

Conceptualizing Operational Technology and Service Quality in Critical Infrastructures – The »DevCon« Approach

J. Schönböck², W. Schwinger^{1,*}, E. Kapsammer¹, B. Pröll¹, W. Retschitzegger¹, D. Graf³, A. Méndez-Porras⁴, L. Cardinale-Villalobos⁴

¹ Institute of Applied Knowledge Processing/
Telecooperation Johannes Kepler University Linz (JKU), Austria

² University of Applied Sciences Upper Austria, Hagenberg, Austria

³ team Technology Management GmbH, Austria

⁴ Instituto Tecnológico de Costa Rica (TEC) Campus Tecnológico Local San Carlos, Costa Rica

* Correspondence: wieland.schwinger@jku.at

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Abstract: *Critical infrastructures (CIs)* such as energy grids, communication networks, and transportation systems constitute the foundational backbone of modern society's social and economic functions. Ensuring their efficient and safe operation by providing appropriate techniques to monitor the underlying *Operational Technology (aka. OT)*, commonly referred to as *Operational Technology Management (OTM)*, is therefore naturally of paramount importance. One crucial key challenge, however, lies in the continuous evolving nature of CI-related OT at a rapid pace, introducing massive heterogeneities, interdependencies and interoperability problems. Consequently, these complex challenges, make achieving effective OTM and integrative service quality hard to achieve. The objective of our research project, »DevCon« is therefore to push forward appropriate techniques that facilitate OTM and *integrative service quality* even amidst of the continuous evolving nature inherent in this kind of systems. In particular, to overcome heterogeneities while explicating interdependencies and ensuring interoperability, we propose conceptualizations of OT objects and service quality, providing the foundations for a pivotal knowledge base. For this, an innovative approach is followed that synergistically combines *inductive methods* in terms of machine learning and *deductive methods* in terms of semantic technologies, thereby leveraging their complementary strengths.

Keywords: Critical Infrastructure (CI); Operational Technology Monitoring (OTM); Machine Learning, Semantic Technologies.

1. Introduction

Critical infrastructures (CIs) such as energy grids, communication networks or transportation systems [1] constitute the foundational backbone of modern society's social and economic functions. Such CIs are vital enablers for elementary services like water and food supply as well as community services including health care and education, thereby exerting significant impact on citizens' lives [2]. Their reliable and faultless functioning is a vital prerequisite for societal well-being, economic prosperity and long-term growth, ultimately impacting social stability. In turn, failing of CIs carries about the danger of wide spread, cascading implications on services relying thereon and potentially causing substantial damaging effects — even in case of seemingly minor failures and breakdowns. Consequently, efficient and safe operation of CIs is therefore naturally of paramount importance [1].

Therefore, to support such operations, a wide range of *Operational Technologies (OT)* [1] is employed for *Operation Monitoring and Control (OMC) of CIs*. OMC spans across a wide range, for example, in case of energy grids, from measuring electric output of a single solar panel avoiding sub-optimal working conditions, to assessing the overall state of electricity distribution over large arrays of substations of a whole country. This entails that OMC operates, both, on quantitative measurements as well as qualitative states like status/failure messages or local incident reports to global analysis of unforeseen impacts. However, ultimately, OMC is vitally dependent on reliable and faultless functioning of the underlying OT that is employed, such as sensors and control devices, which in turn themselves necessitate their monitoring of its proper functioning — aka *Operational Technology Monitoring (OTM)* [1][2].

