool or reference implementation of the standard. Conformance testing is also a prerequisite for interoperability testing. Conformance testing also verifies what part of the standard is implemented if it is not a full scope implementation.

The conformance or compliance testing determines to what extent the implementations under test are in accordance with the whole or partial implementation of a specified standard, or to what extent they do so with regards to specific requirements. The methodology developed here focuses on the interoperability testing, thus the implementations which will be selected to be tested should have as a precondition a pass mark in the conformance testing. Nevertheless, if discrepancies or specific problems will be found during the testing exercises, this will be reflected in the relative reports.

Interoperability testing is a procedure in which two or more implementations (systems, products) within a system are tested if they are able to exchange information according to the final defined functionalities. Implementations are tested in their final configuration together with other components of the total architecture, according to the same BAIOP. The aim is to verify that implementations do indeed work together effectively and interoperate, to deliver the expected results. It should be noted that interoperability testing is significantly different from conformance testing because it is possible for two implementations that individually comply with a standard (resulting in a positive conformance test) to be still unable to interoperate. This situation can arise for example when devices have implemented different or conflicting options or cover a different part of the standard(s).

The SGILab approach is towards creating a platform where quantitative assumptions, experimental options and simulations/emulations are systematically tested to assess the final outcome with reference to the stipulated UC, while identifying the factors jeopardising interoperability. Interoperability testing in the SGILab will be based on a systematic procedure carried out under control conditions. Testing will be based on the BAIOP and the Test Cases, either produced by the manufacturer/producer of the equipment under test, or in its absence developed internally. The IOP will clearly determine the requirements of the particular application, function, community, and/or context, to be tested.

The SGILab procedure aims at simulating or emulating real cases scenarios in order to discover potential functional or communication incompatibilities as well as to illustrate the effects or establish a hypothesis of any lack of conformance or compatibility.

The procedure for interoperability testing shall include:

Identification of candidate "Equipment Under Test" (EUT). An EUT is a physical implementation of an equipment that interacts with one or several other pieces of equipment. The specific functionality of the EUT to be tested is here identified

- Identification of the UC: The UC case is selected from the database and should describe the functionality of the EUT to be tested as defined above
- Identification of the BAP: The BAP is selected from the database and derives from the standard which has been used in the design of the EUT's functionality
- Selection of BAIOPs: Based on the UC and the selected above BAP, BAIOP is automatically produced
- Test cases are created based on the BAIOP and the DoE procedure. A companion document for each test case is also prepared
- Verdict/ Results: the pass/fail verdict and the results of the test cases are filed under the respective Test Case



The process is graphically presented below Figure 8 and it shows the procedure that the lab will follow with the use of a functional JRC database. The whole procedure will be automated with the use of the database which will provide the UC, BAP and BAIOP for the testing purposes based on the specific functionality. The Test Cases will be also created and tailored based on DoE.

Test Cases describe the exact sequences of actions required to be realised so that a verdict can be assigned. Steps should be clear and unambiguous. It is important that the steps can be followed exactly as described, so clarity and precision here plays an important role.

Each Test Case shall have a Test Description comprising the following information:

- A Test Case identifier
- The reference UC upon which the test is based (with UC ID and BAIOP ID)
- The interoperability layer on which the test is executed
- A summary of the test
- The purpose of the test: what is the objective of the specific Test Case
- Description of the test sequence in discrete actions
- The Verdict of the Test Case after the execution of the Test Case is documented here

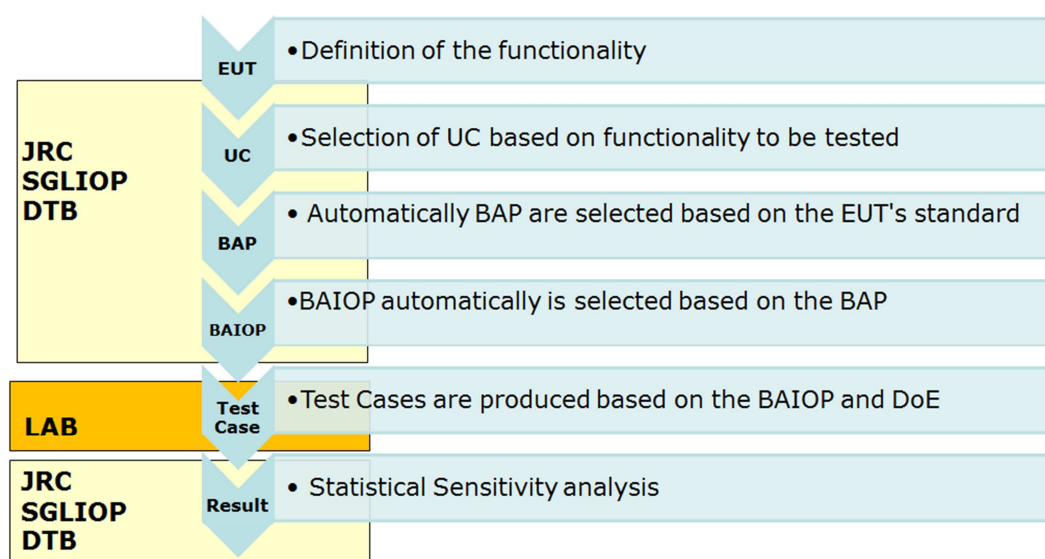
Each Test Case shall also have a companion document. This document is to be filled in during the testing process and it is based on the EUT specifications (hereafter the process becomes device specific). The companion document is filled in once and applies to all the Test Cases. Thus after filling up the companion document, the Test Cases become Specific Device Test Cases and can be used for the IOP testing of the selected EUT. The companion document includes:

- Nameplate specifications
- Technical specifications of the EUT based on its Technical Manual
- Operational specifications of the EUT based on its Technical Manual
- Mounting/ Cabling/Connecting with the SUT of the EUT
- Protection/ Isolation/ Earthing of the EUT
- Specific safety issues
- Configuration/ Initial criteria
- Others (based on the EUT)

For the Test Cases and the Companion document a template has been created in Annex I.

With the use of the database outputs (UC, BAP, BAIOP and TC) the test can be realised then in the physical lab. The result is uploaded back to the database as an evidence for other experiments or further analysis.

**Figure 8** Interoperability Testing Process



## 5.1 Test bed

A Test Bed is a platform for conducting rigorous, transparent, and replicable testing of scientific theories, computational tools, and new technologies.

Test architecture is an abstract description of logical entities, interfaces and communication links involved in a test. Thus a test bed consists of all the elements that support test execution with software, hardware and network configured (instruments, auxiliary services, energy sources, loads, converters, data recorders, panels, users etc.)

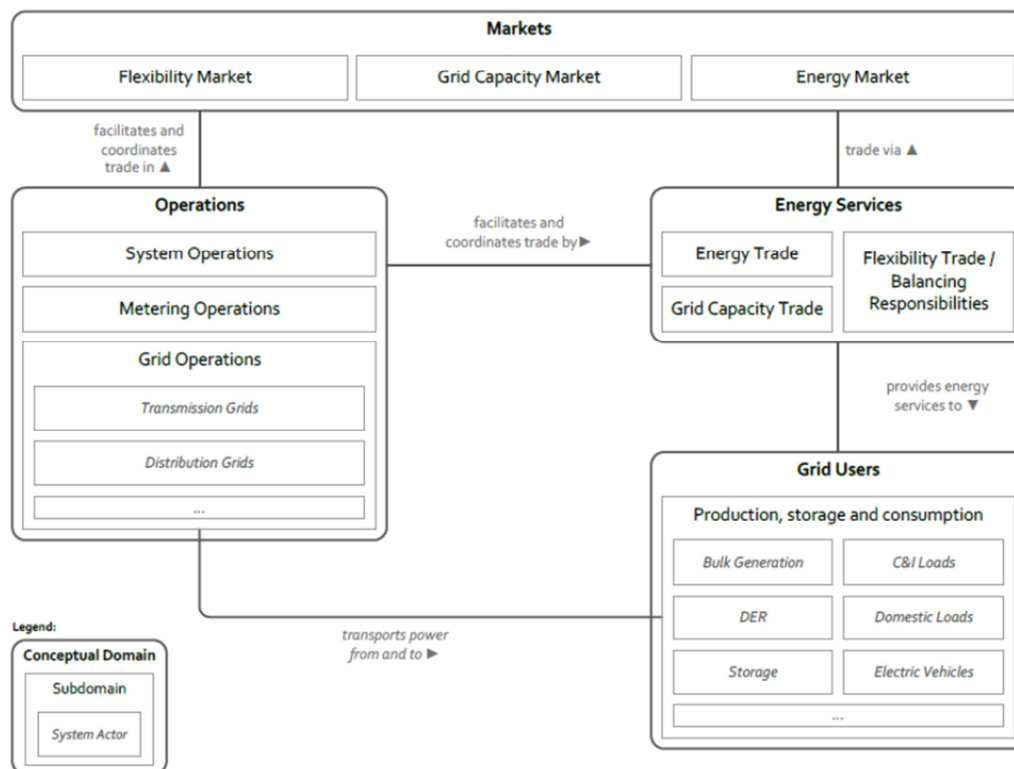
The idea of the test bed is to have a permanent infrastructure for the different areas of work where components or systems can be connected to and assessed from an interoperability perspective. For example, the Advanced Metering Infrastructure test bed will be composed of smart meters, data concentrators, communication networks and control centres that will cover the widest possible range of standards and technologies; this test bed will allow connecting any system (e.g. another smart meter from any manufacturer) to assess its interoperability profile against the reference architecture created. On the other hand though and in order to have the ability to test a number of UCs, test beds should be also flexible and expandable to allow and integrate a number of implementations.

Ideally, the main target is to build test beds as comprehensive as possible in order to allow interoperability testing of components and systems that are based on different international standards. Thus recommended architectures should be used in the design of the test bed. These architectures derive from the conceptual models from CEN/CENELEC/ETSI [12] and seek to serve a common framework enabling the interaction between various stakeholders and aligning the smart grid efforts. Furthermore, these models are well placed on the SGAM thus components, standards and protocols can be clearly defined.

The scope of the report is to develop an IOP methodology and the detailed description of a test bed (instruments, metering and supervisory devices etc.) is out of the scope. Nevertheless, two main conceptual architectures are presented which can be the basis for a test bed design focused in SG functionalities.

## 5.2 Conceptual model for the Smart Grid

**Figure 9** European Conceptual Model for the Smart Grid



Source: [12] CEN-CENELEC-ETSI Smart Grid Coordination Group Smart Grid Reference Architecture, 11-2012

The European Conceptual Model for the Smart Grid describes schematically the future situation of the electrical energy system:

The future situation could best be described as:

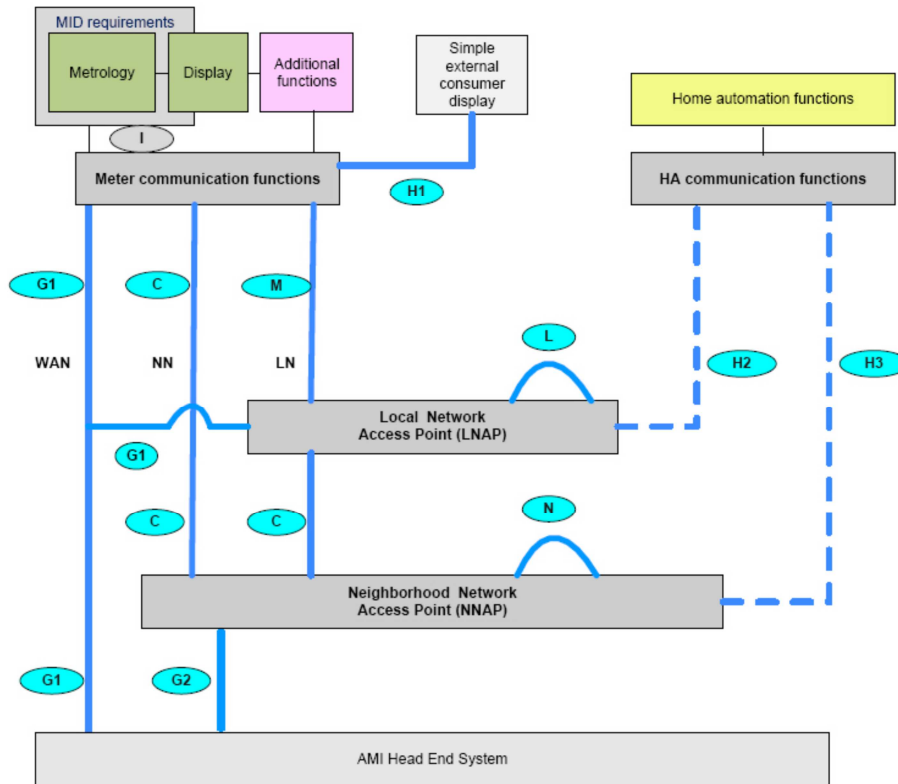
- Demand follows supply, due to the deployment of renewables, which are intermittent in nature
- Growth of the demand due to the electrification of society to meet EU objectives
- Bidirectional flow in the grid: consumers will also produce
- A future grid will need to support:
  - Multiple producing consumers who will sell their electrical surplus to a Virtual Power Plant.
  - Electrical cars
  - The integration of all kinds of distributed energy resources (wind, solar, storage)
- A grid will fulfil these requirements, not only by expanding grid capacity but also by implementing Information and Communication Technologies (ICT) solutions, fully supporting current and future market processes.
- Furthermore a future grid will need the Smart Grid functions, described in the EG1 report of the CEN/CENELEC/ETSI Joint Working Group

The above requirements shall be reflected also in a smart grid test bed.

### 5.3 Advanced Metering Infrastructure test bed

For a smart metering test bed the smart metering architecture recommended by CEN/CENELEC/ETSI is presented [25]. Functional entities and interfaces in a smart metering communications network are presented in Figure 10.

