A Three-Phase Evaluation Approach for new Information and Data Models in the Smart Grid Domain

Christine van Stiphoudt [*], Sergio Potenciano Menci [*], Gilbert Fridgen [*]
[*]SnT - Interdisciplinary Centre for Security, Reliability and Trust, University of Luxembourg,
Luxembourg, Luxembourg, Email: [christine.vanstiphoudt; sergio.potenciano-menci; gilbert.fridgen](at)uni.lu

Abstract

The ongoing digitalisation of the smart grid is resulting in an increase in automated information exchanges across distributed energy systems. This process has led to the development of new information and data models when the existing ones fall short. To prevent potential disruptions caused by flaws in the newly designed information and data models, it is essential to evaluate them during the design process before they are implemented in operation.

Currently, general explicit evaluation approaches outside the smart grid domain stay at a high level without defining clear steps. Meanwhile, implicit evaluation approaches in the smart grid domain focus on testing systems that utilise information and data models already in use for functionality in terms of conformance and interoperability. Notably, no combination of explicit and implicit evaluation approaches for newly designed information and data models offers a clearly defined set of steps during their design process in the smart grid context.

Consequently, we design a three-phase evaluation approach using design science research to address this gap. Our evaluation approach combines explicit and implicit evaluation methods and is applicable when developing new information and data models. We use the development of an information model and data model focused on industrial flexibility descriptions to refine our evaluation approach. Additionally, we provide lessons learned from our experience.

Index Terms

data model, information model, conceptual model, quality characteristics, conformance testing, evaluation, design science research, smart grid

I. Introduction

The ongoing digitalisation process of the smart grid is accelerating automated information exchanges between distributed energy systems [1]. This process has led to the development of new information and data models (IMs & DMs) that bridge gaps where existing models fall short [2]. Well-known examples of these new IMs & DMs include openADR [3] and EEBus SPINE [4]. They support the integration and control of distributed energy resources for flexibility provision.

To avoid potential disruptions caused by design flaws in these emerging IMs & DMs, it is essential to evaluate them during the design phase before they are deployed in operational settings. Yet, existing model descriptions often lack information about how such evaluations are conducted. As a result, model developers who focus on connecting distributed energy resources and industrial flexibility, given its large flexibility potential, have limited guidance for evaluating their models during the design process [5].

When turning into literature, general evaluation methods typically rely on explicit validation techniques that assess models directly, defining frameworks and conceptual quality metrics. However, these approaches remain high-level and rarely provide practical, step-by-step guidance. In contrast, evaluation practices within the smart grid domain tend to be implicit: models are assessed indirectly through system-level testing of functionality, conformance, or interoperability [6]. These tests apply only once models are in use, offering little support for models still under development.

Meanwhile, the broader literature on standard evaluation, relevant for IMs & DMs, suggests that combining explicit and implicit methods can enhance model assessment [6]. Nevertheless, no approach currently integrates both evaluation types in a structured, actionable way for use during the design process in the smart grid context.

This gap leads us to the central research question: *How can new IMs & DMs used in the smart grid context be evaluated during their design process to ensure both conceptual quality and functional adequacy?* In turn, our contributions towards answering the question are:

- A *holistic overview of existing evaluation approaches* related to IM & DM evaluation, taking a general (explicit) and domain-specific focus (implicit).
- A *three-phase evaluation approach* designed using design science research (DSR) combining explicit and implicit model evaluation. Our evaluation approach includes the model scope definition (Phase 1), the explicit model evaluation through conceptually validating the models' quality (Phase 2), and the implicit model evaluation through testing the functionality of model implementations according to the models' scope (Phase 3).

- A *set of quality characteristicss (QCs)* to support the evaluation in Phase 2. We followed an observation-based approach [7], along with a mapping of QCs identified in the literature. We also map QCs to the DM type based on our experience in the evaluation of the energy flexibility information model (EFIM) and energy flexibility data model (EFDM).
- *Lessons learned* from the application of our evaluation approach to the EFIM and EFDM during their design process to move from theory to practice.