In this context, we propose techniques for establishing the basis for monitoring OTs service quality in an integrated way [3] in the course of our research project »*DEVCON*« (*Developing Conceptualizations of OT and service quality for CIs*), with a particular focus on CIs for renewable energy. The main contribution of this paper is to propose techniques for the conceptualization of OT objects and service quality, which collectively serve as a pivotal foundational knowledge base to cope with the challenges of heterogeneity and evolution inherent to CIs. For this, we follow an innovative approach that synergistically combines *inductive methods* in terms of *machine learning* and *deductive methods* in terms of *semantic technologies*, thereby leveraging the strengths of both. Along this contribution, Section II identifies the key challenges present in OTM. Section III puts these challenges into context by presenting our demonstration case. Based on these prerequisites, Section IV lays out the research questions alongside an in-depth discussion of the state-of-the-art and the resulting solution space. In the light of this, we describe our underlying methodology in

Section V, complemented by prospected innovations in Section VI before we finally conclude with a brief summary in Section VII.

2. Challenges in OTM

In the following, crucial challenges present in the field of OTM are identified. A more in-depth discussion with respect to the current state of the art and a possible solution space is provided in Section I,V aligned with the research questions of »DEVCON«.

First of all, from a technical point of view, OTM is more and more based on the Internet-of-Things (IoT)-paradigm, not least due to the ever increasing convergence between OT, Information Technology (IT) and industry 4.0 [4]. As such, OTM is essential across all layers of the OT stack, from low-level devices primarily operating on quantitative data, such as sensors and actuators, via communication gateways to high-level software-based services. Consequently, OTM must account for the full range of OT objects present in energy CIs, like smart meters, temperature sensors, infrared cameras, relays and controllers, as well as the software services that work on top of them.

OT is inherently characterized by numerous heterogeneities, a situation further exacerbated by the fact that OT most often stems from different manufacturers, based on diverse specifications and thus having different operation characteristics, consequently continuously generating heterogeneous data volumes. To make things even worse, OT naturally exhibits diverse interdependencies across all architectural layers rendering interoperability a critical key challenge in CIs [5][6][7][8]. In the light of the dynamic nature of such systems, where the monitored CIs and their OT are constantly evolving (e.g., new solar panels of private households are continuously added), another key challenge emerges: the need to dynamically compose and aggregate OT objects into higher-level more abstract services to enable integrative service quality monitoring[7].

Addressing these challenges in turn requires intertwining of two complementary perspectives: on the one hand, the quantitative data-driven perspective of such systems, best addressed through inductive methods, like machine learning, with, on the other hand, the qualitative analytic perspective, best addressed through deductive methods like semantic model-driven approaches. Hence, effectively addressing these CI challenges demands an adequate conceptualization of the structural OT basis supporting interoperability and built thereupon, an adequate conceptualization of the behavioral OT basis providing the fundament for an appropriate integrated service quality monitoring of OT [8].

3. Demonstration Case

As a demonstration case for the techniques developed in the course of our project, we focus on the energy CI of Costa Rica not least since its energy CI is unique world-wide, having to cope with the aforementioned challenges laid out above. According to Costa Rica's *National Center for Energy Control*, more than 99% of energy is already generated from

renewable sources, comprising a mix of hydro-, wind- geothermal and solar power [9]. Notably, in 2017 Costa Rica operated on 300 consecutive days using only renewable energy alone [10].

Despite of this remarkable success in power generation, the public transportation sector remains one of Costa Rica's most significant weakest links. The adoption of electric vehicles is still limited and thus e-mobility still plays a minor role only and conversely the demand for fossil fuels is still on the rise [11]. To counteract this situation, the Costa Rican government has made the elimination of fossil fuels and the further massive expansion of renewable power generation, especially with respect to the solar power of private households, a national policy priority [9]. This ambitious strategy of extension and decentralization, however, raises the need to also cope with all the substantial technological challenges going along, thereby increasing the importance of effective oversight making the role of appropriate OTM techniques even more crucial [9].

The continuous incorporation of new power sources of different kinds from various manufacturers does not only massively increase heterogeneities, interdependencies and data volumes, which have to be dealt with effectively by OTM. Moreover, it also hinders interoperability and may lead to potentially hazardous fluctuations in power generation, particularly due to distributed generation and the resulting bidirectional energy flows [9]. Although, for assuring OT service quality also in the future, Costa Rica employs the most advanced international regulations available (like the IEEE 1547 standard for Interconnecting Distributed Resources with Electric Power Systems) [9], the scale and complexity of these new developments will demand fundamental OTM upgrades in the current electricity grid [9]. Consequently, there is a critical demand for robust conceptualizations of both the structural and behavioral OT basis of CIs, providing so the fundament for integrated OT service quality monitoring [8].