**Figure 10** Reference architecture diagram for smart metering communications



Source: [17] European Smart Grid Task Force Expert Group 1- Standards and Interoperability. Interoperability of interfaces for the large scale roll out of smart metering systems in EU Member States, August 2016

A simplified overview of the same architecture with a focus on flexibility management is proposed by CEN/CENELEC/ETSI in [17].

### 5.4 Equipment Under Test

The Equipment Under Test (EUT) is the device which functionality and interoperability within the system is going to be tested. It is a physical implementation of an equipment that interacts with one or several other equipment. For the purpose of the test, there are some minimum requirements which the device shall fulfil in order to be identified as an EUT:

- The device should be explicitly described as an actor/functionality within a UC
- The device should have passed a certified conformance test
- The device should be accompanied with a technical manual where all the standards under which the device is designed should be specified (especially communication and information standards)
- The device should be accompanied by safety instructions and operation manual and its implementation should not put other equipment or staff in any danger

## 6 Statistical Analysis of experiments (Step 6)

The data acquired with the execution of the N Test Cases according to the scheme suggested by the DoE procedure allow for two dedicated analyses of experiments [22]:

- **Sensitivity analysis:** when varying the input factors within their realistic intervals (i.e., the standards that they have to comply with) the analyst wants to obtain a ranking of factor importance, determining which are the factors that significantly affect the performance of the system and those that do not influence the system response.
- **Failure analysis:** within the realistic intervals for the input factors, which were selected in compliance with the standards, particular combinations of inputs may lead to a "failure" of the system (i.e., a "fail" as verdict of the interoperability test). In other words, the analyst aims to get insights on the "unwanted" combinations of inputs that lead to a failure of the system and identify the boundary between the verdict "pass" and the verdict "fail".

As mentioned in Step 4.2, the response variable can be continuous (for example ranging in the interval [0; 1] as in the UC *Remote Metering under Power Quality Stress Conditions*) or discrete (for example according to a verdict "pass" or "fail"). Continuous and discrete response variables are treated likewise in the analysis of experiments.

### 6.1 Build the empirical model (Step 6.1)

After performing the N laboratory experiments, an 'experimental matrix' is built, by adding to the sample matrix an additional column on the right, where the values of the measured responses  $\gamma$  are recorded.

In order to have a representative exemplification of all possible situations that may occur during interoperability testing, the authors have used dummy values of the response variable  $\gamma$  in the rest of this chapter.

The experimental matrix obtained by conducting the tests (see Table 6 for the UC example *Remote Meter Read Under Power Quality Stress Conditions*) allows for the construction of an empirical model which, in turn, allows the experimenter to establish cause-and-effect relationships between the input factors and the response variable.

If the response variable were discrete, such as the one displayed in Table 7, the "pass" and "fail" responses are converted into 0 and 1 and then the empirical model can be equally estimated.

**Table 6** Experimental matrix (8 rows and 4 columns), with the values of system response

	$A_1$	$A_2$	$A_3$	$\gamma$
Exp. 1	6.9000	5.9000	4.7500	0.8118
Exp. 2	3.4500	8.8500	2.3750	0.9710
Exp. 3	10.3500	2.9500	7.1250	0.4878
Exp. 4	1.7250	7.3750	8.3125	0.9124
Exp. 5	8.6250	1.4750	3.5625	0.9228
Exp. 6	5.1750	4.4250	5.9375	1.0000
Exp. 7	12.0750	10.3250	1.1875	0.0000
Exp. 8	0.8625	11.0625	6.5313	0.7768

**Table 7** Experimental matrix (8 rows and 4 columns), with discrete values of system response

	$A_1$	$A_2$	$A_3$	$\gamma$
Exp. 1	6.9000	5.9000	4.7500	Pass
Exp. 2	3.4500	8.8500	2.3750	Fail
Exp. 3	10.3500	2.9500	7.1250	Pass
Exp. 4	1.7250	7.3750	8.3125	Fail
Exp. 5	8.6250	1.4750	3.5625	Pass
Exp. 6	5.1750	4.4250	5.9375	Pass
Exp. 7	12.0750	10.3250	1.1875	Fail
Exp. 8	0.8625	11.0625	6.5313	Fail

The empirical model is a mathematical tool that is used to predict the system response at factors' combinations where experiments have not been performed. The execution of the empirical model requires negligible time with respect to collect new system response from a real experiment. Multiple executions of the empirical model over the space of input factors allow the analyst to perform both sensitivity and failure analyses, which are illustrated in Step 6.2.

The methodology recommends building the empirical model using the method of Gaussian Processes (GP), although other tools can be taken in consideration. The theory and other details on GPs are provided in Annex III.

Additional documentation, and the related R package for the GP routine, can be found at:

<https://cran.r-project.org/web/packages/tgp/index.html>

Other software packages embed routines implementing GPs and can be valid alternatives to the suggested R package.

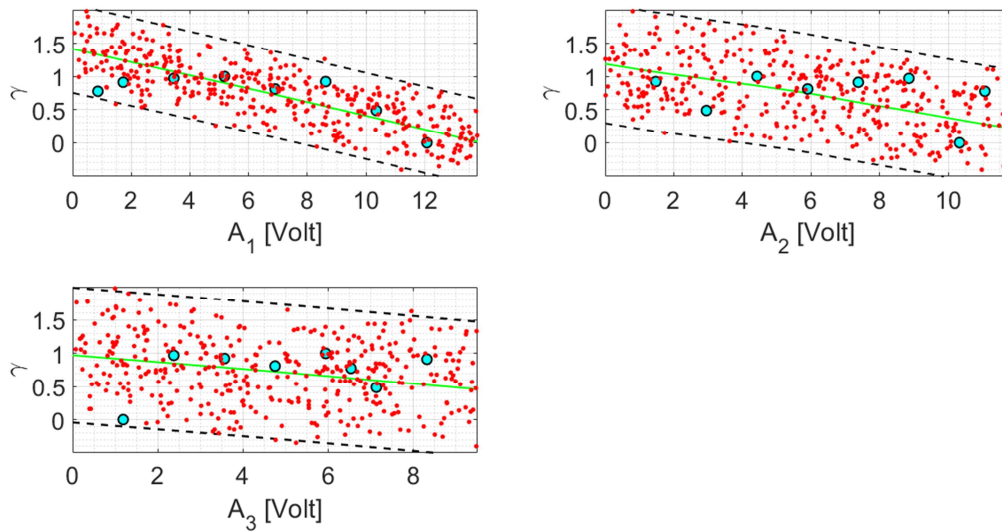
Using the experimental matrix in Table 6 as input to the GP package, the empirical model  $\hat{\gamma} = M(A_1, A_2, A_3)$ , establishing the cause-effect relation between the input factors  $A_1, A_2, A_3$  and  $\gamma$ , is estimated. The empirical model can be executed at any point over the 3-dimensional space with coordinates  $[A_1, A_2, A_3]$  in order to evaluate the corresponding predicted response  $\hat{\gamma}$  without performing the real experiment. The red points in Figure 11 are plots of  $\hat{\gamma}$  vs  $A_1$ ,  $\hat{\gamma}$  vs  $A_2$  and  $\hat{\gamma}$  vs  $A_3$ .

The green lines in Figure 11 represent  $E(\hat{\gamma}|A_k)$ , i.e. the conditional expectation of the response given  $A_k$  (where  $k = 1, 2, 3$ ). They are obtained by averaging all the  $\hat{\gamma}$ 's computed over a fine-resolution uniform grid selected in the space of all factors except  $A_k$ .  $E(\hat{\gamma}|A_k)$  is then computed over all values of  $A_k$ . The variance of  $E(\hat{\gamma}|A_k)$  measures the importance of input factor  $A_k$  (see sensitivity analysis in Step 6.2). Consequently, if  $E(\hat{\gamma}|A_k)$  is a flat line,  $A_k$  is a non important factor. In this example,  $A_1$  is the most important factor, whereas  $A_3$  is the least important.

The dashed black lines are automatically calculated by the GP package and correspond to the 95% confidence bounds of  $E(\hat{\gamma}|A_k)$ , thus giving the accuracy of the empirical model in predicting the conditional expectations.

The 8 experimental points are highlighted in cyan and lie in the cloud of red points within the confidence bounds of  $E(\hat{\gamma}|A_k)$ .

**Figure 11** The three main effect plots, linking  $\hat{\gamma}$  respectively to  $A_1$ ,  $A_2$  and  $A_3$ .



## 6.2 Perform sensitivity analysis and failure analysis (Step 6.2)

After building an empirical model, the execution of both sensitivity and failure analysis follows.

For sensitivity analysis, variance decomposition methods are nowadays recognised as the most popular and versatile. The same R routine <https://cran.r-project.org/web/packages/tgp/index.html> that embeds the GP package also produces the sensitivity analysis illustrated hereafter.

**Table 8** Sensitivity indices for the use case example

	$S_i$	$T_i$
$A_1$	0.6025 (0.0590)	0.6250 (0.0475)
$A_2$	0.2975 (0.0465)	0.3250 (0.0620)
$A_3$	0.000 (0.0393)	0.1250 (0.0815)

Table 8 presents two types of sensitivity indices for the use case example: the first order indices  $S_i$ , which quantify how much a given input affects, per-se, the variance of the system response, and the total order indices  $T_i$ , which supply an overall measure of importance of a given input, taking into account the effects of possible interactions of such input with all the others. Both  $S_i$  and  $T_i$  are shares of the total variance of the response variable and hence are normalised between zero and one. The standard deviations of the sensitivity indices are shown in parenthesis. The evaluation of both sensitivity indices is important to spot non-linear, non-additive input-response relationships that can occur in complex systems. More details on variance-based sensitivity analysis and first/total order sensitivity indices are given in Annex III.

On the other hand, failure analysis aims at discovering the regions of the input factors' space where the system is interoperable, and where is not. For example, in the case of continuous values of response variable  $\gamma$ , one could assume that the system under investigation is considered non-interoperable when the success ratio  $\gamma$  is lower than some threshold value  $\gamma_0$ , defined according to certain standards, e.g.,  $\gamma_0 = 0.9$ :

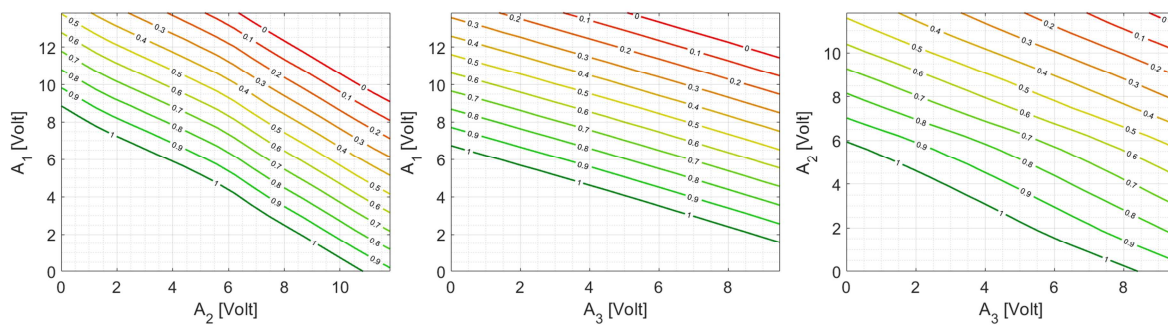
$$\begin{cases} \text{system is interoperable} & \text{for } \gamma > 0.9 \\ \text{system is not interoperable} & \text{for } \gamma < 0.9 \end{cases}$$

In this regard, 2-dimensional plots showing the pattern of the predicted values of  $\gamma$  for each pair of inputs can be produced, becoming useful for failure analysis (Figure 12)

If the empirical model is run over a 3-dimensional regular high-resolution grid, the quantity  $E(\gamma|A_1, A_2)$  can be computed, which represents the conditional expectation of the response for a given value of  $A_1$  and  $A_2$ , varying  $A_3$ .

This arithmetic mean results in a 2-dimensional matrix over the  $A_1$ - $A_2$  plane, which can be easily visualised with a contour plot. The contour plot displays isolines of the  $E(\gamma|A_1, A_2)$  matrix, as shown in the left plot of Figure 12. The middle and right plots represent the isolines for  $E(\gamma|A_1, A_3)$  and  $E(\gamma|A_2, A_3)$ , respectively. The interpretation of the results from Table 8 and Figure 12 is given in step 6.3.

**Figure 12** The three contour plots used for failure analysis, linking  $\gamma$  to  $(A_1, A_2)$ ,  $(A_1, A_3)$  and  $(A_2, A_3)$



### 6.3 Analysis and interpretation of the results (Step 6.3)

Both analytic and visual results are interpreted and lead to a broader understanding of the factors that are mostly responsible for the failure of the system (sensitivity analysis) and the regions of the factors' space that are crucial for interoperability (failure analysis). Sensitivity and failure analyses are powerful tools to be used in a complementary way. Interesting conclusions can be derived from applying these tools by using the results derived from sensitivity analysis as a basis for carrying out the failure analysis.

Starting from sensitivity analysis, Table 8 shows a clear ranking in order of importance of the three factors. The total order indices are slightly larger than the first order effects, meaning that there is a small interaction between the factors, in other words there are some combinations of factors' values which are responsible for interoperability. In conclusion,  $A_1$  is the most influential factor, followed by  $A_2$  and, last,  $A_3$ , which is non influential at all. This information is also useful because it would mean that establishing an ad-hoc standard for  $A_3$  is not essential.

The standard deviations of all the sensitivity indices are small enough to guarantee that their estimates do not overlap and hence there is a clear ranking of the factors.

After carrying out the sensitivity analysis, its results are used to correctly interpret the conclusions which can be derived from the failure analysis, in order to infer which is the domain of failure of the system.



For the use case example, since sensitivity analysis reveals that  $A_1$  and  $A_2$  are the most important factors (with  $A_3$  completely negligible), the attention of the analyst should then focus only on the left plot of Figure 12, which depicts the pattern of the predicted success ratio  $\hat{\gamma}$  over the  $A_1$ - $A_2$  plane. Instead, looking at the plots for  $A_1$ - $A_3$  and  $A_2$ - $A_3$  would be misleading and unusual, since  $A_3$  has already revealed to be non-influential.