We organise the remainder of the paper as follows: In Section II, we define the background given the context of our paper. In Section III, we provide an overview of existing literature in the context of IM & DM evaluation. In Section IV, we describe our research approach. In Section V, we propose our designed evaluation approach for new IMs & DMs used in the smart grid domain. In Section VI, we introduce the supportive set of QCs. In Section VII, we apply our evaluation approach to the EFIM and EFDM during their development. In Section VIII, we discuss lessons learned, limitations and potential future research avenues. In Section IX, we summarise our main findings.

II. Background

Terminology is paramount, especially when discussing multiple domains [8]. In our paper, we consider an interdisciplinary energy informatics domain and a general computer science one. Consequently, in Section II-A, we outline the scope from the perspective of energy informatics, while in Section II-B, we define the terms related to IMs & DMs that we will use throughout our paper.

A. Information exchange in the smart grid

We use the Smart Grid Architecture Model (SGAM) framework [9] as a foundation for our scope in the energy informatics domain. In essence, the SGAM framework combines the smart grid plane with the concept of interoperability layers. The smart grid plane consists of five *domains* (i.e. generation, transmission, distribution, Distributed Energy Resources (DER), customer premises) describing the energy conversion chain and the six *zones* (i.e. process, field, station, operation, enterprise, market) describing hierarchical levels of information management along the electrical processes [9].

Since our focus lies on the evaluation of new designed IMs and DMs used in the smart grid for automated information exchange, we specifically address the information interoperability layer. We consider the definition of communication protocols and hardware, which are also necessary for communication, to be out of scope. We illustrate the use of models in information exchanges in Fig. 1. Although information systems have access to both IM & DM specifications for automated information processing, they only exchange instances of the DM.

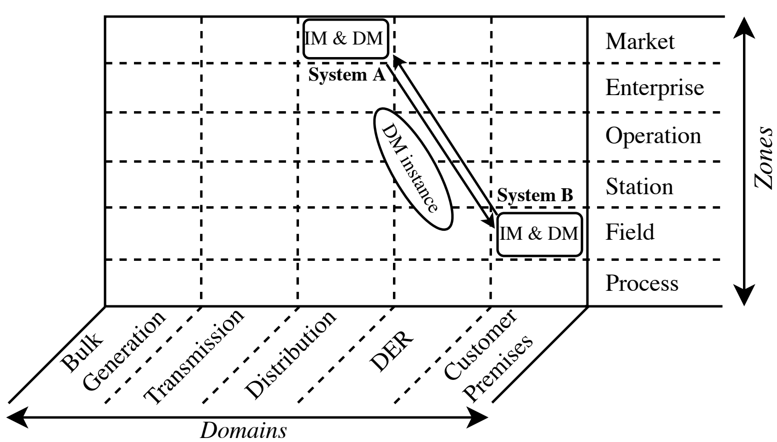

Fig. 1. Simplified visualisation of the information exchange between two systems in the SGAM information layer.

B. Model type definitions

As we combine literature and approaches from different domains, it is essential to analyse the terminology of the model terms used. In this paper, we focus on static models. We understand static models as models that specify descriptive characteristics of a system, as opposed to models that specify behaviour [10]. In Table I, we have listed various model terms and their definitions that we came across during our research. This overview does not claim to be a complete representation of all model terms and definitions. Conversely, we intended to provide an overview of different perspectives and to support terminology used for IMs & DMs given our context.

TABLE I
MODEL TYPE DEFINITIONS.

Model term	Definition	Year	Domain	Reference
Conceptual view	”A collection of objects representing the entities, properties and relationships of interest in the enterprise”	1978	Database Management	[11]
	”A model about the part of the real world captured in the data”; ”a static model of reality”	1994	Database Management	[10]
Conceptual model	”Any collection of specification statements relevant to some problem”	1994	Requirements Engineering	[12]
	”A model of a domain made in a formal or semi-formal language with a limited vocabulary.”	2012	Information systems	[13]
Information model	”A representation of concepts, relationships, constraints, rules, and operations to specify data semantics for a chosen domain of discourse”	1999	Information exchange in manufacturing	[14]
	”[...] model[s] managed objects at a conceptual level, independent of any specific implementations or protocols used to transport the data.”	2003	Network management	[15] (RFC 3444)
Data model	”[...] [is] defined at a lower level of abstraction and include many details. [It is] intended for implementors and include protocol-specific constructs.”	2003	Network management	[15] (RFC 3444)
Platform independent model (PIM)	”A model that is independent of [...] a platform”	2014	Model Driven Architecture	[16]
Platform specific model (PSM)	”A model of a system [that] is defined in terms of a specific platform”	2014	Model Driven Architecture	[16]

