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Towards modeling future energy infrastructures - the ELECTRA system engineering approach

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***Abstract*—Within this contribution, we provide an overview based on previous work conducted in the ELECTRA project to come up with a consistent method for modeling the ELECTRA WoC approach according to the methods established with the M/490 mandate of the European Commission. We will motivate the use of the IEC 62559 use case template as well as needed changes to cope particularly with the aspects of controller conflicts and Greenfield technology modeling. From the original envisioned use of the standards, we show a possible transfer on how to properly deal with a Greenfield approach when modeling.**

Keywords*—*Smart Grid Modeling, SGAM, Systems Engineering, ELECTRA

INTRODUCTION

In the ongoing development of the electric power infrastructure towards a smart grid, system engineering methods have an important facilitating role. The deployment and increased integration of information technologies into the current system have already pushed system engineering methods and standardization further, such as with the US IntelliGrid and Modern Grid initiatives or the European M/490 mandate. Yet, potentially beneficial more fundamental changes to the control paradigms that govern power system operation are difficult to conceive and require a holistic architectural view [1], [2]. In particular if the change affects the physical parameters and behaviour, also experience and qualification from experiments at lab-scale as well real-scale is also required. As highly distributed large-scale and strongly coupled cyber-physical infrastructure, electric power systems are not amenable to rapid paradigm shifts in their operation, so an incremental development approach is commonly adopted. However, in such case, where architectural changes affect the power infrastructure at many layers simultaneously and a major fraction the coordinating structures, both technically bottom-up and organizationally top-down, are under development, a Greenfield space for development is required to bypass the tendency toward incremental development. The ELECTRA Integrated Research Program offers such a space - also for the reflection on architectural support: we find that systems engineering methodologies for Smart Grids as ultra-large scale cyber-physical infrastructures are still under development.

SMART GRIDS - A CONVENTIONAL VIEW ON THE UNCONVENTIONAL NEW OPERATION PARADIGM

With by-directional power flows occurring from the feed-in of renewables, operation and monitoring of the infrastructure changes. New sensors with corresponding data, new actors and new control technology have to be deployed and incorporated into the legacy systems. This new grid is usually called the Smart Grid. According to the most prominent definition by the US NIST (National Institute of Standards and Technology), the Smart Grid "is a modernized grid that enables bidirectional flows of energy and uses two-way communication and control capabilities that will lead to an array of new functionalities and applications." With this definition in place, the convergence of ICT (information and communication technology), communication networks and power grid operations had an impact in the discipline of informatics. For Europe, the Smart Grid ETP (European Technology Platform) defined the term as follows: "Smart Grid is an electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both in order to efficiently deliver sustainable, economic and secure electricity supplies." To properly cope with the problem of dealing with this ICT-based control, the discipline of Energy Informatics emerged, coined mainly by the definition from [3].

Clearly, new particular requirements for the informatics domain emerge from their application in smart grids, as well as new challenges for electrical power engineering in dealing with bidirectional power flows. However, key engineering challenges reside with the integration of an emerging complex and large-scale cyber-physical infrastructure coupling phenomena and interactions across physical and information systems, which can hardly be addressed in an incremental approach. In contrast to the conventional Smart Grids point of view, this contribution focuses on the Greenfield re-engineering of grid operation paradigms according to the ELECTRA project objectives, with emphasis on the distributed WoC architecture as described in [4]. In this work we discuss the role and adaptation of systems engineering methods in the context of smart grid development applicable to Greenfield development.