More in detail, if for example the statement "system is not interoperable for  $\gamma < 0.9$ " holds, the analysis of the  $A_1$ - $A_2$  plot shows that relatively high values of  $A_1$  ( $A_1 > 10$  V) are always responsible for the failure of the system, regardless of the values of  $A_2$ . This confirms the conclusion " $A_1$  is the most influential factor" derived from the sensitivity analysis.

Instead, for lower values of  $A_1$ , the system is not interoperable only for high values of  $A_2$  (which then becomes important only in combination with  $A_1$ , but not per-se). This is an example in which international standards for  $A_1$  and  $A_2$  are respected but the system is not interoperable for some of their combinations.

#### 6.4 Add new design points and perform new analysis (Step 6.4)

If the analyst is not satisfied with the accuracy of the results (for instance, the sensitivity indices are not accurate enough, or the confidence bound of the scatter-plots in Figure 11 are unacceptably loose), a number of additional experiments can be executed (if enough experimental budget is available). In this case the procedure restarts from step 4.5 of the DoE.

Based on the resources available, the analyst can choose how many new design points/experiments s/he can afford (e.g., two more). The additional factors' values are again generated by using the same sampling strategy selected in step 4.5. If the Sobol' LP $\tau$  quasi-random number sequences generator is used, a number of additional points equal to a power of two is required to ensure homogeneous coverage of the space of the inputs.

The new experiments are executed (see Chapter 5) and a new version of the empirical model is developed (step 6.1). Both sensitivity and failure analysis can be repeated (step 6.2).

For the use case example, the results from step 6.4 using two additional design points ( $N = 10$ ) are given in

Table 9 (sensitivity analysis) and Figure 13 (failure analysis). Beginning from Figure 13, the contour plots for  $A_1$ - $A_3$  and  $A_2$ - $A_3$  are no longer shown, since the plot linking  $\hat{\gamma}$  with  $[(A_1, A_2)]$  is the only meaningful one for the purpose of failure analysis.

**Table 9** Sensitivity indices for the use case example ( $N = 10$ )

	$S_i$	$T_i$
$A_1$	0.5925 (0.0358)	0.6450 (0.0393)
$A_2$	0.2925 (0.0400)	0.3050 (0.0354)
$A_3$	0.0975 (0.0401)	0.1150 (0.0363)

**Figure 13** The contour plot used for failure analysis, linking  $\hat{\gamma}$  to  $(A_1, A_2)$ , with  $N = 10$  points.

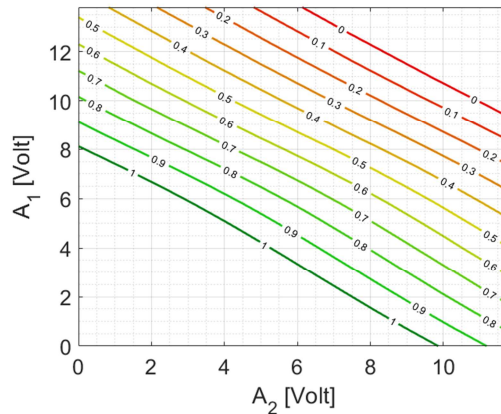


Table 9 provides more accurate values for the sensitivity indices. Note the smaller values for the standard deviations. The ranking of the factors in order of importance is confirmed.

Instead, in Figure 13 the  $\hat{\gamma}=0.9$  (which is assumed to be the interoperability boundary as an example) is more shifted towards the lower-left corner.

The iterative scheme of adding new experimental points can be repeated as many times as deemed appropriate until reaching a sufficient level of accuracy of the sensitivity indices estimates (in terms of their standard deviations) and / or the pattern of the resulting contour plots looks quite stable.

For example, with two more experiments ( $N = 12$ ) the accuracy of the sensitivity indices improves, with the values of their standard deviations further reduced (Table 10), but the pattern of the success ratio is further shifted towards lower values of  $A_1$  and  $A_2$  (Figure 14, left). In particular, a lack of interoperability caused by high values of  $A_1$  (regardless of  $A_2$ ) is undoubtedly confirmed, but now the failure domain ( $\hat{\gamma} < 0.9$ ) occupies a broader region of the  $A_1$ - $A_2$  plane.

With  $N = 14$  points, the pattern of the contour plots from the failure analysis become finally stable and reasonably defendable. Compared with the case with  $N = 12$  points, this stability of results suggests that there is no further need to execute more experiments.

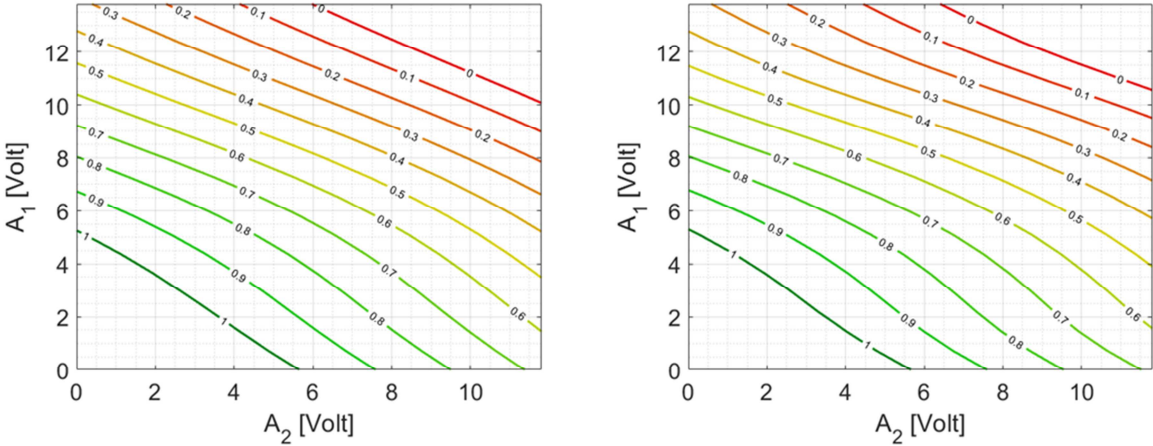
In this situation, the analyst can easily conclude that the domain where there is interoperability is confined in the region

$$A_1 + A_2 < 6 \text{ V}$$

**Table 10** Sensitivity indices for the use case example (N = 12)

	$S_i$	$T_i$
$A_1$	0.5975 (0.0453)	0.6450 (0.0424)
$A_2$	0.2725 (0.0395)	0.3150 (0.0405)
$A_3$	0.000 (0.0374)	0.0950 (0.0375)

**Figure 14** The contour plots used for failure analysis, linking  $\hat{\gamma}$  to  $((A)_1, (A)_2)$ , with N = 12 (left) and N = 14 (right) points



## **7 Database for the support of the Interoperability Testing Methodology**

A database is a fundamental component of the information system supporting the interoperability methodology. All the results of a testing will be stored in the database for further analysis and archiving. Tools could be developed at a later stage for extracting rules or patterns that enrich our understanding and extend our knowledge about certain type of interoperability tests. The ultimate goal is to form a knowledge base supporting both facts and reasoning capabilities about those facts.

The development of such a database system includes the following stages, which also determine the life cycle of the database development:

1. Definition and Planning
2. Requirements elicitation and analysis
3. Database Design
4. Database Implementation

### **7.1 Definition and planning phase**

The definition and planning phase includes activities related to realisation of the system as part of the interoperability testing methodology. Its purpose should include support to storing Uses Cases and BAPs. The main tasks of the system (like archiving, restoring etc.) should be clearly mentioned and the resources needed should be included in the description. The boundaries of the system should be clearly specified. This could include connections with the interoperability testing methodology at several stages and links to other potential systems of the Smart Grid Interoperability Laboratory. Stakeholders, users and utilisation of the system should be also included in the description.

### **7.2 Requirements elicitation and analysis**

During this phase requirements are collected from the users and stakeholders. The requirements state who is going to use the system and determine the roles of certain users as well as the information exchanged. Users could be other subsystems. It is important during this phase to describe the data used or gathered and provide as much as possible available details of the data as well as additional requirements for the database system taking into consideration the testing methodology. Every stage of the methodology may have different needs for storing or retrieving data and consequently different requirements. This requires a careful observation of each stage of the methodology and registration of potential storage needs or database support. These needs should be discussed with potential users. Potential problems should be stated. A use case of describing the basic functionality and the roles of the subsystems in the testing methodology will be sufficient. This use case should be able to specify external behavior, basic functional requirements including potential evolution of the system. The requirements should be checked for completeness, consistency and correctness.

### **7.3 Database design**

This is one of the most critical phases in the development. The design phase can be subdivided into:

- Conceptual design
- Logical Design
- Physical Design

During this conceptual phase the conceptual model of the database should be developed. An object oriented model (UML) or an entity relationship model (ER) should be developed. This is a high level data model of the specific application of the testing

methodology. Attributes of entities or storing objects should be also included in the model.

During the logical design phase the conceptual model is translated into a database schema. This means that a UML model is translated into a class diagram and object links or an entity relationship diagram is translated into relations. However because the testing methodology will naturally produce semi-structured data for which detailed ER or OO model cannot be easily defined, an XML modelling could be also used for unstructured or weakly structured data.

The Physical design is concerned about the storage technology to be used. It could be Relational Data Base Management System (RDBMS), Object Oriented Data Base Management System (OODBMS), Semi structured XML Data Base Management System (XDBMS) or a combination of technologies.

## **7.4 Implementation**

The Physical Design will drive the implementation of the system. SQL will be used for implementing RDBMS, a high level programming language will be used in OODBMS, XML and XQuery will be used in XDBMS.

## **8 Conclusions**

The report presents a methodology for developing smart grid interoperability tests, which is based on procedures developed by several standardisation bodies and working groups. It can be seen by those who work in smart grid interoperability as a set of working steps to complete an interoperability test. The methodology provides a theoretical analysis of working means or methods that have been proposed for tackling the complexity imposed by the concept of smart grid interoperability. It also presents a unified approach for developing interoperability testing specifications by using and extending best practices with main target to achieve a common framework. This systematic approach will further facilitate and encourage the transition of the classical energy system toward the smart grid, since the smart grid integrates different assets and applications into one functional system.

The methodology is used mainly for prototyping interoperability tests and consist of 6 steps; use case creation, basic application profile (BAP) creation, basic application interoperability profile (BAIOP) creation, statistical design of experiment, testing and statistical analysis.

The procedure described in chapters 4 and 6 provides the experimenter with an understanding of the methodology workflow. An eight-step procedure is proposed to support the Statistical Design and Analysis of Experiments of Interoperability (4.1-4.4 and 6.1-.6.4). To achieve the expected outcomes of the experimental program, the procedure is enriched with sensitivity analysis and failure analysis. The procedure is based on modern methods of design and analysis of experiments, namely quasi-random number generators, Gaussian processes empirical modelling techniques and global sensitivity analysis based on the decomposition of the variance of the system response.

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## List of abbreviations and definitions

AMI	Advanced Metering Infrastructure
BAIOP	Basic Application Interoperability Profile
BAP	Basic Application Profile
EPRI	Electric Power Research Institute
EUT	Equipment Under Test
HES	Head End System
ID	Identifier
IEC	International Electrochemical Commission
LNAP	Local Network Access Point
MDM	Meter Data Management
NNAP	Neighbourhood Network Access Point
PLC	Power Line Communication
QoS	Quality of Service
SGAM	Smart Grid Architecture Model
SG-CG	Smart Grid Coordination Group
SG-CG/SP	Smart Grid Coordination Group/ Sustainable Processes
SGILab	Smart Grid Interoperability Laboratory
TC	Test Case
TCP/IP	Transmission Control Protocol/ Internet Protocol
UCMR	Use Case Management Repository
UC	Use Case
UML	Unified Model Language
XML	Extensible Markup Language

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## Annexes

### Annex I. Templates

#### Annex I.1 SGILab UC template

##### UC.1.1 General

##### UC.1.2 Name of Use Case

ID	Domain <i>see Annex A Selection List</i>	Name of Use Case	Level of Depth <i>Cluster, High Level Use Case, Detailed Use Case</i>

##### UC.1.3 Version management

Changes / Version	Date	Name Author(s) or Committee	Domain Expert	Area of Expertise / Domain / Role	Title	Approval Status  <i>draft, for comments, for voting, final</i>

##### UC.1.4 Basic information to Use Case

Source(s) / Literature	Link	Conditions (limitations) of Use

<b>Maturity of Use Case</b> – <i>in business operation, realized in demonstration project, , realised in R&amp;D, in preparation, visionary</i>
<b>Prioritisation</b>
<b>Generic, Regional or National Relation</b>

<b>View</b> - <i>Technical / Business</i>
<b>Further Keywords for Classification</b>

### UC.1.5 Scope and objectives of Use Case

Scope and Objectives of Function

### UC.1.6 Narrative of Use Case

Narrative of Use Case
<b>Short description</b> – max 3 sentences
<b>Complete description</b>

### UC.1.7 Actors: people, systems, applications, databases, the power system, and other stakeholders (from CEN-CENELEC-ETSI Smart Grid Coordination Group – Sustainable Processes list of actors)

Actor Name	Actor Type	Actor Description	Further information specific to this Use Case

### UC.1.8 Issues: Legal Contracts, Legal Regulations, Constraints and others

Issue - here specific ones	Impact of Issue on Use Cases	Reference – law, standard, others

### UC.1.9 Preconditions, Assumptions, Post condition, Events

Actor/System	Triggering Event	Pre-conditions	Assumption

### UC.1.10 Referenced standards and / or standardisation committees (if available) from IOP TOOL and IEC smart grid standards map found in <http://smartgridstandardsmap.com/>

Relevant Standardisation Committees	Standards supporting the Use Case	Standard Status