4. Research Question and Solution Space

Based on the challenges identified above and the specific characteristics of our demonstration case, the »DEVCON« project addresses the following two complementary research questions:

RQ1: How to conceptually represent the structural basis of renewable energy grids in terms of underlying OT for building up a renewable energy knowledge base allowing to (i) overcome OT heterogeneity (ii) explicate their diverse interdependencies, and (iii) facilitate interoperability as basis for integrated OT service quality monitoring (cf. RQ2).

RQ2: How to conceptually represent the behavioral basis of the renewable energy grid in terms of OT service quality to provide a solid foundation for an integrative OT service quality monitoring based thereupon.

4.1. Solution Space RQ1

The substantial heterogeneities and complex interdependencies observed across different architectural layers of the IoT-based OT—such as those in Costa Rica’s energy grid—, being of both, technical and organizational nature, result in isolated systems from various manufacturers that operate on distinctly different data models, thus, lacking interoperability [16]. Interoperability, however, is an indispensable prerequisite not only for integrated service quality monitoring but also for coping with the continuous evolution in CIs, particularly in light of Costa Rica’s recent push for further extending the energy grid with distributed local solar power generators. Therefore, a conceptual representation of OT is crucial, both, at a *type-level* and more crucial at an *instance-level* since this would allow for building up a smart renewable energy grid knowledge base providing an overview of different OT objects and their respective types employed within the smart grid [16][20][21][22].

Considering the scientific research question in this respect, firstly, heterogeneity in OT systems is a broadly discussed open challenge [5] encompassing (i) the object’s type (e.g., simple sensor or complex software services), (ii) the object’s instantiations (e.g., a concrete physical sensor), and (iii) the object’s criticality (e.g., a low critical energy sensor or a high critical safety equipment).

Secondly, another crucial issue is the diversity of interdependencies between OT objects [20] including (i) different kinds of relationships, e.g., objects existentially impact others or being optionally interlinked/backups of others (ii) diversity of communication regarding, e.g., sensation/actuation/status messages and standards (e.g., TCP/IP) and technologies (e.g., LAN, ZigBee, Bluetooth).

To effectively manage this substantial heterogeneity and these complex interdependency dimensions, there is a need for an abstract, i.e., model-based, semantic conceptualization of OT objects and their interdependencies in terms of an ontology (i.e., a “T-box”) [21]. However, as shown in [12], “no existing ontology is comprehensive enough to document all the concepts required for semantically annotating an end-to-end IoT application”. Additionally, the systems’ vast scale and the resulting massive amount of data generated by OT objects presents a research question by itself, requiring automatic data-driven methods for ontology population with existing OT objects, building up a renewable energy knowledge base in terms of the ontology’s “A-box” [21].

4.2. Solution Space RQ2

Due to reasons of substantial heterogeneities, an integrated service- oriented OTM perspective across individual OT objects, is quite limited [16]. While from a spatial perspective, a solar energy farm comprises, for example, solar panels, controlling motors, electric transformers, communication and IT infrastructure as well as surveillance sensors and monitors to name just a few, from an OTM perspective, these systems are often isolated [17]. As a result, comprehending the OT service quality of a solar energy farm in its entirety is limited not least since an integrated service quality model is missing [18].

To address this, first of all, there is a need for appropriate service quality formalizations, i.e., a conceptual Service Quality Meta Model (SQMM) to define a Service Quality Model (SQM), comprising service quality attributes and service quality metrics including rules for service quality assessment, for the entire OT. While there exist approaches such as QoSOnt [14] or OWL-Q [13], Kritikos et al. [13] point out that “*there is no commonly agreed way to specify service quality*”.