The term *conceptual view* originates from the domain of database management. A publication with over 500 citations is [11] that defines a conceptual view as a *”collection of objects representing the entities, properties and relationships of interest in the enterprise”*. [10] refer to the conceptual view as a static model of reality. In related domains, such as requirements engineering and information systems, the term *conceptual model* is more commonly used. For instance, [13] defines a conceptual model as a domain model specified in a formal or semi-formal language. A closely related term used in the literature is IM [15]. For instance, [14] defines IMs as *”a representation of concepts, relationships, constraints, rules and operations that specify data semantics for a chosen domain”*. In the context of network management, [15] define IMs as descriptions of objects at a conceptual level that exclude implementation- or protocol-specific details. In contrast, they define the term DM as a specification at a lower level of abstraction, including implementation and protocol-specific details. Although the term DM is frequently used in the literature, it is often not defined and aligns with the definition of conceptual models/ IMs, as seen in [17]. In the context of model-driven development, the terms platform independent model (PIM) and platform specific model (PSM) are often used to distinguish between abstract, platform-independent representations and those tailored to specific implementation environments. PIM is more based on business concepts and requirements, while PSM has a closer focus on technology [16]. Although the distinction between PIM and PSM appears to be similar to that between IMs & DMs, only PIM can be assigned to the SGAM information layer according to [18].

Given the practical importance of distinguishing between conceptual and implementation-specific models in the smart grid domain, we adopt the terminology of IMs & DMs as defined by [15]. In addition, the term IM is also more prevalent in the context of the smart grid domain than the term conceptual model. This prevalence is reflected in the naming of widely used standards, such as Common Information Model (CIM) or Energy Interoperation (EI). In this paper, we refer to the terms IMs & DMs as follows:

IMs define the structure of data [19]. They model objects at a conceptual level that is implementation- and protocol-agnostic [15] and easier for humans to understand. The level of abstraction defined in the information model (IM) is determined by the modelling needs of its designers [15]. IMs can be described informally using natural languages (e.g. English) or formally using formal or semi-formal structured languages (e.g. Unified modeling language (UML)).

DMs define the format of data facilitating automated exchange and processing [19]. DMs consider a lower level of abstraction and include implementation-specific information [15]. One IM can be mapped onto different DMs [14]. However, for reliable information and data exchange, information systems must agree on the same interpretation rules [20], thus using the same DM. DMs can be described in schema specifications using markup languages such as Extensible Markup Language (XML) or notations such as JavaScript Object Notation (JSON) [19]. We refer to the result of mapping data to a DM as DM instance.

III. State of the art in model evaluation, validation and testing

In this section, we summarise the literature on both general evaluation approaches and those specific to smart grids across three streams: the validation of standards, relevant to IMs & DMs (see Section III-B), explicit model evaluation approaches (see Section III-C), and implicit model evaluation approaches (see Section III-D). We define evaluation as the assessment of the extent to which criteria are met, validation as the process of determining whether requirements are met, and testing as a specific method used for validation, according to the definitions by [21] and the European Telecommunications Standards Institute (ETSI) [6].

A. Literature search approach

We conduct a literature review that combines integrative and narrative literature reviews to synthesise literature from different domains on the subject of IM & DM evaluation. For the integrative review, we adopt the guidelines proposed by [22], while for the narrative review, we adopt the guidelines of [23]. The purpose of the integrative review is to explore different perspectives on the topic, break down discipline-specific silos, and redirect research efforts [24]. Given the complexity of the topic, we decided to incorporate a narrative review within the integrative literature review. Narrative reviews can support integrative reviews in focusing on the synthesis of the different categories and making the integrative review more manageable [24].