### UC.1.11 General Remarks

General Remarks

### UC.2 Drawing or Diagram of Use Case

**Drawing or Diagram of Function** – recommended “context diagram” and “sequence diagram” in UML

**UC.3 Step by step analysis of Use Case**

S.No	Primary Actor	Triggering Event	Pre-Condition	Post-Condition

**UC.3.1 Steps – Normal sequence**

Function Name :						
Step No.	Event	Description of Process/Activity	Information Producer	Information Receiver	Information Exchanged	Technical Requirements ID

**UC.3.2 Steps – Alternative, error management, and/or maintenance/backup scenario**

Use Case Name :						
Step No.	Event	Description of Process/Activity	Information Producer	Information Receiver	Information Exchanged	Technical Requirements ID

## Annex I.2 SGILab BAP template

### BAP.1.1 Identifiers

BAPs ID	USE CASE ID	Standards

### BAP.1.2 Version management

Changes / Version	Date	Name Author(s) or Committee	Domain Expert	Area of Expertise / Domain / Role	Title	Approval Status <i>draft, for comments, for voting, final</i>

### BAP.1.3 Referenced documents/ terms/ definitions

Source(s) / Literature	Link	Conditions (limitations) of Use

Terms	Definitions

### BAP.1.4 Functionality

Scope and Objectives of Functionality

### BAP.1.5 Analysis of the standard(s)

Analysis

## Annex I.3 SGILab BAIOP template

### BAIOP.1.1 Identifiers

BAIOP ID	BAPs ID	USE CASE ID

### BAIOP.1.2 Version management

Changes / Version	Date	Name Author(s) or Committee	Domain Expert	Area of Expertise / Domain / Role	Title	Approval Status <i>draft, for comments, for voting, final</i>

### BAIOP.1.3 Referenced documents/ terms/ definitions

Source(s) / Literature	Link	Conditions (limitations) of Use

Terms	Definitions

### BAIOP.1.4 Scope and objectives of BAIOP

Scope and Objectives of Functionality

### BAIOP.1.5 Testing process

#### BAIOP.1.5.1 Pre-test definitions

Pre- test definitions	
Evaluation Criteria	
Specification of EUT	
Technical Specification	(definition of the minimum technical requirements)
Operational specifications	(definition of the minimum operational requirements)
Initial Criteria	(unambiguous identification to ensure that the EUT is correct, safety requirements to avoid hazard during testing, further passed tests as precondition for the interoperability test)



<b>Specification of SUT</b>	
Test Bed	
Devices/ Equipment	
Technical Specifications	
Operational Specifications	
Configuration	
Interfaces/ Communication Infrastructure	
Service Access Point	
Special Equipment	
Software	
Metering and control infrastructure	
Measuring values	
<b>Others</b>	
Ambient Conditions	
Human Intervention	
Staffing and training needs	
Security Aspects	

## Annex I.4 SGILab Statistical DOE template

### DOE.1 Identifiers

BAIOP ID	BAPs ID	USE CASE ID

### DOE.2 Design

Design	Descriptions
Define the goals of the experiment	
Identify the system responses to be measured	
Identify the input factors	
Identify intervals of variation of the inputs	
Sample N values for the inputs within their intervals of variation	

### DOE.3 Test definitions/ test cases (this table is used as many times as the Test Cases)

Test Case ID	
BAIOP ID/ UC ID	
Interoperability Layer	
Summary of the Test	
Test Purpose	
<b>Test Description</b>	
Step 1	
Step2	
Step n	
Verdict	

### DOE.4. Companion document (to be filled in after the selection of EUT)

EUT ID	
BAIOP ID/ UC ID	
NamePlate	
Technical Specification	

<i>Operational Specification</i>	
<i>Mounting/ Cabling/Connecting</i>	
<i>Protection/ Isolation/ Earthing</i>	
<i>Specific safety issues</i>	
<i>Configuration/ Initial criteria</i>	
<i>Others (based on the EUT)</i>	

## Annex II. Example: Remote meter read under power quality stress conditions SGILab UC template

### UC.1.1 General

### UC.1.2 Name of Use Case

<b>ID</b>	<b>Domain</b> <i>see Annex A Selection List</i>	<b>Name of Use Case</b>	<b>Level of Depth</b> <i>Cluster, High Level Use Case, Detailed Use Case</i>
1/2016	Advanced Metering Infrastructure (AMI)	Remote Metering Under Power Quality Stress Conditions	Primary (high level use)

### UC.1.3 Version Management

<b>Changes / Version</b>	<b>Date</b>	<b>Name Author(s) or Committee</b>	<b>Domain Expert</b>	<b>Area of Expertise / Domain / Role</b>	<b>Title</b>	<b>Approval Status</b> <i>draft, for comments, for voting, final</i>
Version 1.0 Use case description	10-10-2016	Alexandre Lucas Stefano Tarantola	Primary	Energy systems & Statistics	Researchers	For Comments
Version 2.0 Use case description Update to actor's description, to maintain consistency with Cen/ Cenelec/Etsi SG-CG-Sustainable Processes Doc. 2012 (Annex A)	14-10-2016	Alexandre Lucas	Primary	Energy systems	Researchers	For Comments
Version 3.0 Diagram at the end inserted to show some applicable standards on the communication layer.	19-10-2016	Alexandre Lucas	Primary	Energy systems	Researchers	For Comments
Version 4.0 Input to design of experiments	11-10-2017	Alexandre Lucas Stefano Tarantola	Primary	Energy systems	Researchers	Proceed to experiment
Version 5.0 Update to match the templates	27-03-2018	Alexandre Lucas	Primary	Energy systems	Researchers	Proceed to experiment

### UC.1.4 Basic Information to Use Case

Source(s) / Literature	Link	Conditions (limitations) of Use
Smart Grid Interoperability tool - SGCG WebSite	<a href="http://www.cencenelec.eu/standards/Sectors/SustainableEnergy/SmartGrids/Pages/default.aspx">http://www.cencenelec.eu/standards/Sectors/SustainableEnergy/SmartGrids/Pages/default.aspx</a>	NA
Discern - Distributed Intelligence for Cost-effective and Reliable Solutions Project (FP7) Website – Tools and Final	<a href="http://www.discern.eu/project_output/finalreport.html">http://www.discern.eu/project_output/finalreport.html</a>	NA
Cen/Cenelec/Etsi Smart Grid Coordination Group – Smart Grid Reference Architecture Nov 2012 pp.107	<a href="http://ec.europa.eu/energy/sites/ener/files/documents/xpert_group1_reference_architecture.pdf">http://ec.europa.eu/energy/sites/ener/files/documents/xpert_group1_reference_architecture.pdf</a>	NA
Cen/Cenelec/Etsi SG-CG-Sustainable Processes Doc. Nov 2012 pp.,101	<a href="http://ec.europa.eu/energy/sites/ener/files/documents/xpert_group1_sustainable_processes.pdf">http://ec.europa.eu/energy/sites/ener/files/documents/xpert_group1_sustainable_processes.pdf</a>	NA
Smart Grid Coordination Group M490/I – Smart Grid Interoperability Methodologies to facilitate Smart Grid system interoperability through standardisation, system design and testing 31-10-2014 pp.116	<a href="ftp://ftp.cencenelec.eu/EN/EuropeanStandardisation/HotTopics/SmartGrids/SGCG_Interoperability_Report.pdf">ftp://ftp.cencenelec.eu/EN/EuropeanStandardisation/HotTopics/SmartGrids/SGCG_Interoperability_Report.pdf</a>	NA

<b>Maturity of Use Case</b> - <i>in business operation, realised in demonstration project, , realised in R&amp;D, in preparation, visionary</i>
Under development in the JRC SGILab
<b>Prioritisation</b>
<ul style="list-style-type: none"> <li>• Obligatory, must be supported by metering standards</li> <li>• Business need (long term impact)</li> <li>• To be finished in 2016</li> </ul>
<b>Generic, Regional or National Relation</b>
Generally applicable in Europe

<b>View</b> - <i>Technical / Business</i>
Technical
<b>Further Keywords for Classification</b>
Smart Metering, Meter Reading. Power Quality, AMI, Concentrator, PLC

### UC.1.5 Scope and objectives of Use Case

<b>Scope and Objectives of Function</b>
<p>The scope of this Use Case is determined by the SM-CG functional reference architecture (SMCG Sec0041 DC) that describes the functional entities of the Advanced Metering Infrastructure (AMI) .</p> <p>The Use case objective is to analyze the performance of communication of metadata between a smart meter and an concentrator subject to disturbances of various intensities in the grid. This means, it assumes that at an initial stage there is already interoperability between the components. The goal is to check if the existing interoperability is disrupted when power quality deteriorates.</p>

### UC.1.6 Narrative of Use Case

<b>Narrative of Use Case</b>
<p><b>Short description</b> - max 3 sentences</p>
<p>Considering the PLC communication option of some smart meters, which use the physical electrical infrastructure, this Use Case analyses how the periodic collection of meter data by an concentrator device is affected by different low power quality scenarios.</p>
<p><b>Complete description</b></p>
<p>PLC is considered as one of the main options for communication between smart meters and concentrators. The conditions under which this communication is foreseen considers a certain level of power quality assured by the grid. However, the power quality levels may vary within ranges stated in specific standards (eg EN 50160). There is a need to investigate if, when varied from their nominal values, power quality parameters could have an impact on the interoperability between the smart meter and the concentrator.</p> <p>In the Ispra SGILab making use of the power amplifier (PA) equipment, a tri-phase connection will be made to the smart meter test bed. The PA will be initially used to generate a reference clean power supply to feed a load connected to the test bed. Using a smart meter analyser, the communication performance will be recorded.</p> <p>At a second stage the PA will be configured to supply electricity with low levels of power quality by changing the related parameters in the Simulink software of the PA.</p> <p>Under these stress-tests the communication performance will again be recorded by the smart meter analyser.</p>

### UC.1.7 Actors: People, systems, applications, databases, the power system, and other stakeholders (from CEN-CENELEC-ETSI Smart Grid Coordination Group – Sustainable Processes list of actors)

<b>Actor Name</b>	<b>Actor Type</b>	<b>Actor Description</b>	<b>Further information specific to this Use Case</b>
A (operator)	Person	<p>MDC</p> <p>Entity that offers services on a contractual basis, to collect metering data related to supply and to provide them to the relevant actor. The party is responsible for meter reading and quality control of the reading</p> <p>MO</p> <p>Entity which offers services on a contractual basis to provide, install, maintain, test, certify and decommission physical metering equipment related to a supply</p> <p>MDA</p> <p>Entity which offers services to aggregate metering data by grid supply point on a contractual basis</p>	

B (user of the Smart Meter)	Person	Consumer End user of electricity, gas, water or heat MO - Entity which offers services on a contractual basis to provide, install, maintain, test, certify and decommission physical metering equipment related to a supply	
MDMS	System	MDMS - System for validating, storing, processing and analyzing large quantities of meter data.	
HES	System	Central Data System collecting data via the AMI of various meters in its service area.	The HES communicates via a WAN directly to the meters and/or to the NNAP of LNAP
NNAP	System	The Neighbourhood Network Access Point is a functional entity that provides access to one or more LNAP's, metering end devices, displays and home automation end devices connected to the neighbourhood network (NN). It may allow data exchange between different functional entities connected to the same NN	Optional functionality that results in optional steps in the Use Case
LNAP	System	The Local Network Access Point is a functional entity that provides access to one or more metering end devices, displays and home automation end devices connected to the local network (LN). It may allow data exchange between different functional entities connected to the same LN	Optional functionality that results in optional steps in the Use Case
SM	System	Meter with additional functionalities one of which is data communication	

**UC.1.8 Issues: Legal contracts, legal regulations, constraints and others**

<b>Issue</b> <i>- here specific ones</i>	<b>Impact of Issue on Use Cases</b>	<b>Reference</b> - law, standard, others
Interoperability standardisation Mandate CEN/Cenelec/ETSI activities	Performance and accuracy to be reached	Smart Grid Mandate /490

**UC.1.9 Preconditions, assumptions, post condition, events**

<b>Actor/System</b>	<b>Triggering Event</b>	<b>Pre-conditions</b>	<b>Assumption</b>
B		B has a contract with A	An AMI Meter/Device is installed at the premises and operational
B, A and SM	Operates loads under nominal values		
SM	Depending on the data, information may be subjected to a push or pull dynamics. If pull "A" receives a request for periodic metering data. If push then "A" send it spontaneously according to settings	Communication with the meter can be established. The meter reading scheme and data collection schemes are available at HES level (optionally at LNAP & NNAP)	GPRS/GSM

**UC.1.10 Referenced Standards and / or Standardisation Committees (if available)  
from IOP TOOL and IEC smart grid standards map found in  
<http://smartgridstandardsmap.com/>**

<b>Relevant Standardisation Committees</b>	<b>Standards supporting the Use Case</b>	<b>Standard Status</b>
CEN / CENELEC	EN 61850-7-4 Communication networks and systems for power utility automation - Part 7-4: Basic communication structure - Compatible logical node classes and data object classes	IS
CEN/CLC TC13	EN 62056-31:1999 Ed. 1.0, <i>Electricity metering – Data exchange for meter reading, tariff and load control</i>	IS
CEN/CLC TC13	EN 62056-42:2002 Ed. 1.0, <i>Electricity metering – Data exchange for meter reading, tariff and load control – Part 42: Physical layer services and procedures for connection-oriented asynchronous data exchange</i>	IS
CEN/CLC TC13	EN 62056-61: 2006 Ed. 2.0, <i>Electricity metering - Data exchange for meter reading, tariff and load control - Part 61: Object identification system (OBIS)</i>	IS
CEN/CLC TC13	EN 62056-62:2006 Ed. 2.0, <i>Electricity metering - Data exchange for meter reading, tariff and load control - Part 62: Interface classes</i>	IS
CEN/CLC TC 294	EN 13757-1:2002 Ed. 1.0, <i>Communication systems for meters and remote reading of meters – Part 1: Data exchange</i>	IS
IEC TC 57	EN 61334-5-1:2001 Ed. 2.0, <i>Distribution automation using distribution line carrier systems – Part 5-1: Lower layer profiles – The spread frequency shift keying (S-FSK) profile</i>	IS
IEC TC 57	EN 61334-4-32:1996 Ed. 1.0, <i>Distribution automation using distribution line carrier systems – Part 4: Data communication protocols – Section 32: Data link layer – Logical link control (LLC)</i>	IS
IEC	IEC61000-2-4 Electromagnetic compatibility (EMC) - Part 2-4: Environment - Compatibility levels in industrial plants for low-frequency conducted disturbances 2014 ed.2.0	IS
IEC	"IEC, IEC 61000-3-12 Electromagnetic compatibility (EMC) - Part 3-12: Limits - Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current > 16 A and ≤ 75 A per phase, 2011."	IS