THE ELECTRA PROJECT

One of the basic ideas of ELECTRA is that the large-scale deployment of Renewable Energy Sources (RES) connected to the power network at all voltage levels will require radically new approaches for real-time control that can accommodate the coordinated operation of millions of devices, of various technologies, at many different scales and voltage levels, dispersed across the Pan-European grid. ELECTRA addresses this challenge, and aims to establish and validate proofs of a concept that utilises flexibility from across traditional boundaries in a more holistic fashion. The ELECTRA consortium

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TABLE I. OVERVIEW OF USE CASE VARIANTS IN ELECTRA

Abbr.	Var.-ID	High-Level Use Case	Variant keywords
IRPC	1.2.1	Inertia Response Power Control	df/dt
IRPC	2.2.2	Inertia Response Power Control	virtual synchronous rotor
FCC	2.1.1	Frequency Containment Control	dead-band; merit order
FCC	2.5	Frequency Containment Control	adaptive CFPC
BRC	1.1	Balance Restoration Control	transactive dispatch
BRC	1.2	Balance Restoration Control	distributed observable
BRC	1.5	Balance Restoration Control	policy-based
BSC	1.1.1	Balance Steering Control	reactive
BSC	1.3.1	Balance Steering Control	pre-emptive
PVC	1.5	Primary Voltage Control	V-setpoint
PPVC	1.1.1	Post-Primary Voltage Control	Interior Point Method
PPVC	1.1.2	Post-Primary Voltage Control	Genetic Algorithm

believes that a new control concept is needed and set out to develop and test horizontally-distributed control schemes reinforced with vertically-integrated coordination strategies to provide for a dynamic power balance that is closer to its equilibrium value than a conventional central control scheme [5]. The proposed control structure has been termed Web-of-Cels (WoC). One particular aspect we will deal with in this contribution is how to properly model the concept of the WoC in terms of SGAM, how to extend the use case template for controller conflict resolution aspects and come up with SGAM examples taking this into account.

THE WEB-OF CELLS APPROACH IN ELECTRA

The high level architectural concept, called WoC, is summarized in [9]. The ELECTRA project aims for a decomposition of the existing organization of system operation into a so-called WoC. Within this concept, each cell assumes responsibility for both real-time balance and voltage control of the cell, thus, minimizing the dependency on inter-cell communication for overall secure system operation. The WoC architecture ensures overall system stability by a combination of decentralized and distributed control patterns for frequency and voltage control. For each cell, operators maintain an accurate view on the overall cell state and ensure secure operation by coordinating imbalance setpoints across cells, allocating and dispatching of reserves within the cell. Inter-cell coordination provides for efficient system-wide management and economic optimization.

In the first phase of the ELECTRA project, six high-level use cases [9] have been identified. Through a process of technical refinement and prioritization of alternatives, detailed variants of the high-level use cases have been described. An overview is provided in Table I. All use cases have been modeled in IEC 62559, taking into modeling as described in [4]. Within the previous contribution, we have outlined the basics on the need for a proper structured way of modeling according to the M/490 mandate guidelines utilizing the SGAM and Use Case methodology. Figure 1 shows as a graphical abstract the contribution extended from the first methodological paper [4], in which we presented the overall M/490 process with the corresponding tools and envisioned extensions by ELECTRA. Revisions in the right hand side of the tool-chain represent new contributions in this second phase of the project.