To enhance transparency, we use a protocol for the search and analysis process as suggested by [25]. Although we describe a structured approach, we do not intend to conduct a systematic review due to the complexity of the topic, the resources required, and the requirement of explicit inclusion and exclusion criteria to drastically reduce the sample [26]. We apply the protocol illustrated in Fig. 2 to three research streams. The first two research streams focus on general evaluation approaches, while the third focuses primarily on smart grid-specific approaches. In the first research stream, we examine validation methods for standards relevant to IMs & DMs (see Section III-B). In the second research stream, we examine general explicit model validation techniques that focus on assessing the quality of conceptual models (see Section III-C). In the third research stream, we examine primarily smart grid-specific implicit model validation techniques that focus on testing model implementations for conformance and interoperability. By integrating general evaluation methods with those tailored specifically for smart grids, we can draw on a broader spectrum of established techniques to enhance the assessment of IMs & DMs within smart grid environments.

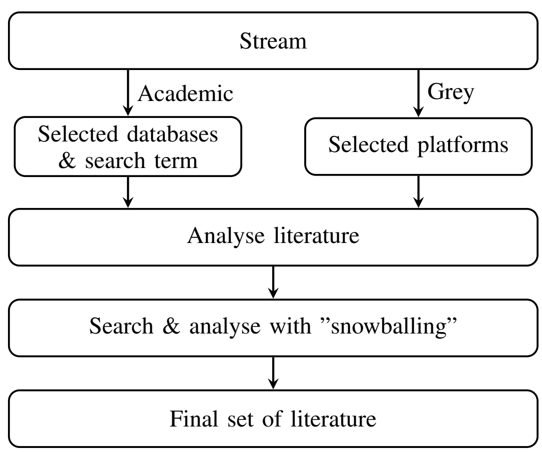

Fig. 2. Structured search and analysis protocol for combined literature review.

We explore academic and grey literature for the three different research streams. In the academic literature, we use IEEE, Scopus and ACM databases, employing combinations of the following search terms: *data model/information model/conceptual model*, *quality/evaluation/validation/testing*, *interoperability/conformance/conformity*, *smart grid*. Our focus is on peer-reviewed journal articles and conference proceedings written in English. For grey literature, we search on Google Scholar and websites of standardisation bodies and research projects like CORDIS [27] for EU projects. We focus on standard specifications and reports.

In our analysis, we select the literature based on its relevance to the overarching topic. Where deemed appropriate by the authors, we analysed both the core components and the complete manuscript.

To enhance the effectiveness of our search and discover additional relevant literature related to our topic, we conduct a ”snowballing” search, as described by [28]. By tracking the references in previously found articles and examining the citations of these papers, we aimed to increase the effectiveness of our search and discover more relevant literature related to our topic.

B. Validation methods for standards specifying physical characteristics

The validation of standards is intended to ensure that their specified requirements fulfil the intended objectives [6]. Examples of standards specifying IMs & DMs are CIM [29] and OpenADR 2.0b [30]. [6] as one standardisation body differentiates between the validation of standards specifying physical characteristics and standards specifying behaviour. Since we define IMs & DMs in Section II-B as static models that specify descriptive characteristics rather than dynamic behaviour, we will refer in the following to standards specifying physical characteristics.

A practical method for explicit validation of standards is the review process [6] consisting of the following four main steps: 1) Planning the reviews, 2) Preparing the review, 3) Reviewing the specification, and 4) Processing change proposals. Besides explicit validation of standards, [6] lists implicit validation methods where validation is only a by-product. This includes conformance and interoperability testing, which are essential in a smart grid to ensure interoperable interaction between components. [6] also recommends the use of validation methods at different points in the development process.

To summarise, the validation methods suggested for standards specifying physical characteristics encompass both explicit and implicit validations. However, the review method for explicit validation does not specifically address the characteristics of IMs & DMs.

C. Explicit model evaluation approaches

Existing explicit model evaluation approaches aim to evaluate the quality of conceptual models. Several standards define the term quality. ISO 9000 addresses quality management, ISO/IEC 9126 deals with software product quality, and ISO 2510 addresses the product quality of Information and Communication Technology (ICT) and software products. Even if IMs & DMs may be seen as part of software products, no standard specifically addresses the quality of IMs & DMs. [7] proposes the following definition for conceptual model quality that is consistent with the ISO 9000 definition: "*The totality of features and characteristics of a conceptual model that bear on its ability to satisfy stated or implied needs*". In our paper, we refer to these characteristics as QCs [10]. The literature also refers to the terms: quality goals [12], quality factors [17] or attributes [31]. In Section III-C1, we summarise such characteristics for conceptual models, which are referred to as IMs in Section II. In Section III-C2, we describe the approaches to evaluate models against these characteristics. Both the literature on QCs and the evaluation frameworks address IMs & DMs from a general computer science perspective.