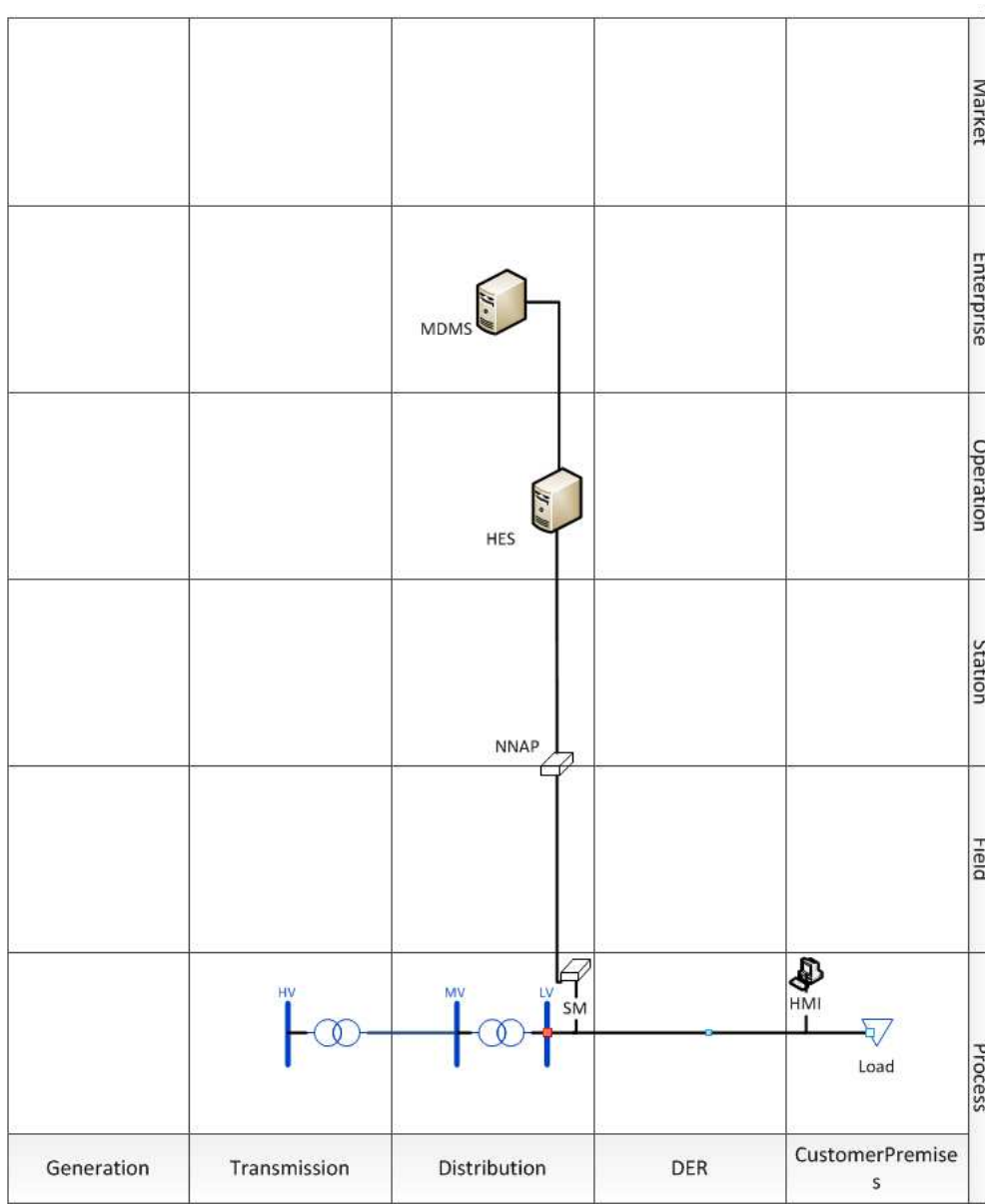
**UC.1.11 General remarks**

General Remarks
This Use Case is under development in the SGILab in Ispra. Expected finalisation of the work is Q4 2018

**UC.2. Drawing or diagram of Use Case**

The following diagrams illustrate a possible mapping of Smart metering operation at the Component Layer:

**Figure 15** Component layer of example



### 3. Step by step analysis of Use Case

#### UC.3.1 Steps – Normal sequence

<b>Function Name :</b>						
<b>Step No.</b>	<b>Event</b>	<b>Description of Process/Activity</b>	<b>Information Producer</b>	<b>Information Receiver</b>	<b>Information Exchanged</b>	<b>Technical Requirements ID</b>
1	SM (smart meter) sends information or is requested to send to NNAP (concentrator)		SM	NNAP concentrator	Data Collection Schemes	
2	A meter reading scheme is activated at HES level	HES informs Smart Meter about activation of meter reading scheme by Executing secondary UC "Set meter parameters" Option: if meter data is to be pushed by the meter: HES informs the meter about activation of data collection scheme. Option: request goes through NNAP and or LNAP	HES	NNAP, LNAP or Smart Meter	Data Collection Schemes	
3	The Timer triggers a meter read	When the deadline for meter reading is reached, the Timer triggers a meter read If Pull communication, Timer triggers meter read at HES level. If Push Communication, Timer triggers meter read at Smart Meter level.	Timer	Smart Meter or HES	Trigger	
4	Meter read is triggered	Execute secondary UC "Provide metering data". Optionally through NNAP and or LNAP	Meter	HES	Requested metering data	
5	HES received metering data	HES forwards metering data to actor "A"	HES	A	Requested metering data	
6		Repeat step 3-5 until the condition in step 7 is met				
7	Actor "A" no longer needs the considered metering data from the Smart Meter (can also be a change of schedule)	Actor A deactivates the meter reading scheme and/or data collection scheme at HES level.	A	HES	Data Collection Schemes	
8	Actor A has deactivated meter reading scheme at HES level.	HES informs Smart Meter about deactivation of meter reading scheme and/or data collection scheme by Executing secondary UC "Set meter parameters" Optionally if meter data were pushed by the meter: HES informs the meter about deactivation of data collection scheme. Optionally through NNAP and or LNAP.	HES	NNAP, LNAP or Smart Meter	Data Collection Schemes	

**UC.3.2 Steps – Alternative, error management, and/or maintenance/backup scenario**

<b>Use Case Name :</b>						
<b>Step No.</b>	<b>Event</b>	<b>Description of Process/Activity</b>	<b>Information Producer</b>	<b>Information Receiver</b>	<b>Information Exchanged</b>	<b>Technical Requirements ID</b>
1	Actor B (consumer) operates under low power quality limits	Low power quality if negatively impacts the PLC communication and NNAP (concentrator) is unable to receive all	SM	NNAP	None/partial in an expected time	
2	Deadline nbr of trails is reached to send metering data and actor NNAP (concentrator) has not received all required data.	Actor NNAP (concentrator) requests a remote on demand reading of Smart Meter.	NNAP	SM	Possible warning/alert/error unable to read meter	

## SGILab BAP template-example

### BAP1.1 Identifiers

BAPs ID	USE CASE ID	Standards
1	1/2016	IEC61000-2-4

### BAP.1.2 Version management

Changes/ Version	Date	Name Author(s) or Committee	Domain Expert	Area of Expertise/ Domain / Role	Title	Approval Status <i>draft, for comments, for voting, final</i>
Version 1	27/03/ 2018	Alexandre Lucas	Primary	Energy systems & Statistics	Research ers	Proceed to experiment

### BAP.1.3 Referenced documents/ terms/ definitions

Source(s) / Literature	Link	Conditions (limitations) of Use
CEN / CENELEC EN 61850-7-4	Communication networks and systems for power utility automation - Part 7-4: Basic communication structure - Compatible logical node classes and data object classes	Specifies the information model of devices and functions generally related to common use regarding applications in systems for power utility automation. It also contains the information model of devices and function-related applications in substations. In particular, it specifies the compatible logical node names and data object names for communication between intelligent electronic devices (IED).
CEN / CENELEC EN 61850-7-410	Communication networks and systems for power utility automation - Part 7-410: Basic communication structure - Hydroelectric power plants - Communication for monitoring and control	Specifies the additional common data classes, logical nodes and data objects required for the use of IEC 61850 in a hydropower plant.
CEN / CENELEC EN 61850-7-420	Communication networks and systems for power utility automation - Part 7-420: Basic communication structure - Distributed energy resources logical nodes	The document specifies object models of DER information that can be exchanged between DER devices and any systems which monitor, control, maintain, audit, and generally operate the DER devices.
CEN / CENELEC EN 62056 (all parts)	Electricity metering data exchange - The DLMS/COSEM suite	IEC62056 standards are the International Standard versions of the DLMS (Device Language Message Specification) / COSEM (Companion Specification for Energy Metering) specification.
IEC IEC 62056-1-0	Electricity metering - Data exchange for meter reading, tariff and load control - Glossary of terms - Part 1: Terms related to data exchange with metering equipment using DLMS/COSEM	This Technical Report reflects the most important terms used in International Standards after the publication of IEC 62051 in 1999. The new terms are mainly related to data exchange with metering equipment for meter reading, tariff and load control using DLMS/COSEM as specified in the IEC 62056 series of standards.
IEC IEC 62056-5-3	Electricity metering data exchange - The DLMS/COSEM suite - Part 5-3: DLMS/COSEM application layer	This standard specifies the COSEM application layer in terms of structure, services and protocols, for COSEM clients and servers.

IEC IEC 62351-7	Power systems management and associated information exchange - Data and communication security - Part 7: Network and system management (NSM) data object models	IEC/TS 62351-7 defines network and system management (NSM) data object models that are specific to power system operations. These NSM data objects will be used to monitor the health of networks and systems, to detect possible security intrusions, and to manage the performance and reliability of the information infrastructure.
IEC IEC 62351-8	Power systems management and associated information exchange - Data and communications security - Part 8: Role-based access control	This technical specification covers the access control of users and automated agents to data objects in power systems by means of role-based access control (RBAC).
IEC IEC/EN 61850 (all parts)	Communication networks and systems for power utility automation	Communication networks and systems for power utility automation
ISO ISO 8601 (EN 28601)	Data elements and interchange formats - Information interchange - Representation of dates and times	This International Standard is applicable whenever representation of dates in the Gregorian calendar, times in the 24-hour timekeeping system, time intervals and recurring time intervals or of the formats of these representations are included in information interchange.
IEC 61000-3-12	States the current harmonic limits allowed in LV systems	"IEC, IEC 61000-3-12 Electromagnetic compatibility (EMC) - Part 3-12: Limits - Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current > 16 A and ≤ 75 A per phase, 2011."
IEC 61000-2-4	States the voltage harmonic limits allowed.	IEC61000-2-4 Electromagnetic compatibility (EMC) - Part 2-4: Environment - Compatibility levels in industrial plants for low-frequency conducted disturbances 2014 ed.2.0

<b>Terms</b>	<b>Definitions</b>
N/A	N/A

#### **BAP.1.4 Functionality**

<b>Scope and Objectives of Functionality</b>
<p>As described in the methodology, Interoperability analysis may be performed by using different configurations of options within standards or by studying the influence of a third party interference in the well-functioning of the system under study.</p> <p>The goal of the present study is, considering a well-functioning system comprised of a smart meter and a concentrator communication through PLC, to try to cause an interoperability disruption by injecting harmonics on the power of the system.</p>

#### **BAP.1.5 Analysis of the standard(s)**

<b>Analysis</b>
<p>To such functionality equipment are chosen to be in compliance with IEC 61000 standards which will be the focus of the study. Of importance to notice are the sections related to the harmonic distortion which is the disturbance intended to be caused in the interoperability test. These chapters of the standards are IEC61000-3-12 and 61000-2-4 which refer to the admissible values of total and individual current harmonic distortion and admissible voltage harmonic distortion. The tables summarizing these values are presented below. Due to the nature of the PLC communication the aim will be to focus on the voltage harmonics.</p> <p>The technology used for PLC is PRIME (PoweRline Intelligent Metering Evolution) and technical characteristics may be found on the Prime Alliance technical specification document</p>

**Table 11** Maximum Harmonic Current Distortion in Percent of IL set in IEC 61000-3-12

Minimum R <sub>SCE</sub>	Admissible individual harmonic current I <sub>h</sub> /I <sub>ref</sub> (%)				Admissible harmonic parameters (%)	
	I5	I7	I11	I13	THC/I <sub>ref</sub>	PWHC/I <sub>ref</sub>
33	10.7	7.2	3.1	2	13	22
66	14	9	5	3	16	25
120	19	12	7	4	22	28
250	31	20	12	7	37	38
≥350	40	25	15	10	48	46

The relative values of even harmonics up to order 12 shall not exceed 16/h%. Even harmonics above order 12 are taken into account in THC and PWHC in the same way as odd order harmonics. Linear interpolation between successive R<sub>SCE</sub> values is permitted

R<sub>SCE</sub> - Short-circuit ratio; I<sub>h</sub>-Harmonic current component; I<sub>ref</sub> -Reference current; THC-Total Harmonic Current; PWHC-Partial Weighted Harmonic Current