COMPLEXITY IN LARGE SCALE INFRASTRUCTURES

In 1973, Rittel and Webber [10] describe common dilemmas in the theory of planning. The authors argue that users or stakeholders tend to ask the questions “What do the systems do?” instead of “What are they made of?” and, in addition, also do not address the most important question “What should those systems do?” Therefore, they argue that the task of goal-finding is the most important task in planning theory. Within the industrial age, the idea of planning, in common with the idea of professionalism, was dominated by the overarching idea of the concept of efficiency. In the early days, the systems analysts pronounced themselves with “arrogant confidence” that they were ready to take anyone’s perceived problems, diagnosing the hidden characters, exposing its true nature and excise its root causes. As distinguished from problems in natural sciences, which are separable, definable and have many findable solutions, social problems are ill-defined as they rely upon political judgment for resolution, and, worse, can never be solved but have to be re-solved over and over again. Rittel and Webber [10] outline that planners, and engineers, tend to focus on such so-called *tame* or *benign problems*. For those tame problems, the mission is always clear, the problems are well-defined and stable, and have mostly a definite stopping point. The found solution can be evaluated as right or wrong, typically belongs to a class of similar problems and has solutions, which can be tried and/or abandoned. In contrast, *wicked problems* lack a clarifying trait, as they have at least ten characteristics one can identify them based on: Typically, there is no definitive formulation of wicked problems; mostly the formulation is part of the larger problem. Then, wicked problems have no stopping rule, there is no “that’s good enough” for a single solution. This leads to the trait that solutions to wicked problems are not true-or-false but only good-or-bad. There will never be an immediate or ultimate test to the solution of a wicked problem, and every solution to a wicked problem is a one-shot operation, there is possibly no trial-and-error learning possible. Every attempt counts significantly, mostly from the perspective of cost and time. In addition, wicked problems do not have an enumerable set of possible solutions; there is no list of permissible operations to be done to solve it. Every wicked problem can be considered essentially unique, no learning, no classes of problems are available. In addition, every wicked problem might as well only be a symptom of another, much larger problem.

As opposed to the conventional view, we take the assumption that the concept of Smart Grid, as well as systems-of-systems coalitions in general, have characteristics of wicked problems.

The discipline of systems engineering is defined by INCOSE as follows [11]: “Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem. It integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. It considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.”

Building on top of this, the most relevant aspect in the context of the ELECTRA engineering method is systems-of-systems (SoS) research. Sommerville [11] defines systems-of-systems according to the US Department of Defense (DoD)

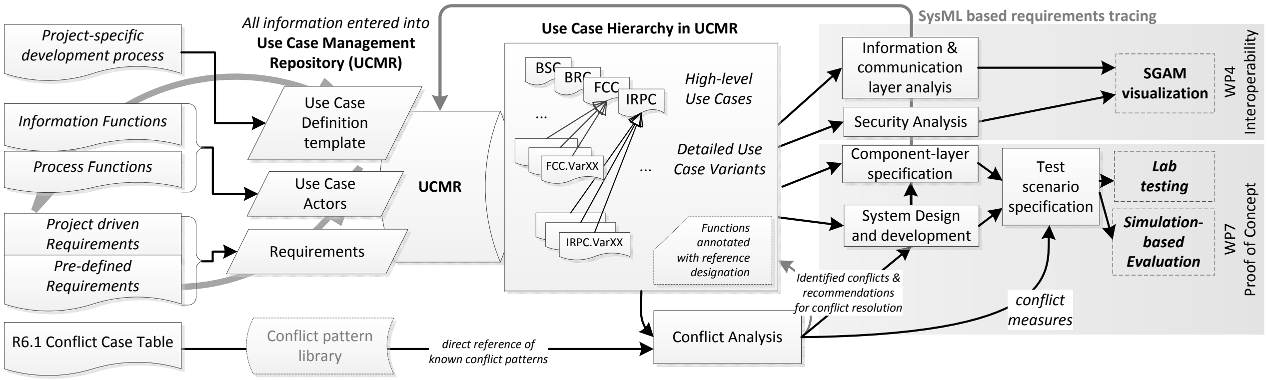

Fig. 1. ELECTRA requirements process with the outputs needed for the later work packages in ELECTRA, such as lab testing (WP7) and interoperability analysis (WP4). Project specific inputs are listed on the left and their mapping to the project specific UCMR via template, actor list and requirements is illustrated; all central process elements are recorded in the UCMR; systematic control domain and actor modeling enable functional conflict identification and an amended use case template [4], [6], [7] enables recording of conflict analysis outcomes in use case context; finally SGAM reference designation and SysML annotations then enable visual inspection and requirements tracing toward lab testing. The test specification process is also supported by SGAM as outlined in [8]; greyed out elements have not been implemented in ELECTRA.

definition as follows: "A System-of-Systems is defined as a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities." We conclude that the Rittel idea can be applied also to Ultra-Large Scale Systems (ULSS) and conclude that the conventional electricity grid and the change in operation paradigms can make those paradigms applicable to electric transmission and distribution.