1) Quality characteristics: In the following, we focus on literature that directly relates to the quality of conceptual models and therefore exclude literature on data/information quality, such as [32], [33].

The analysed literature represents sets of QCs either as theoretical frameworks or as lists. Theoretical frameworks relate multiple QCs to each other, while lists only enumerate them. For example, [12] define and relate model quality using four QCs (termed quality goals) based on linguistic theory. The SEQUAL framework extends the number of quality goals—referred to as quality levels [34]. These levels synthesise multiple perspectives on model quality and are based on semiotic theory, a field concerned with signs and their meanings. Similarly, the CMQF framework builds on the work of [12] and its subsequent extensions, combining it with the ontological model of [35]. It defines twenty-four QCs, which are mapped to four layers representing the basic modelling process and the object of interest. The three theoretical frameworks [12], [34], [36] mention syntactic correctness or syntactic quality as one QC, making it fundamental.

As previously stated, lists enumerate individual QCs without a theoretical framework relating them. For example, [10] defines fourteen QCs, illustrating them with examples from database management. [14] mentions seven QCs based on experiences of model development in the manufacturing sector. [17] define eight QCs, which they apply in field and laboratory experiments. While all three lists are practically orientated, our analysis reveals an overlap of nine QCs between them.

Given the large number of existing sets of QC, researchers have attempted to consolidate them through categorisation [10], [37]. However, the reasoning behind these categories is not always clear. To avoid excessive classifications with limited benefits, [38] emphasises, in the context of data quality classification, the need for justification if specific sets of QCs are created. Additionally, some papers have proposed quantitative metrics to objectively measure QCs. Given that practitioners have found that these metrics offer only marginal benefits for improving IMs [39], we exclude them from our analysis.

To summarise, while the sets of QCs defined within theoretical frameworks are often abstract, those defined in lists tend to be more specific and therefore more useful for practical applications [40]. However, their definitions are often vague, complicated, or even absent [12] and vary between different studies [41]. Moreover, these criteria are typically defined only for IMs, as per our definitions in Section II). In most cases, the intended use of the models they refer to is not explicitly stated.

2) Conceptual model evaluation frameworks: In addition to the specification of QCs, the literature defines conceptual model evaluation frameworks that support the understanding and assessment of conceptual model quality. This literature is closely related to the literature on QCs in Section III-C1. We classify the frameworks into four categories: theory, practice, theory-and-practice, and hierarchical.

The first category is theory-driven. The framework introduced by [12] aims to identify QCs referred to as quality goals and means of achieving them. It applies to conceptual models and the modelling process. [34] extends this framework by incorporating principles from semiotic theory, maintaining the distinction between goals and means. It applies to the quality of models and modelling languages. Similarly, [36] builds on the framework of [12] and its subsequent extensions and combines it with the ontological model of [35]. It applies to the evaluation of conceptual models and the modelling process.

The second category is practice-driven. [42] propose a framework for the evaluation and improvement of IMs (see definition in Section II). [17], [39] later refine this framework. Similar to the theory-driven frameworks [12], [34], they also distinguish between goals (i.e. quality factors) and means (i.e. improvement strategy). However, concepts such as stakeholders, quality review, quality issue, and improvement strategy emphasise their practical orientation.

The third category combines both theory and practice. [40] build upon the theory-driven [43] and the practice-driven [42] frameworks to analyse their mutual influence.

The fourth category proposes hierarchical structures. [31] propose a meta-model for evaluating and improving the quality of conceptual models. The model instantiation results in a hierarchical structure with quality goals, dimensions, attributes, metrics, and transformation rules.

To summarise, all frameworks contribute to the understanding of conceptual model quality. Most distinguish between goals and means. However, a framework providing a structured guiding process for the conceptual evaluation of new models is missing.