**Table 12-** Voltage Distortion Limits set in IEC 61000 2-4

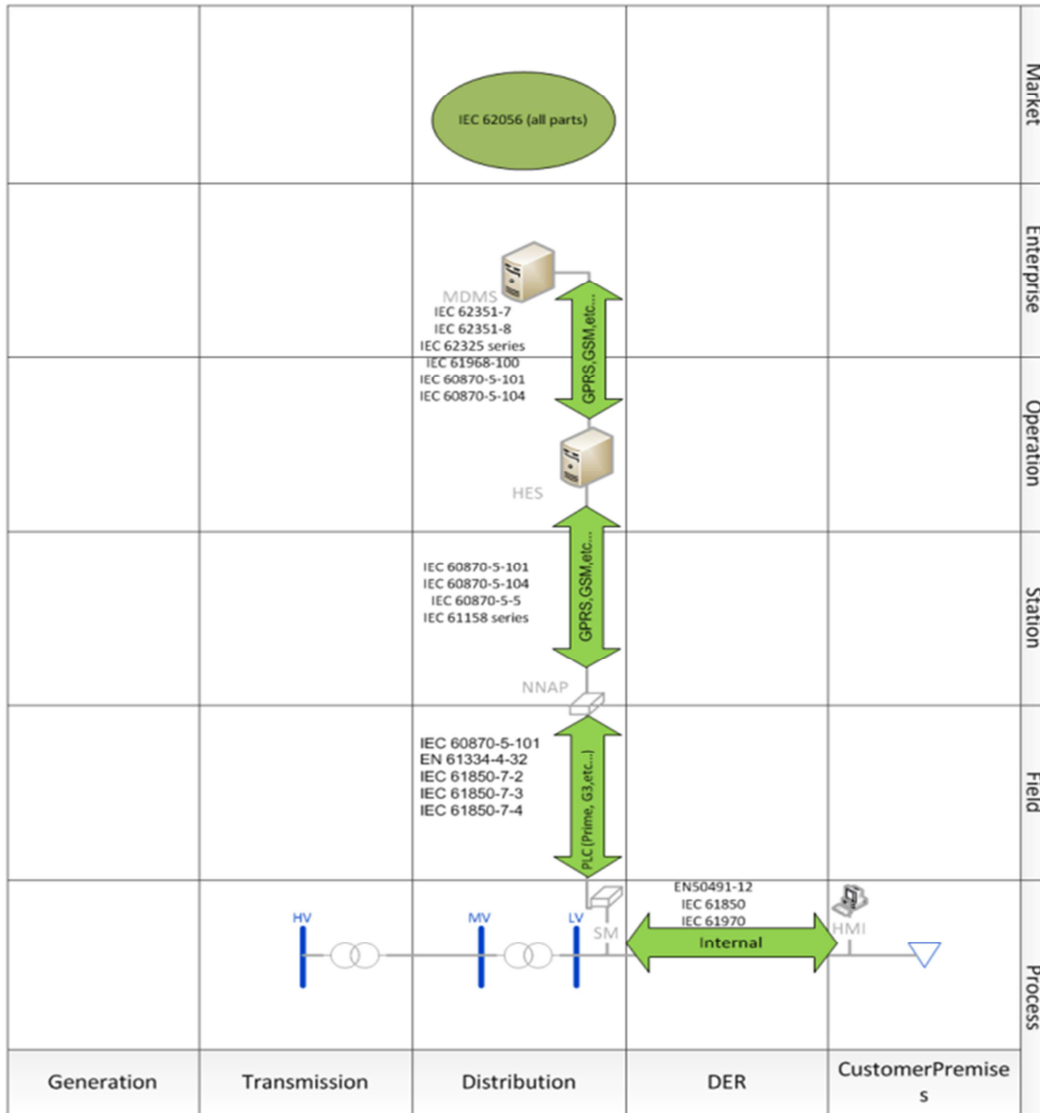
Harmonic order n (Non multiples of 3)	Class 1 μn [%]	Class 2 μn [%]	Class 3 μn [%]
5	3	6	8
7	3	5	7
11	3	3.5	5
13	3	3	4.5
17	2	2	4

Class 1 Compatibility level lower than public (laboratory instrumentation, some protection equipment, etc.). Class 2 Compatibility level equal to public (any equipment designed for supply from public networks). Class 3 Compatibility level higher than public (equipment in the presence of welding machines, rapidly varying loads, large converters, etc.)

<b>THD<sub>v</sub></b>	5%	8%	10%
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The communication layer nevertheless is described below. Since the EUT will be a smart meter unit and a NNAP or concentrator, the communication observation will focus on the Field Zone and between the distribution and customer's premises domains referenced on the SGAM.

**Figure 16** Communication layer of example



## SGILab BAIOP template-example

### BAIOP.1.1 Identifiers

BAIOP ID	BAPs ID	USE CASE ID
1	1	1/2016

### BAIOP.1.2 Version management

Changes / Version	Date	Name Author(s) or Committee	Domain Expert	Area of Expertise / Domain / Role	Title	Approval Status <i>Draft for comments, for voting, final</i>
Version 1	27/03/2018	Alexandre Lucas	Primary	Energy systems &	Researcher	Proceed to experiment

### BAIOP1.3 Referenced documents/ terms/ definitions

Source(s) / Literature	Link	Conditions (limitations) of Use
IEC	IEC61000-2-4 Electromagnetic compatibility (EMC) - Part 2-4: Environment - Compatibility levels in industrial plants for low-frequency conducted disturbances 2014 ed.2.0	States voltage harmonics limits

Terms	Definitions

### BAIOP.1.4 Scope and objectives of BAIOP

Scope and Objectives of Functionality
In this section we describe how the set of standards referred to in the BAP (IEC61000) is used on the experiment. First of all we define from all Power quality parameters to analyze. In the present case we focus on, it's the total harmonic distortion and it's individual components. This choice directs the study to IEC 61000-2-4 or IEC 61000-3-12. However since it's PLC communication we want to focus on, the standard referring to the voltage limits is used (IEC 61000-2-4).

### BAIOP1.5 Testing process

#### BAIOP.1.5.1 Pre-Test definitions

Pre- Test Definitions	
<b>Evaluation Criteria</b>	<p>Evaluation of the error rate of package transfer. Let <math>\epsilon x = 1 - Pr/Ps</math> be the error rate given by the amount of packages lost where Pr is Packages received over a period of time x and Ps packages sent over the same period of time x. Interoperability expected evaluation:</p> <ul style="list-style-type: none"> <li>- Absence of Failure in communication (<math>\epsilon x = 0</math>; Pass)</li> <li>- Partial communication failure (<math>\epsilon x &gt; 0</math>) (Not Pass)</li> <li>- Total loss of communication (<math>\epsilon x = 1</math>)</li> </ul> <p>Pass or not pass test. Possible interoperability regions identification is partial loss occurs.</p>



<b>Specification of EUT</b>	
<b>Technical Specification</b>	<p>Smart Meter and data concentrator</p> <p>Data Concentrator:</p> <p>Communication with smart devices for energy measurement through PLC communication via DLMS/COSEM.</p> <p style="text-align: center;">General</p> <p>230 V a.c. (up to 300V, 50 Hz)</p> <p>3 x Voltage inputs</p> <p>4 x Current inputs</p> <p style="text-align: center;">Diagnostic Communication Interfaces</p> <p>PLC (three phase, up to 1 module)</p> <p>Prime, G3PLC or similar</p> <p style="text-align: center;">DLMS/COSEM</p> <p>Smart Meter:</p> <p>Prime, G3PLC or equivalent communication matching the one from the Data concentrator Connections 1 phase or 3 phase,</p> <ul style="list-style-type: none"> <li>▪ Voltages 220 V (<math>\pm 20\%</math>) - 230 V (<math>\pm 15\%</math>)</li> <li>▪ Base current (maximum) 10 (80) A</li> <li>▪ Minimum reading requirements: Voltage, frequency, currents, time stamp</li> </ul>
<b>Operational specifications</b>	<p>Since a single phase meter is being considered all equipment must be connected to Voltages 230V (<math>\pm 15\%</math>) under the same circuit and line/phase so that the concentrator can detect the smart meter.</p>
<b>Initial Criteria</b>	<p>Initial tests are advised to ensure that the meter and the concentrator are communicating and packages are being exchanged. Also the frequency exchange (300s, 600s etc...) of such packages should be observed so that it can be applied to the experiment when the inputs are varied.</p>
<b>Specification of SUT</b>	
<b>Test Bed</b>	<p>The test bed in this case is the lab infrastructure dedicated to the use case. The equipment will be placed below the Power Amplifier in the lab in a dedicated bus bar, connected directly to the AC channel used as a voltage source.</p>
<b>Devices/ Equipment</b>	<p>As Hardware connected to the Power Amplifier there will be The concentrator the smart meter and a dummy load so consumption can be recorded. The laptop where the Perytons data analyzer will be connected to is advised to use a separate line!</p>
<b>Technical Specifications</b>	<b>See EUT</b>
<b>Operational Specifications</b>	<b>See EUT</b>
<b>Configuration</b>	<p>The Power Amplifier needs to be set to work as a voltage source and the AC channel enabled in the corresponding Simulink model. The setting should be 230Vrms and 50Hz</p>
<b>Interfaces/ Communication Infrastructure</b>	<p>The interfaces with the analyst are the Simulink model, the Power amplifier hardware to turn it on and the laptop which contains the Perytons software</p>
<b>Service Access Point</b>	JRC SGILAB Control room access and lobby access
<b>Special Equipment</b>	<p>Perytons or similar external dongle/block to analyze data transfer and corresponding software</p>

<b>Software</b>	Peryton software v5.4 Simulink with VS triphase model to input harmonic content on the power module HMI provided by the concentrator to visualise voltage
<b>Metering and control infrastructure</b>	Smart meter by EFACEC supplier Concentrator by EFACEC supplier
<b>Measuring values</b>	Number of packages being sent by the meter and number of packages received by the concentrator (Beacons and alive signals excluded)
<b>Others</b>	
<b>Ambient Conditions</b>	Ambient temperature in the lab is kept within a range of 20-25°C
<b>Human Intervention</b>	An operator has to initiate the power module and introduce the input variables (harmonic content) and start the recording session on the Perytons software.
<b>Staffing and training needs</b>	Simulink general knowledge, Perytons general knowledge
<b>Security Aspects</b>	lab safety procedures

## SGILab DoE template-example

### DOE.1 Identifiers

BAIOP ID	BAPs ID	USE CASE ID
	1	1/2016

### DOE.2 Design

Design	Descriptions
<b>Define the goals of the experiment</b>	A data concentrator is supposed to collect periodical meter data from a smart meter through the physical electrical infrastructure. The goal is to investigate the interoperability between the two devices under grid disturbances of increasing intensity
<b>Identify the system responses to be measured</b>	The response variable is defined as the success ratio $\gamma=r/p$ between the number of packets successfully received by the concentrator (r) and the total number of packets sent by the smart meter (p).
<b>Identify the input factors</b>	The input factors are the amplitudes A_1, A_2 and A_3 of voltage harmonics multiple of 50 Hz, i.e. the third harmonic (150 Hz), the fifth (250 Hz) and the seventh (350 Hz)
<b>Identify intervals of variation of the inputs</b>	Having considered standard IEC61000-2-4 , the intervals for the factors in the use case example have been selected as: A_1~U(0,13.8 V); A_2~U(0,11.8 V); A_3~U(0,9.5 V);
<b>Sample N values for the inputs within their intervals of variation</b>	Six values are sampled from intervals defined in step 4

**DOE.3 Test definitions/ Test cases** (this table is used as many times as the Test Cases)

<b>Test Case ID</b>	1
<b>BAIOP ID/ UC ID</b>	1/1_2016
<b>Interoperability Layer</b>	Communication
<b>Summary of the Test</b>	<p>Taking the limits of the standards for voltage harmonics, the outcome of the interoperability test may be:</p> <ul style="list-style-type: none"> <li>• Absence of Failure in communication (Pass)</li> <li>• Partial communication failure (loss &gt;1 package) (Not Pass)</li> <li>• Total loss of communication (Not Pass)</li> </ul> <p>The partial scenario will generate regions of interoperability studied by sensitivity analysis.</p>
<b>Test Purpose</b>	Register the number of packages being sent and received between the SM and the Concentrator when changing the Harmonic content of the Power line
<b>Test Description</b>	
<b>Step 1</b>	Perform initial measurements between the Smart meter and the concentrator to assure that the communication occurs successfully. This means verifying that the number of packages sent (Ps) are the same as the packages received (Pr). Let $\epsilon$ be the error rate given by $1 - Pr/Ps$ , the initial stage must verify $\epsilon=0$
<b>Step2</b>	Choose initial number of variables to be changed (individual harmonic amplitude values) and sample size of experiments.
<b>Step 3</b>	Explore the range of possible values within the standard IEC 61000-2-4, for voltage total harmonic distortion.
<b>Step 4</b>	If regions are found and a precision confidence interval is desired go to step 2 and 3 adjusting the range to the regions identified.
<b>Verdict</b>	

**DOE.4. Companion document (to be filled in after the selection of EUT)**

<b>EUT ID</b>	1
<b>BAIOP ID/ UC ID</b>	1/1
<b>NamePlate</b>	Smart Meter - EFACEC Energy Box Data Concentrator - SmartGate
<b>Technical Specification</b>	<p>Smart Meter and concentrator by EFACEC manufacturer</p> <p>Concentrator:</p> <p>Communication with smart devices for energy measurement through PLC communication via DLMS/COSEM.</p> <p>General</p> <p>230 V a.c. (80V to 265V, 50 or 60Hz)</p> <p>SD Card</p> <p>3 x Voltage inputs</p> <p>4 x Current inputs</p> <p>4 DI + 4 DO</p> <p>88 to 300 V d.c.</p> <p>Diagnostic Communication Interfaces</p> <p>1 x RS232</p> <p>2 x USB</p> <p>2 x 10/100 BASE-TX (RJ 45)</p> <p>1 x RS232 / RS485</p> <p>1 x RS485</p> <p>1 x GPRS port</p> <p>PLC (three phase, up to 1 module)</p> <p>Yitran</p> <p>Prime</p> <p>1 x RF Mesh (external module)</p> <p>Communication Protocols</p> <p>IEC 60870-5-104 (TCP/IP)</p> <p>Web Services</p> <p>DLMS/COSEM</p> <p>SNTP, Communication Protocol</p> <p>Smart Meter:</p> <p>IEC 62052-11, IEC 62053-21, IEC 62053-23, IEC 60529: IP51</p> <p>Certified by MID (2004/22/CE), PRIME T5 1.3ed. and CENELEC (EN 50065)</p> <p>Connections 1 phase, 2 wires</p> <p>Voltages 220 V (±20%) - 230 V (±15%)</p> <p>Base current (maximum) 10 (80) A</p> <p>Total records for measures: +A, -A, +Rc, -Rc, +Ri, -Ri, total and incremental per contract per rate, Pmax and Pmax timestamp</p>

<b><i>Operational Specification</i></b>	230V and 50Hz equipment
<b><i>Mounting/ Cabling/Connecting</i></b>	Desirable to be stand-alone units to allow flexibility of installation. Casing should allow direct connection to power on the equipment
<b><i>Protection/ Isolation/ Earthing</i></b>	No additional devices are needed. Earthing and protection system already foreseen as part of the infrastructure of the lab
<b><i>Specific safety issues</i></b>	Beware of live parts exposed to low voltage(particularly where the connections are made)
<b><i>Configuration/ Initial criteria</i></b>	Pre-sets from the manufacturer
<b><i>Others (based on the EUT)</i></b>	

## **Annex III**

### **Annex III.1: (Global) Sensitivity Analysis**

Sensitivity analysis, associated to specific design of experiments, is instrumental to assess how much the output of a system is affected by changes in the system inputs as well as to identify the most critical inputs (De Roquigny et al., 2008; Saltelli et al., 2008). Sensitivity analysis requires a series of experiments to be executed using different values of the input factors.