Based on their theory of ULSS, Sommerville et al. motivate a roadmap of research questions towards a smarter way to deal with systems aspects. Their Top Ten research agenda can also be applied to Smart Grids. The authors raise the following questions:

1) How can we model and simulate the interactions between independent systems?
2) How can we monitor coalitions of systems and what are the warning signs of problems?
3) How can systems be designed to recover from failure?
4) How can we integrate socio-technical factors into systems and software engineering methods?
5) To what extent can coalitions of systems be self-managing?
6) How can we manage complex, dynamically changing system configurations?
7) How can we support the agile engineering of coalitions of systems?
8) How should coalitions of systems be regulated and certified?
9) How can we do a probabilistic verification of systems?
10) How should shared knowledge in a coalition of systems be represented?

From our point of view, we would like to focus on the key aspects of both automation and process control in application to Smart Grids. For automation we see the following main characteristics as challenging from the Sommerville research agenda: *functional perspective*; *overarching system functions* (decomposition); *integration information consistency*. At process level, we see the following main characteristics: *electrical engineering*, *degrees of freedom in operation*, *dynamically coupled physical systems*; and *timescales of coupling individual components*. This leads to the following research questions we need to address with the developed systems engineering method based on M/490 work in the context of the ELECTRA IRP project.

Directly related to the ULSS research questions identified above, in ELECTRA the methods have to answer to the following main questions:

ad-2) How can we *monitor* coalitions of systems? e.g aspects like warning signs of problems, conflicts or misuse;

ad-7) How can we support the *agile engineering* of coalitions of systems? e.g. aspects like translatable, flexible design processes; referencing, role of Model-Driven Engineering, tackle the heterogeneity of interfaces, design process degrees of freedom, best practice - design science - utility of artifacts;

ad-10) How can we achieve a *shared knowledge representation*? e.g. aspects like competing reference architecture models; reference designation concepts.

Those questions were mainly addressed when developing the concept of the tool-chain for ELECTRA. Conflicts arising have to be properly modeled and referenced via the SGAM and UCMR shall take those conflicts into account; the agile engineering relies ob the proper modeling of interfaces with common semantics, including processes for revision of interface semantics, a thorough documentation of the development process, the functional and non-functional requirements. Using the SGAM and the Use Case template from IEC 62559, those issues can be properly addressed but have to be further extended for the ELECTRA WoC paradigm.

For Smart grid projects in general, also include the following issues should be addressed:

ad-1) Modeling and simulation can be addressed by lab-trials and co-simulation frameworks;

ad-3) Design for recovery (classic engineering/operating modes vs. resilience) is incorporated on modern systems design;

ad-4) Human factors are addressed by concepts of how to run projects (ELECTRA: WP8; general trend in SG projects to involve transdisciplinary partners)

ad-5) Self-managing concepts and autonomy are addressed by decentral design aspects (WoC concept; MAS research;...)

ad-6) How can we manage self-managing, dynamically reconfigurating systems (three classes mostly: deterministic self-management, obscure self-management, explanatory self-management)

ad-8) coalitions regulation, certification also employing probabilistic valuation and validation metrics;

ad-9) methodologies for both probabilistic verification of services provided by coalitions as well as for assessment of coalitions functional integrity.

The questions raised here and their answers provide a theoretical background and motivation for the tool-chain adaptations for ELECTRA from the conceptual systems engineering point of view, and identify challenges for future developments. In comparison to the original process proposed in [4], Figure 1 also demonstrates the changes we had to undergo as with regard to the original plan in order to make the tooling from the EC mandate work for ELECTRA purposes.

APPLYING IEC 62559 AND SGAM TO A GREENFIELD APPROACH

We briefly present within this section what is the original tool-chain and how it differs in ELECTRA. We focus on practical aspects and relate how the way SGAM domains and zones may be treated in that very scope. We point out that conflict analysis of controllers is hard to be modeled in either of the methods without actually extending the state-of-the-art models. Finally, we end up on pointing out what is different in ELECTRA from the context point of view and report how we dealt with this context adjustment.