D. Implicit model evaluation approaches

Implicit model evaluation approaches aim to test model implementations and test models as a by-product [6]. The implicit evaluation approach is essential for models used in operation. [6] mentions conformance and interoperability testing as one implicit validation method for standards relevant to IMs & DMs. Since interoperability is a critical topic for information exchange in the smart grid [44], we focus in Section III-D1 on conformance testing approaches (considered a prerequisite for interoperability testing) and in Section III-D2 on interoperability testing approaches. Whereas the two previous sections focus on general evaluation approaches, this section also considers smart grid-specific approaches.

1) Conformance testing: The aim of conformance or conformity testing [45] is to verify the correct implementation of a standard or specification [44]. It evaluates products or systems against the requirements specified in a standard or specification [46] and is considered a prerequisite for interoperability testing [44]. In the computer science domain, standardisation bodies propose methodological approaches for conformance testing. [47] summarise well-known general approaches. For instance, the ISO/IEC 9646 standard specifies a general methodology to test the conformance of products to Open Systems Interconnection specifications [48]. Based on this standard, ETSI develops conformance test specifications at the European level [49]. For application-independent test specifications, they specified TTCN-3, a testing and test control notation [50]. For the energy domain, [51] and [52] provide examples of conformity-related standards and frameworks for testing the conformance to standards. One example is the ENTSO-E CGMES Conformity Assessment Framework [53]. It tests applications supporting the CIM standards 61970-600-1 and 61970-600-2 developed for transmission system operators (TSOs) to facilitate data exchanges in system operations, network planning, and integrated electricity markets [53].

The execution of tests requires infrastructure [44]. Test beds can provide this environment, including hardware, simulators, instrumentation and software tools, among others [21]. An example is the Interoperability Test Bed developed within the European Commission's DIGIT project developed to support conformance testing of information technology (IT) systems [54]. Test beds should also reflect domain-specific requirements, such as specified by [44].

To summarise, standardisation bodies and associations address conformance testing from both methodological and implementation perspectives and thereby contribute to assessing the correct functionality of implemented specifications. However, since they address models already in use, they are often associated with complexities that can be excessive during model evaluations in the design phase.

2) Interoperability testing: The CEN-CENELEC-ETSI Smart Grid Coordination Group defines interoperability as *"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"* [44]. Since achieving interoperable information exchange is a significant challenge, particularly in the context of the smart grid, various interoperability testing approaches exist. [52] analyses existing approaches regarding their challenges and requirements for harmonisation. In the following, we provide an overview of some of the main approaches focusing on interoperability testing.

For instance, the Joint Research Centre (JRC) defined the Smart Grid Interoperability Testing methodology [44]. It aims to assess the ability of technological implementations in smart grid components to exchange and use that information effectively. The focus is on the implementation of devices or protocols that are directly supported by the standard. The methodology consists of six steps, including the use case specification, profile creation, design and analysis of the experiment, and actual testing. To automate some of the activities, JRC has developed the Smart Grid Design of Interoperability Tests (SG-DoIT) [55]. Additionally, this web-based application stores the results of the interoperability testing process.

The IES approach to interoperability proposed by the Smart Grids Austria technology platform also foresees the storage of test specifications and test results [56]. The approach is based on processes in the healthcare domain but has been adopted for the energy sector. It addresses the interoperability of information exchange between ICT systems. The three pillars of the approach include (1) the specification of integration profiles, (2) the organisation and implementation of interoperability peer-to-peer test events, so-called Connectathons, and (3) the publicly available making of the profiles and test results. The open-source software testbed Gazelle [57] supports the management of both interoperability and conformance tests and can be used to conduct these tests.

The National Institute of Standards and Technology (NIST) Framework and Roadmap for Smart Grid Interoperability [46] defines interoperability profiles as a subset of implementation requirements derived from existing standards tailored to specific implementation. These profiles clarify which elements of a standard should be used to ensure consistent interoperability across devices and systems. They aim to reduce the complexity of implementation and testing. The framework also emphasise the importance of public accessibility and visibility of interoperability profiles. Similarly, [51] identify standards for interoperability profiles within the energy domain.

Whereas further approaches, such as the ERIGrid Holistic Test Description (HTD) [58] or a testing methodology to check the compliance with the Code of Conduct (CoC) for smart appliances, can be associated with interoperability testing, they do not address them directly.