#### **Annex III.1.1 Local versus global**

Most of the sensitivity analyses met in the literature are local measures, based on partial derivatives of the system response with respect to one input factor at a time. Although computationally very efficient, these local analysis techniques are only informative at the base point where they are computed. In other words, they do not provide an exploration of the rest of the space of the input factors. This would matter relatively little for linear systems, in which the property at a point away from the baseline can be computed quickly by linear extrapolation using first-order point derivatives, but it would greatly matter for non-linear systems and for systems which present interactions among their input factors.

One often deals with considerable uncertainty in the input factors that will translate in uncertainty of the output(s). Therefore, methods based on exploring the whole space of uncertainty of the input factors are preferable, based on the consideration that a handful of data points judiciously selected in that space is far more effective, in the sense of being informative and robust, than estimating derivatives at a single data point in the center of the space.

By so doing, one can move from a local to a global sensitivity analysis.

In this methodology report the global approach is adopted, in which the inputs are varied over their entire ranges of uncertainty and the space of uncertainty is explored using (quasi) Monte Carlo techniques. With this approach, the simultaneous effects of the input factors on the system output can be assessed.

#### **Annex III.1.2 Three settings for Sensitivity Analysis**

It is common to find cases in the literature where different sensitivity tests are applied to the same problem in a non-structured fashion. This practice can yield a variety of results, e.g. in terms of ranking the input factors in order of importance, with no guidance as to which we should believe or privilege. Therefore, a careful consideration of the output of interest and the concept of 'importance' we aim to is relevant: this would in general allow for the identification of the most appropriate setting for a given problem and, in turn, the sensitivity test to be applied.

- Sensitivity analysis is used in basically three settings, which are described below (Saltelli et al., 2004; Saltelli and Tarantola, 2002):
- Identify what input factor (or group of factors) mainly drives the response (factor prioritisation).
- Find those input factors that do not affect the response at all (factor fixing).
- Seek what combinations of input factors' values correspond to responses in a given range of values, e.g., optimal or extreme values (factor mapping).

The ideal use of the 'factor prioritisation' setting is for the prioritisation of research, i.e. to allow the identification of the factor(s) that most deserve(s) further analysis or measurement, or for the identification of the most critical factors for interoperability.

The 'factor fixing' setting is concerned with fixing non-influential factors, i.e. to identify the factor (or groups of them) that one can fix at any given value within its (their) range of variation without affecting the system response variability. This has implications in the process of simplifying experimental procedures (i.e., reducing the input factors to be varied) and in identifying the factors for which establishing ad-hoc international standards is not important.

Finally, the 'factor mapping' setting consists in categorising the responses in two groups, such as "experiment successful / the system is interoperable / acceptance region" or "experiment unsuccessful / no interoperability between the devices / failure region" and the question addressed is "which factors are mostly responsible for producing responses in the region of interest?". Factor mapping enables identifying critical regions in the space of the input factors that result in interesting values of the response, such as the boundary between the region where the system is interoperable and the region where it is not.

### **Annex III.1.3 Variance-based methods vs classic approaches**

The first two settings illustrated in A1.3 are addressed using an elegant and popular approach, which nowadays has established itself as a reference among practitioners of global sensitivity analysis, which is based on the decomposition of the variance of the system output according to its input factors. The approach studies how the variance of the system output depends on the uncertain input factors and can be decomposed accordingly (Saltelli et al., 2010).

Variance-based measures reveal to be very powerful since the contribution of each input factor to the total variance is an effective and simple measure of the importance of the input factors.

Contrarily to classic design of experiments in which the factors' values are selected with a given theoretical model in mind, such as a linear model, a quadratic polynomial, etc., the variance based methods are model-free, i.e. they work for any kind of model, be it linear, non-linear, additive or non-additive, monotonic or non-monotonic, and almost all can treat sharp discontinuities in the input-response relationship.

Moreover, classic designs require an analysis of the residuals (i.e. the differences between model predictions and observations) to test the validity of the model assumptions and possibly propose a revision of the model itself, implying starting the tests again with a revised design. In variance-decomposition methods, a-posteriori statistical testing for the validity of model assumptions is not necessary because no model assumptions are made.

### **Annex III.1.5 The variance decomposition of the process response**

Let us assume that  $\mathbf{X} = (X_1, X_2, \dots, X_k)$  is the vector of  $k$  input factors and  $Y$  is the system response. The following quantities can be defined:

- $E(Y|X_i)$ , the conditional expectation of the response for a given value of  $X_i$ ,  $i = 1, 2, \dots, k$ . This expression is the arithmetic mean of all the responses obtained by varying all the factors except  $X_i$ , which is maintained fixed at a given value.  $E(Y|X_i)$  is a function of  $X_i$ .
- $E(Y)$ , the average of the measured responses  $Y$  over the  $N$  experiments.
- $V(Y)$ , the variance of the measured responses  $Y$  over the  $N$  experiments.

The quantity:

$$S_i = \frac{V[E(Y|X_i)]}{V(Y)}$$

is the proper measure to use for the 'factor prioritisation' setting and is called *main effect* (or *first order sensitivity index*). The main effect quantifies the proportion of variation of



the response variable  $Y$  explained by the input factor  $X_i$ : the factor with the largest  $S_i$  is the most influential factor, i.e. the one which, on average, once determined, would cause the greatest reduction in variance of the response variable  $Y$ .

The quantity:

$$T_i = \frac{E[V(Y|X_{\sim i})]}{V(Y)}$$

is the proper measure to use for the 'factor fixing' setting and is called *total effect* (or *total order*) *sensitivity index*.  $X_{\sim i}$  indicates all factors except  $X_i$ . A negligible value of  $T_i$  is indicative of a factor that can assume any value within its range of variation without affecting the system response  $Y$ . This could help in simplifying future experiments without considering that variation of that factor.

The computation of both  $S_i$  and  $T_i$  requires evaluating multi-dimensional integrals. For their computation, the suggested methodology makes use of *quasi-random* number sequences (Sobol', 1967; Broda, 2017), namely algorithms that generate samples with special uniformity properties (see Annex 2).

It is usual to consider a variance-based analysis as informative if it produces at least the main effects  $S_i$  and the total effects  $T_i$  for all the input factors in the experiment under study.

Computational efficiency is critical in sensitivity analysis and the challenge is to minimise the number of experiments needed to estimate the sensitivity indices at a desired level of accuracy.

However, additional experiments may be required to improve the accuracy of the sensitivity estimates through an iterative process by increasing  $N$ . While for the first order indices efficient estimation procedures are available which are independent from the number of factors under analysis, this is less the case for the total sensitivity indices. When estimating the  $T_i$  one can either use a sample based approach, whose computational cost depends from the number of factors, or approaches based on statistical modelling, in particular Gaussian processes.

Details of the methods available for the estimation of  $S_i$  and  $T_i$  can be found in (Saltelli et al., 2010).

## **Annex III.2: Quasi-random sampling designs**

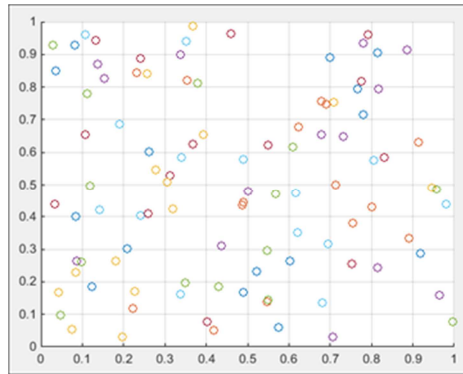
Several schemes for experimental design in the space of input factors are available in the literature, such as simple random designs, stratified designs, Latin Hypercube designs, full and fractional factorial designs. They are briefly examined in the following subsections.

### **Annex III.2.1 Random sequences**

Random number generators available in most software applications allow extracting coordinates of sample points from uniform distributions over the unit interval. Such sample points are scattered across the domain of input factors with the objective to cover the domain itself homogeneously.

In practice, the sample points are not evenly distributed across the input domain, exhibiting both clusters and gaps. When a cluster of points occurs, statistical analyses obtained from function values calculated at those points are overemphasised while, where a gap exists, function values are not sampled and the statistical analyses can be unreliable because the behavior of the function in such area is not accounted for. An example of a random sampling in a 2D space of input is provided in Figure 17.

**Figure 17** Random sampling of N=100 points



### Annex III.2.2 Stratified sampling

Sample designs sometimes use stratified sampling to reduce the error in the estimation of statistical quantities. Stratification is the process of dividing members of the population into homogeneous subgroups before sampling. In stratified sampling, the domain of each input is divided into subintervals and the sampling is constrained so that each subinterval contains the same number of sample points. The points themselves may be selected systematically to lie at particular locations within these subintervals, or may be sampled randomly within each subinterval.

### Annex III.2.3 Full and fractional factorial sampling

A family of classic sample schemes is that of the 'one at a time' (OAT) designs, where only one input factor changes values between consecutive simulations.

As an example, with three input factors, if one assumes that each of them takes two values (or levels), for convention +1 and -1, a *full* factorial design results in the matrix reported in Table 13.

**Table 13:** example of *full* factorial design in the space of three input factors

$X_1$	$X_2$	$X_3$
<b>+1</b>	+1	+1
<b>-1</b>	+1	+1
<b>+1</b>	-1	+1
<b>-1</b>	-1	+1
<b>+1</b>	+1	-1
<b>-1</b>	+1	-1
<b>+1</b>	-1	-1
<b>-1</b>	-1	-1

In this sampling, any change in value between two consecutive output values (say  $y_i$  and  $y_{i+1}$ ) can only be attributed to a change in input factor  $x_i$  (from -1 to +1). Each change of input factors corresponds to a move from one corner of the sample hypercube to an adjacent corner, along an edge of the hypercube.

However, such a sampling strategy turns out to be inefficient when the number of input factors is large, and when only a few of them are influential, that is often the case. Therefore, most of the simulations would be devoted to determining the very small effects of non-influential factors, and very little new information would be collected.

In general, for  $k$  input factors a full factorial design would consist of  $s^k$  sample points (where  $s$  is the number levels for each factor), and thus the experimenter should have to deal with a massive number of simulations/experiments for the subsequent statistical analyses.

However, it is possible to select a smaller, feasible design that can still produce useful statistical results. This leads to a variation of the full factorial scheme, i.e. the *fractional* factorial design. In general, a full factorial design on 2 levels for  $k$  factors (which would produce a sample of  $2^k$  points) can be converted into a fractional factorial design with much less points though capable of collecting useful statistical information (see example in Table 14).

**Table 14:** example of fractional factorial design with seven input factors

$X_1$	$X_2$	$X_3 = X_1X_2$	$X_4$	$X_5 = X_1X_4$	$X_6 = X_2X_4$	$X_7 = X_1X_2X_4$
+1	+1	+1	+1	+1	+1	+1
-1	+1	-1	+1	-1	+1	-1
+1	-1	-1	+1	+1	-1	-1
-1	-1	+1	+1	-1	-1	+1
+1	+1	+1	-1	-1	-1	-1
-1	+1	-1	-1	+1	-1	+1
+1	-1	-1	-1	-1	+1	+1
-1	-1	+1	-1	+1	+1	-1

### Annex III.2.4 Quasi-random sequences

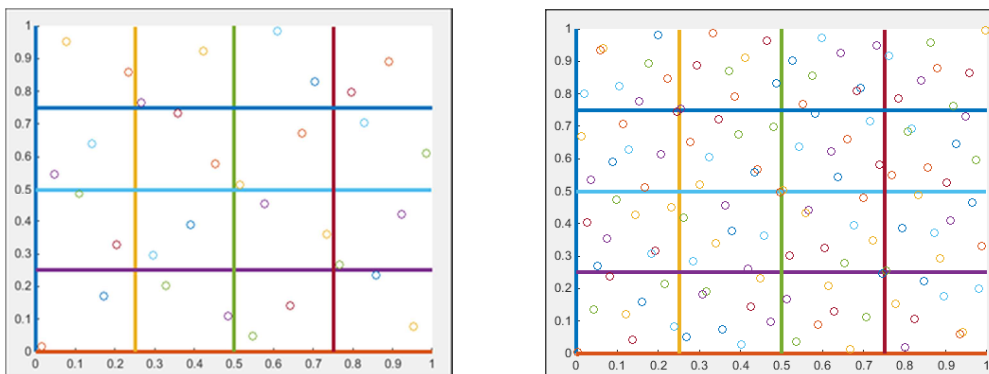
As mentioned in Annex IV.2.1, samples generated randomly tend to show gaps and clusters.