Adaptation of the existing tool chain for ELECTRA

The state of the art on how to apply the methods of the M/490 has been summarized in [4]. The next paragraphs mainly summarize the extended presentation from the previous contribution as well as new functions arising in the second phase.

ELECTRA IRP Inputs: Currently, the method of IEC 62559 relies on the annexes from the standard itself. As for ELECTRA, we have developed new actors, actor taxonomies and functions. Based on the IEC 62559-3 standard, libraries for ELECTRA specific glossary have been developed and imported in the standardized format.

UCMR: Within ELECTRA, we use a use case management repository (UCMR) which was initially developed by OFFIS for the CEN/CENELEC ETSI M/490 Sustainable Processes group for German DKE. The second, refined version was used in the context of ELECTRA. As of the time being, we found some issues arising from specific requirements which led to a change in the template of the IEC 62559 as depicted in the annex of this paper. One particular non-functional requirement is the identification of controller conflicts in the very scope of the WoC structure. Therefore, we opted for an extension and new rule sets and clarifications to use the IEC 62559 template.

Conflict Analysis: As part of the process outlined in [4], a semi-formal pattern-based conflict analysis has been proposed, in part based on a method formulated in [12]. Whereas the conflict analysis itself is part of the desired project outcome, the formal basis and process for its direct application could not be implemented. However, the use case specification with harmonized actors, proved a sufficient basis for a direct expert-based evaluation and enabling referencing of potential conflict cases. Another adjustment to the process related to the utilization of conflict cases: expert feedback regarding (functional) specification conflicts were taken into account in the development process, such that a formal iteration, as envisioned earlier, did not need to be established. Further relevant conflict aspects then become part of non-functional requirement to be taken into account during system development and test specification (as depicted in figure 1).

Mapping to Standards: One particular issue of the development of the SGAM was to act as a reference designation system in order to structure the discussion in the M/490 mandate on identifying standardisation gaps. The SGAM was used to put existing standards into context with functions for the future smart grids based on existing components and business models. Therefore, there is a thorough knowledge base from the SG-CG (Smart Grid Coordination Group) on which standards shall be applied to which layer, domains and zones of systems in an SGAM model. However, usually, the creation of an SGAM model relies on allocation of existing components. In ELECTRA, we would have to start with functions as depicted in figure 2 and 3 of this contribution This leads to a more complicated mapping to standards because device related standards cannot be assessed since the function can be implemented at various levels and locations.

3D SGAM Model: SGAM can be seen as either a reference designation system but also as a communication measure on Smart Grid solutions and their various dimensions. Within the mandate, first models mostly utilized a Microsoft PowerPoint based representation dealing with five individual 2D planes. This has proven to be the easiest and fastest way to fill out use cases for SGAM models, however, links between layers can only be implicitly seen aligning the systems and the individual coordinates from the layers. In addition, there is virtually no interaction, filtering or highlighting (e.g. heat-maps for security) possible. In ELECTRA, we have created an integrated 3D model which can be rendered in a browser and act as a model for a smart grid solution, linking individual layers and making annotation of communication links, data exchanged, standards used and payload schemata possible.

Develop a concept for implementing the lab trials: One aspect of the ELECTRA project is testing the documented and previously mentioned use cases in order to find resolutions for certain conflicts arising. As a preparation, the so called Control levels have been mapped into the SGAM, showing the individual cascade which can occur from a functional viewpoint in Figure 2. Controls cannot be allocated exactly to