To summarise, various approaches to interoperability testing exist, encompassing methodologies, frameworks, and tools. Interoperability testing procedures can be synthesised into four main phases [52]: 1) Identify and define test cases, 2) Plan test and set-ups, 3) Execute the tests, 4) Report the test needs. However, the testing approaches are not harmonised, profiling and test case specifications are diverse, and approaches are purpose-specific [52]. Additionally, similar to conformance testing, the interoperability testing approaches address models already in use, and the execution may aim for certification [46]. Thus, the processes are often associated with complexities that can be excessive during model evaluations in the design phase.

E. Summary and research gap

This combined literature review provides a broad perspective on the evaluation of IMs & DMs. The methods, frameworks, and tools discussed each address specific purposes in the evaluation context. However, the following research gaps become apparent for the evaluation of IMs & DMs used in the smart grid. First, while there is extensive literature on defining and evaluating the quality of conceptual models, similar work for DMs is lacking. Second, these existing general evaluation approaches often remain at a high level of abstraction and typically do not provide structured, step-by-step guidance that model developers can follow. Third, while general evaluation methods typically rely on explicit validation techniques, smart grid-specific approaches tend to use implicit validation and address models that are already in use. The broader literature on standards evaluation relevant for IMs & DMs suggests that combining explicit and implicit methods can improve the model assessment [6]. However, there is currently no approach that integrates both explicit and implicit methods in a structured, actionable way for use during the design process in the smart grid context.

IV. Research approach

Based on our identified research gap, we propose a new evaluation approach for IMs & DMs used in the smart grid in their design process. We describe the design process in Section IV-A. During this design process, we identified the need to consolidate a list of QCs to support our new evaluation approach. We describe the consolidation process in Section IV-B.

A. How did we design the new evaluation approach?

Since we design a new evaluation approach, we draw on the DSR approach [59]. Our new evaluation approach combines explicit model evaluation, ensuring conceptual model quality, and implicit model evaluation, ensuring functionality of IMs & DMs concerning the defined model's scope. The design science research methodology (DSRM) that we follow consists of an iterative process with six steps (see Fig. 3).

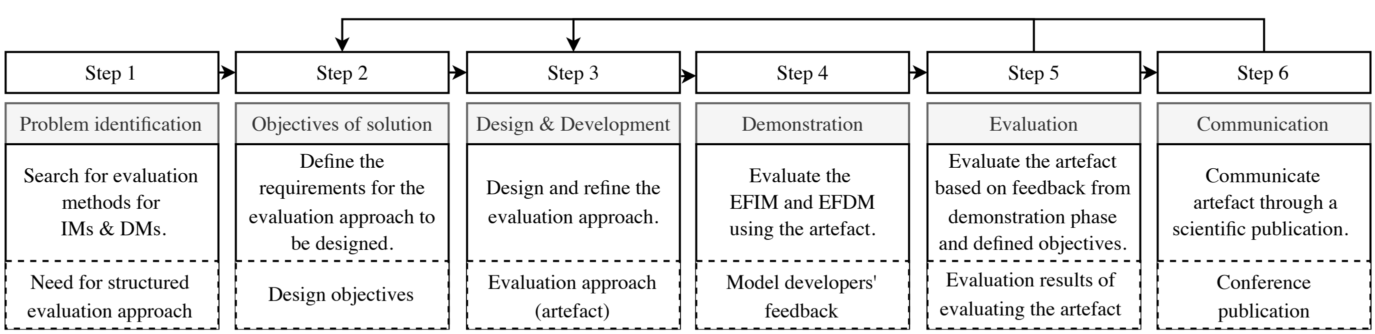

Fig. 3. Adopted and applied DSRM process based on [59].