A mathematical measure called *discrepancy* characterises the *unevenness* of a sequence of points in a multidimensional space. Smaller discrepancy values are better for numerical integration and, hence, for sensitivity analysis.

Random sequences have a relatively high discrepancy. Other sequences, called low-discrepancy sequences, are optimal for sensitivity analysis. Among those, the quasi-random sequence of Sobol' (Sobol', 1967; Broda, 2017) is adopted in this methodology. The algorithm that generates quasi-random sequences is able to somehow bias the selection of new points to keep them away from the points already present in the sample. As a consequence, the sample is more homogeneous and the evaluation of multi-dimensional integrals, required in sensitivity analysis, is more accurate. Examples of 2-dimensional quasi-random points for different sample sizes are shown in Figure 18.

It's interesting to notice that when the size is a power of 2, the sample shows exactly the same number of points in each square.

**Figure 18:** Example of quasi-random samples, with  $N=32$  (left) and  $N=128$  (right) points. Note that there are exactly 2 points per square in the left figure, and 8 points per square in the right one.



## Annex III.3

### Annex III.3.1 Empirical modelling

Data acquired by performing the measurements at selected design points enable the analyst to construct an empirical model that approximates the input-response relationship. The empirical model allows the response variable to be computed from a set of inputs without the need to perform an additional experiment. A good quality empirical model is a prerequisite to perform successfully this task. A review of techniques is provided in (Castelletti et al., 2012). Classic approaches encompass polynomial response surfaces (Myers et al., 2002), neural networks, Gaussian processes (Sacks et al., 1989; Santner et al., 2003), polynomial chaos expansions (Sudret, 2008), etc. The methodology adopts Gaussian process empirical models (Sudret, 2017), which is reviewed in the next subsections.

### Annex III.3.2 Gaussian processes

Let's suppose that a dataset  $D$  of  $n$  observations is available:

$$D = \{(x_i, y_i) | i = 1, \dots, N\}.$$

Given this (training) dataset, one wishes to make predictions for new inputs  $x_*$ . This inductive problem requires moving from the finite training dataset  $D$  to a function  $f$  that makes predictions for all possible input values.

By definition, a Gaussian Process (GP) is a collection of random variables,  $Y(x)$ , any finite number of which have a joint Gaussian distribution.

A GP is completely specified by its mean function  $m(x)$  and covariance function  $k(x, x')$ :

$$m(x) = \mathbb{E}[f(x)]$$

$$k(x, x') = \mathbb{E}[(f(x) - m(x))(f(x') - m(x')))]$$

In particular, the random variables represent the value of the function  $f(x)$  at location  $x$ .

In mathematical terms, a GP is defined as follows:

$$Y(x) = \beta^T f(x) + \sigma^2 Z(x)$$

where

- $\beta^T f(x) = \sum_{j=1}^p \beta_j f_j(x)$  is the mean value of the GP, the so-called *trend*. It consists of the basis functions  $\{f_j(\cdot), j = 1, \dots, p\}$  which are linearly combined with the regression coefficients  $\{\beta_j, j = 1, \dots, p\}$ .
- $\sigma^2$  is the (constant) process variance.
- $Z(x)$  is a zero-mean, unit-variance stationary Gaussian process.

A GP is referred to as *simple* kriging when the trend is supposed to be a known constant:

$$\beta^T f(x) = \beta_0$$

A GP is referred to as *ordinary* kriging when the trend is an unknown constant, i.e. there is a single function  $f_1(x) = 1$ :

$$\beta^T f(x) = \beta_1 f_1(x) = \beta_1$$

In the general case where the trend is a linear combination of selected functions is called *universal* kriging.

The zero-mean, unit-variance stationary GP  $Z(x)$  is fully characterised by an *autocorrelation function*  $R(\cdot; \theta)$ , where  $\theta$  are hyper-parameters to be estimated. The covariance function of the GP then reads:

$$k(x, x') = \sigma^2 R(x, x'; \theta)$$

The autocorrelation function is a crucial ingredient for a kriging predictor, since it contains the assumptions about the function one wants to learn. Several autocorrelation functions are available. The *square-exponential* function and the *Matérn* kernels are the most widely used.

Once the format of the GP is chosen, the (so far unknown) parameters  $(\boldsymbol{\beta}, \boldsymbol{\theta})$  are fitted by conditioning the GP to the data  $D$ .

Of interest is the prediction of the system performance at a new input value,  $x_*$ , denoted by

$$\hat{Y}_* = Y(x_* | Y(x_1) = y_1, Y(x_2) = y_2, \dots, Y(x_N) = y_N).$$

To characterise this conditional random variable, one considers the joint (unconditional) distribution of  $[Y_*, Y_1, \dots, Y_N]^T$ . By construction, it is a  $(N + 1)$ -dimensional Gaussian vector whose mean value vector and covariance matrix are as follows:

$$\begin{bmatrix} Y_* \\ \mathbf{Y} \end{bmatrix} \sim \mathcal{N}_{1+N} \left( \begin{bmatrix} f_*^T \boldsymbol{\beta} \\ \mathbf{F} \boldsymbol{\beta} \end{bmatrix}, \sigma^2 \begin{bmatrix} 1 & \mathbf{r}_*^T \\ \mathbf{r}_* & \mathbf{R} \end{bmatrix} \right)$$

where:

- the regression matrix reads:

$$F_{ij} = f_j(x_i), \quad i = 1, \dots, N \text{ and } j = 1, \dots, p$$

- the vector of regressors  $f_*$  of size  $p$  at point  $x_*$  reads:

$$f_* = [f_1(x_*), f_2(x_*), \dots, f_p(x_*)]^T$$

- the correlation matrix reads:

$$R_{ij} = R(x_i, x_j; \boldsymbol{\theta})$$

- the cross-correlation vector, which gathers the cross-correlation between the current point  $x_*$  and the points in the experimental design, reads:

$$\mathbf{r}_* = [R(x_1, x_*; \boldsymbol{\theta}), R(x_2, x_*; \boldsymbol{\theta}), \dots, R(x_N, x_*; \boldsymbol{\theta})]^T$$

It can then be proved that the conditional GP, i.e. the conditional random variable  $\hat{Y}_*$  at any location  $x_*$ , is Gaussian and reads:

$$\hat{Y}_* \sim \mathcal{N}(\mu_{\hat{Y}_*}, \sigma^2_{\hat{Y}_*})$$

where  $\mu_{\hat{Y}_*}$  is the mean vector (also called *predictor*) and  $\sigma^2_{\hat{Y}_*}$  is the conditional variance (also called *kriging variance*).

In particular, the mean predictor is made of a regression part,  $f_*^T \hat{\boldsymbol{\beta}} = \sum_{j=1}^p \hat{\beta}_j f_j(x_*)$ , and a local correction term,  $\mathbf{r}_*^T \mathbf{R}^{-1}(\mathbf{y} - \mathbf{F} \hat{\boldsymbol{\beta}})$ . It can be shown that this correction term makes the predictor *interpolate* the experimental design, i.e.:

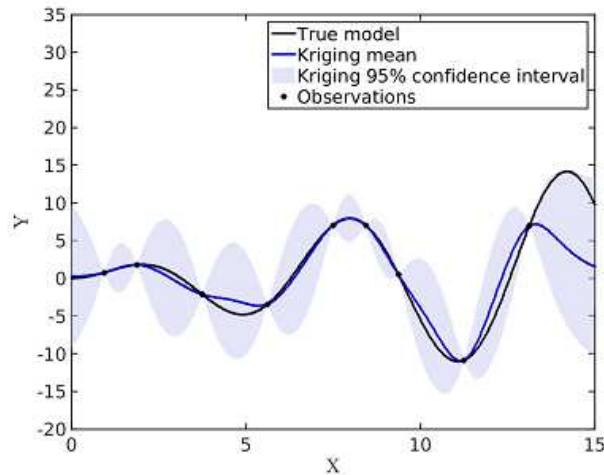
$$\mu_{\hat{Y}_i} \equiv \mu_{\hat{Y}(x_i)} = y_i \quad \forall x_i \in D$$

Therefore, as the mean predictor is interpolating, one can prove that:

$$\sigma^2_{\hat{Y}_i} \equiv \sigma^2_{\hat{Y}(x_i)} = 0 \quad \forall x_i \in D$$

In other words, the kriging variance gives an indication of the uncertainty of this prediction: it is exactly zero at the points of the experimental design, and large in regions of the input parameter space with little information (see an example in Figure 19).

**Figure 19:** An example of kriging model for a simple 1-dimensional analytic function. Note how the kriging variance (i.e. the shaded area) is large in regions far from the experimental points (where it is zero).



Due to the *Gaussianity* of the predictor, one can also derive confidence intervals in each point, hence enabling to characterise the level of uncertainty of the predictor.

In practice, in order to obtain a kriging model, the following steps are needed:

- Select the functional basis of the kriging trend.
- Select the appropriate correlation function  $R(x, x'; \theta)$ .
- Estimate the hyper-parameters  $\theta$  and the Gaussian process variance  $\sigma^2$  by setting up and solving an optimisation problem.
- Using the optimal value of  $\theta$ , the rest of the unknown kriging parameters ( $\sigma^2, \beta$ ) can be calculated.

Then, predictions for new points can be easily made in terms of mean and variance of  $\hat{Y}_*$ .

In conclusion, the probabilistic formalism of Gaussian processes allows one to compute the predicted value of the system response at a given  $x_*$  as a Gaussian random variable. Moreover, the mean predictor reveals to be the best linear unbiased estimation of the GP at point  $x_*$  conditioned on the observations gathered in the experimental design.

### **Annex III.3.3 Treed Gaussian process (TGP)**

The standard approach in the literature for building empirical models is to model the system output with a stationary smooth Gaussian process. However, this approach proved to be vulnerable to some drawbacks.

In particular, some disadvantages of the standard form of a GP have been highlighted; the most relevant of them is probably the fact that GP models are usually *stationary* in the sense that the same covariance structure is used throughout the entire input space, which may be a too strong modelling assumption.

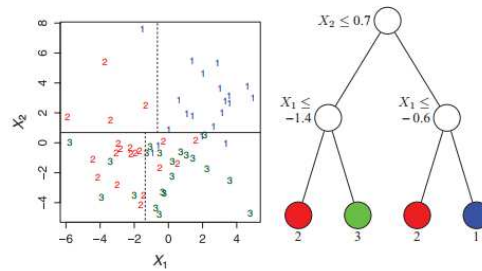
Moreover, in many real-world spatial and stochastic problems, such a uniform modelling of uncertainty may be not desirable. Instead, some regions of the space will tend to exhibit larger variability than others, and many spatial modelling problems require more flexibility than is offered by a stationary GP.

On the other hand, fully non-stationary Bayesian GP models can be difficult to fit, and are not computationally tractable for more than a relatively small number of data points.

One way to address all these shortcomings and to achieve a more flexible, non-stationary process is to use a *partition* model, i.e. an empirical model which divides up the input space into regions, and fits separate stationary GP models independently within each region.

Treed partition models typically divide up the input space by making binary splits on the value of a single factor (e.g.,  $x_2 \leq 0.7$ ) so that partition boundaries are parallel to coordinate axes. Multiple partitions can be created across different factors (see example in Figure 20) and an independent GP is estimated for each partition.

**Figure 20** Example of multiple partitions



A complete mathematical description of treed Gaussian processes (TGP) is given in (Gramacy and Lee, 2012).

In particular, for empirical model construction the proposed methodology makes use of an R package (`tgp`) which implements the TGP model (see Gramacy, 2007) for a detailed description) and can be found at:

<https://cran.r-project.org/web/packages/tgp/index.html>

### Annex III.3.4 Sensitivity Analysis and TGP

The `tgp` package contains the implementation of the Bayesian regression framework. Recently, new advanced features have been implemented in the `tgp` package (see

<https://cran.r-project.org/web/packages/tgp/vignettes/tgp2.pdf> ,

including global sensitivity analysis and, in particular, the sensitivity indices  $S_i$  and  $T_i$  (and their statistical error) illustrated in Step 8 and Annex III.1.5.

### Annex IV

A few concluding remarks related to aspects that are currently being addressed by the team:

1. Measurement error: In physical experiments, measurement error may affect both the input parameters and the measured output values. This aspect can be addressed when building the GP empirical model by adding a measurement noise, called nugget effect, in the analysis.

2. Identification of the best GP model: It is good practice to test several GP models, with several trends (regression part) and several autocorrelation kernels. The quality of the obtained empirical model can be measured in practice by a leave-one-out approach [26], and can vary drastically depending on the selected options. The best model with the smallest error shall be retained and used. In the case of small experimental designs, as it is the case here, the polynomial-chaos-kriging approach [26] has shown excellent results with regard to the usual GP approach and will be tested.

3. Active learning of the boundary: It is envisaged to embed in the methodology adaptive sampling techniques (a review is available in [27]) which *actively learn* from the results of the previous experiments and help the experimenter to decide where to optimally insert the new design points to obtain a better boundary between pass and fail.

4. Sensitivity Analysis: it is envisaged to consider the use of discrete inputs in sensitivity analysis, which allow the analyst to choose discrete scenarios / assumptions in order to appreciate how important the variability across scenarios / assumptions is. Moreover, the testing of moment independent methods for sensitivity analysis [28] will be considered besides the variance-based approach. Moment independent methods could be particularly interesting in view of the fact that the response measure is either in the safe or failure domain. Lastly, the generalisation of sensitivity analysis formulas to acknowledge dependency (correlation and constraints) between factors is envisaged [29].



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doi:10.2760/08049

ISBN 978-92-79-96855-6