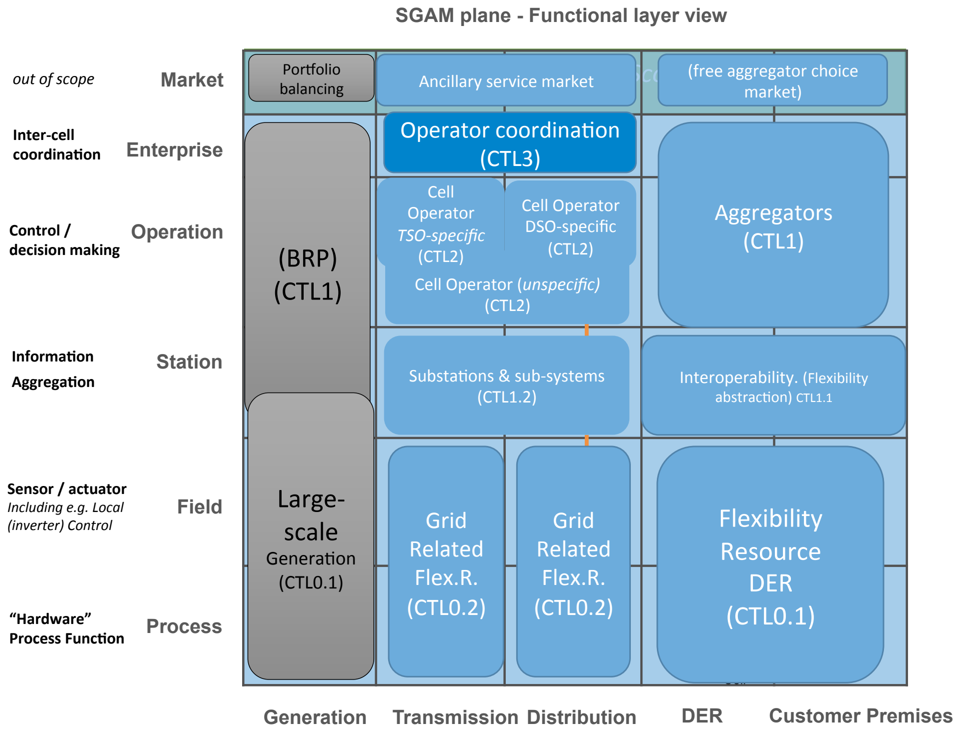

Fig. 2. Mapping of the WoC concept domains to SGAM Plane - Function Layer. Grey domains on the left hand side identify out-of-scope regions for the WoC concept. For the ELECTRA project, also the Market Zone is out of scope.

Procurement Phase (BRC 1.1)

Function	CTL
Resource Flexibility Calculator	CTL-0.1/1.1
Reserve Aggregator	CTL-1
Cell Electrical Data Observer	CTL-1.2
Cell State Estimator	CTL-2
Merit Order Building	CTL-2
Reserve Volume Setpoint Provider	CTL-3

Real time Operation Phase (BRC 1.1)

Function	CTL
Cell Imbalance Observer	CTL-2
BRC Controller	CTL-2
Portfolio Power Controller	CTL-1
DER Controller	CTL-0.1