Again, the large number of OT objects prevalent in CIs makes it infeasible to manually specify service quality rules for each OT object and its implication to overall service quality [16]. While parts can be defined explicitly, conceptual OT representation knowledge could allow to implicitly derive service quality formalizations based on data-driven methods, thereby alleviating the burden of manual specification given the large number of OT objects [19]. Although plenty of work exists [13], generic service quality formalizations are sparse and hardly applicable for CI's large-scale settings.

5. Methodology

The methodology adopted in the »DEVCON« project builds on four major pillars, comprising: (1) a design research approach, (2) a synergetic, integrative combination of deductive and inductive methods, (3) a framework-driven architecture for reuse and general applicability and (4) a comprehensive evaluation strategy.

5.1. Design Research Approach

The research questions described above are investigated following a clear methodological approach based on the well-known *design research approach* [15]. In accordance with this approach, each research question is systematically decomposed into concrete challenges and corresponding requirements as already initially discussed in this paper. This decomposition facilitates the formulation of an overall picture of the project's outcome, which is further refined incrementally, along the technical insights gained throughout the process. These insights together with the approaches' decision-making process (cf. below) and the design rationale behind will be documented continuously. This serves two main purposes: (i) to guarantee that the evolution of the design process can be traced more easily and (ii) to allow for the resulting artifacts to be evaluated more efficiently, thus ensuring the overall quality of the project's outcome.

5.2. Integrative Combination of Deductive and Inductive Methods

Our approach focuses on the synergetic, integrative combination of *deductive* and *inductive methods* to address RQ1 and RQ2. On the one hand-side, *deductive methods* will comprise the employment of semantic technologies in terms of ontologies to build up an energy knowledge base. The utilization of semantic technologies allows to deal with heterogeneity and to explicate direct, but also derived, OT interdependencies along with the

service quality formalization rooting there up. On the other hand-side, inductive methods of deep learning like neural networks allow to populate and enrich the conceptual representation in the knowledge base, that have been originally built up by deductive methods. This data-driven perspective allows to continuously reflect the current state of the system in the light of its ever-evolving nature, which is especially important in the context of Costa Rica's energy infrastructure pursuing its current enormous extension and decentralization efforts.

5.3. Framework-Driven Architecture

A framework-driven architecture is proposed to be employed allowing to reuse and integrate existing OT representations and service quality formalizations possibly helpful for covering the requirements placed by the domain of smart energy grids. Such a framework thereby provides the basis to take into account specifics of Costa Rica's energy CI while capitalizing on the existing body of conceptualizations put forward by research and industry. Beyond that, a framework-driven architecture can serve also as the basis for adaptation towards other CI domains like transportation or communication [1]. This is not least since, despite their domain specificity, CIs still have numerous commonalities, like being safety-critical, dynamic, large-scale and data-rich environments which are geographically distributed and constantly evolving.

5.4. Evaluation Strategy

Complementing our methodology, we lay out an evaluation strategy based on proof-of-concept prototyping, domain-specific scenarios and usage of real-world energy grid data.

Proof-of-Concept Prototyping. The focus of the »DEVCON« project is naturally not to provide ready to deploy solutions for CI operators but rather to establish an overall understanding of the problem and possible solutions though proof-of-concept prototyping. This would allow to demonstrate the feasibility of proposed ideas for each of the research questions, thereby also combining and adapting approaches in the area of IoT towards the specific conditions of Costa Rica's renewable energy landscape.

Scenario-based Systematic Evaluation. For evaluation of the project results, a systematic strategy based on domain-specific scenarios and use cases for both RQs is foreseen. These domain-specific scenarios and use cases are developed for both research questions, grounded in the catalogue of challenges and requirements derived earlier (cf. "Design Research Methodology") especially considering specifics of Costa Rica's renewable energy landscape. Foreseen are tailored scenarios for, both. abnormal operation cases (improper function of OT objects are impeded by others) as well as normal ones (inter-operating objects in light of certain services). Given the fact that ground-truth data (gold standard A-Box) is not readily available, we intend to resort to simulated data based on real-world datasets. Thereby, properties of simulated data like status message distribution, and failure frequencies of certain OT types, should be modelled to replicate real-world data characteristics.