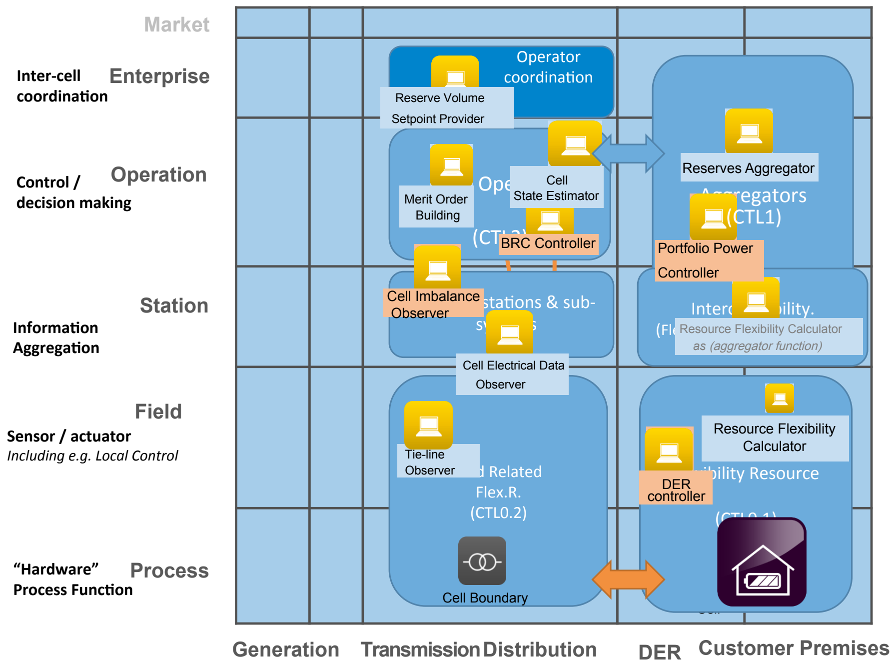

Fig. 3. Example mapping of function-actors of BRC 1.1 use case into SGAM. Functions are grouped into relevance for two operation phase, corresponding to two different time scales of interactions.

individual layers, therefore, clusters have been defined within the project for this. Based on this very concept, first mappings of the use cases to SGAM layers have been created from the functional point of view which, one example is depicted in Figure 3 of this contribution. The BRC 1.1. use case is mapped onto the SGAM, showing at which level certain functions will be implemented and allocated.

Security analysis: Based on the definition of the SGAM layers. an individual assessment of the threats and possible mitigation for the interfaces based on ENISA and NISTIR 7628 requirements will be done. This is based on either the location of the function/actor in the SGAM, leading to a mapping onto the existing classes of systems analysed by the standards as well as by their interfaces and payloads exchanged. The SGAM Mapping of the ELECTRA functions will provide threats and mitigation strategies to deal with those threats.

Results drawn from the application in ELECTRA

Systems engineering point of view - soundness of the method: Within the ELECTRA project, we aligned the methods to be applied with a systems engineering concept mainly focusing on the complexity of the problem to be addressed. Here, the theory of Rittel *et al.* was applied and put in the context of so called wicked problems. As for the Smart grid, we could see based on the characteristics that, indeed, it can be seen as a so called wicked problem with the corresponding inherent attributes. To tackle this system-of-systems problem from a methodological point of view, we could benefit from the research questions defined by Sommerville *et al.*. Within the project, our tool-chain has tackled some of the most prominent questions, however, a direct application was not possible without imposing changes and extensions.

Project point of view - applicability in the project: From the project point of view, different issues have to be taken into account. First, creating use cases as a collaborative approach has to be agreed upon ideally at proposal time. A process must be set-up to deal with the aspects of agreeing on a common set of actors, control levels and a system operation paradigm. In addition to the input data, refinement of the template might have to take place due to the Greenfield approach. However, the method provides means to have a common understanding and documentation of the results for all partners as well as the commission. In addition, the artifacts created can be re-used in different context like security analysis or standards assessment. Ramp-up time to get to know the tools and methods was rather high. Future projects shall re-use existing knowledge and speed up due to experiences gained. One challenge specific to ELECTRA has been the need for on-line collaboration tools and processes adjusted to on-line collaboration. In practice this lead to a two-pronged approach in which the required inputs were first drafted in other tools before adoption into the UCMR.

CONCLUSIONS

This contribution presented a way to adopt the existing SGAM and IntelliGrid methodology and processes for Smart Grid Architecture Modeling to the scope of systems engineering for Smart Grids at the solution level from the evaluation point of view. For ELECTRA, an approach to adopt the tools Use case, UCMR, SGAM and visuals was evaluated based on the theoretical foundations set in [4]. Based on this initial methodology, this contribution extends the previous work by adding the scientific background of the methods applied, reporting first results of application of the changed modeling paradigm to ELECTRA use cases and addressing changes which had to be done when applying the Use Case and SGAM methods, thus, providing information for projects on how to tailor the systems engineering methods and how to establish it in a Greenfield approach project.

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