Data Sets from Costa Rica's Renewable Energy Grid. The necessary real-world data will be provided by Instituto Tecnológico de Costa Rica (TEC), having a data source a total of 1,380 installed solar panels (1302 located in the Cartago central Campus and 72 located in San Carlos regional campus) [23][24][25]. These installations include five rooftop and three ground-based photovoltaic systems aimed at producing carbon-neutral electricity to reduce the institution's overall energy expenditure. This small panel farm encompasses a range of photovoltaic technologies from different manufacturers, technologies and operating characteristics, continuously generating heterogeneous data volumes thus providing an ideal testbed for the approach proposed in the »DEVCON« project.

6. Prospected Innovations

Overall, the *main innovations* of »DEVCON« stem from the original and synergetic integrative combination of inductive and deductive methods. These innovations are rooted in tackling both, scientific-technical and application-oriented challenges and are targeted towards *concepts* and *techniques* elaborated along the two research questions, as described in the following.

6.1. Innovations for RQ1

Although numerous ontologies exist to represent IoT systems, CIs and smart energy grids in particular, according to [12], to date none of them seem to offer the expressiveness required for a comprehensive representation of OT systems in CIs. Many proposals are a composition of existing upper ontologies enriched with concepts for domain-specific IoT systems [16], often lacking, however, concepts for (i) different granularity levels of IoT architectures, (ii) dealing with context situations of OT service quality and (iii) coping with data-driven population and enrichment.

Accordingly, the innovation addressing RQ1 are twofold:

(1) *Ontology-based OT Conceptualizations.* Development of OT *conceptualizations*, based on existing ontologies and augmented with domain-specific concepts to capture the distinct peculiarities of OT objects and interdependencies within CIs.

(2) *Data-driven Ontology Population and Enrichment.* Elaboration of adequate *data-driven techniques* facilitating the automatic population of this ontology-based OT conceptualization with concrete OT objects (i.e., building up the A- box) and its possible enrichment (i.e., the T-box).

6.2. Innovations for RQ2

While there exists plenty of research dealing with service quality and Service Description Languages [16], according to [13], there is *no commonly agreed way to specify service quality* in IoT also considering *data-driven methods*. Nevertheless, existing ontologies [13], can be

used as basis being enriched with domain-specific and context-related aspects meeting the requirements for OTM in CIs. Consequently, the innovation for the second RQ is twofold:

(1) *Ontology-based Conceptualization of OT Service Quality*. Development of conceptualization for OT *service quality attributes and metrics*, grounded on existing (IoT-) ontologies and extended with domain-specific concepts to tackle the peculiarities of service quality of OT objects.

(2) *Data-driven Methods for Integrative Service Quality Assessment*. Elaboration of adequate *data-driven techniques* building the basis for the integrative assessment of service quality, which is addressed very sparsely in existing approaches.

6. Conclusion

We proposed techniques for the conceptualization of operational technology (OT) objects and the associated service quality, thereby building up a pivotal knowledge base to cope with substantial heterogeneity and continuous evolution inherent to CIs. For this, an approach has been put forward by synergistically combining inductive methods in terms of machine learning and deductive methods in terms of semantic technologies. Thereby, we discussed possible challenges and implied solutions in the light of Costa Rica's world-wide unique renewable energy grid, not least since such smart energy grids require, due to their distributed nature, particular extensive OT and according concepts for OTM to guarantee its efficient and safe operation. A proper conceptual representation of OT and its interdependencies together with formalizations of its service quality is therefore an even more pressing issue, which emerges as a critical and urgent area for further research and development needing to be urgently tackled.

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