In this first step, we analyse existing evaluation approaches to understand the current status. To identify relevant literature, we conducted a combined literature review as described in Section III-A. Existing approaches often lack structured steps and a combined evaluation method for IMs & DMs consisting of explicit and implicit model validations. In the second step, insights from our literature review helped us to define the objectives for the solution (i.e. our proposed evaluation approach). We defined the following three objectives the evaluation approach should fulfil: (1) the evaluation approach should address the evaluation of both IMs & DMs; (2) the evaluation approach should be applicable to practitioners, meaning that the steps defined should be clear and unambiguous; (3) the evaluation approach should combine explicit and implicit validation methods. The third step requires the creation of the artefact (i.e. our proposed evaluation approach). We designed the evaluation approach iteratively based on the state of the art in model evaluation, validation and testing (see Section III). In particular, we used the suggestions of [6] to combine explicit and implicit validation methods. For the design of the explicit model evaluation phase, we used the framework proposed by [17], [39] as a basis to ensure the conceptual model quality given its practical relevance (see Section III-C2) and combined it with steps of a basic review process specified by [6]. For the design of the implicit model evaluation phase, we used the findings from the analysed literature on testing model implementations (see Section III-D) to ensure the functionality of IMs & DMs concerning the defined model's scope. Due to the diversity of existing testing approaches and the varying scopes of the models, we decided to design a modular phase that can be adapted according to the model's needs. It also allows for keeping the evaluation approach general, while still ensuring its suitability for use in the smart grid domain. The fourth step demonstrates the use of the artefact (i.e. our proposed evaluation approach). We demonstrated the designed evaluation approach by applying it during the development of the EFIM and EFDM. We used the model developers' feedback on the usability and understandability of the designed evaluation approach in the following step to evaluate and refine it. The fifth step requires the evaluation of the artefact (i.e. our proposed evaluation approach). We evaluated the artefact 1) against the objectives we defined in the second step and 2) based on the model developers' feedback on the application in the fourth step. Based on the results acquired, we iteratively continued with the design in step 3. In total, we conducted seven iterations. The sixth step requires the communication of the artefact (i.e. our proposed evaluation approach). We presented the evaluation approach to expert groups (e.g. in a symposium) and contributed the final evaluation approach in this conference publication.

B. How did we consolidate sets of QCs for practical application?

During the iterative design of the evaluation approach, we identified the need to consolidate a supportive list of QCs for the explicit IM & DM evaluation at the conceptual level. Besides the missing consensus identified in the literature review (see Section III-C1) on which QCs to use, the demonstration in step 4 revealed that existing sets of QCs cannot be clearly distinguished or are not directly comprehensible. It was also not possible to assign all defects identified to the QCs from the literature. We therefore derived a consolidated supportive set of practically applicable QCs in three stages. First, we used an observation-based (inductive) approach, as mentioned by [7] to analyse the results of the development process of EFIM and EFDM. We consulted their development team and created a classification of defects they identified, which formed the basis for defining an initial set of six QCs (i.e., semantic correctness, increase usability, instance uniqueness, essentialness, unambiguity, singularity). Second, we mapped these six QCs identified through the observation-based approach with 29 QCs identified in the literature with practical experience [14]/studies [17]/examples [10]. We mapped QCs with the same name or concept. The resulting supportive list contains 21 QCs (see Section VI), including three that have not yet been listed in the literature. Third, since none of the analysed publications specifies QCs for the evaluation of DMs as defined in Section II-B, we analysed the set of 21 QCs to identify those that align with the definition of the DM type. Our mapping is based on either 1) observed defects in the EFDM evaluation or 2) analytical considerations. Specifically, we analysed whether the implementation of the definitions in the IM should be verified in the DM with respect to each QC.

V. Our artefact: An evaluation approach for new information and data models during their design process

The artefact resulting from the design process described in Section IV using DSR is a structured evaluation approach as illustrated in Fig. 4. Our evaluation approach is mainly based on works from [17], [39], [6]. We combine both explicit and implicit validation methods to enhance the model evaluation. While explicit model evaluation is essential to ensure the model's conceptual quality, implicit model evaluation is important to ensure its functionality. We split our evaluation approach into three phases: Phase 1 - model scope definition (see Section V-A), Phase 2 - explicit model evaluation (see Section V-B), and Phase 3 - implicit model evaluation (see Section V-C). We keep the explicit evaluation modular and enable the integration of established test methods (see Section III-D). This enables the tailoring of the evaluation according to the model's scope and the status of the development, and enables the inclusion of new methods in Phase 3. Although we do not specify testing methods in our evaluation approach, this paper emphasises conformance and interoperability testing since these are commonly used in the smart grid domain.

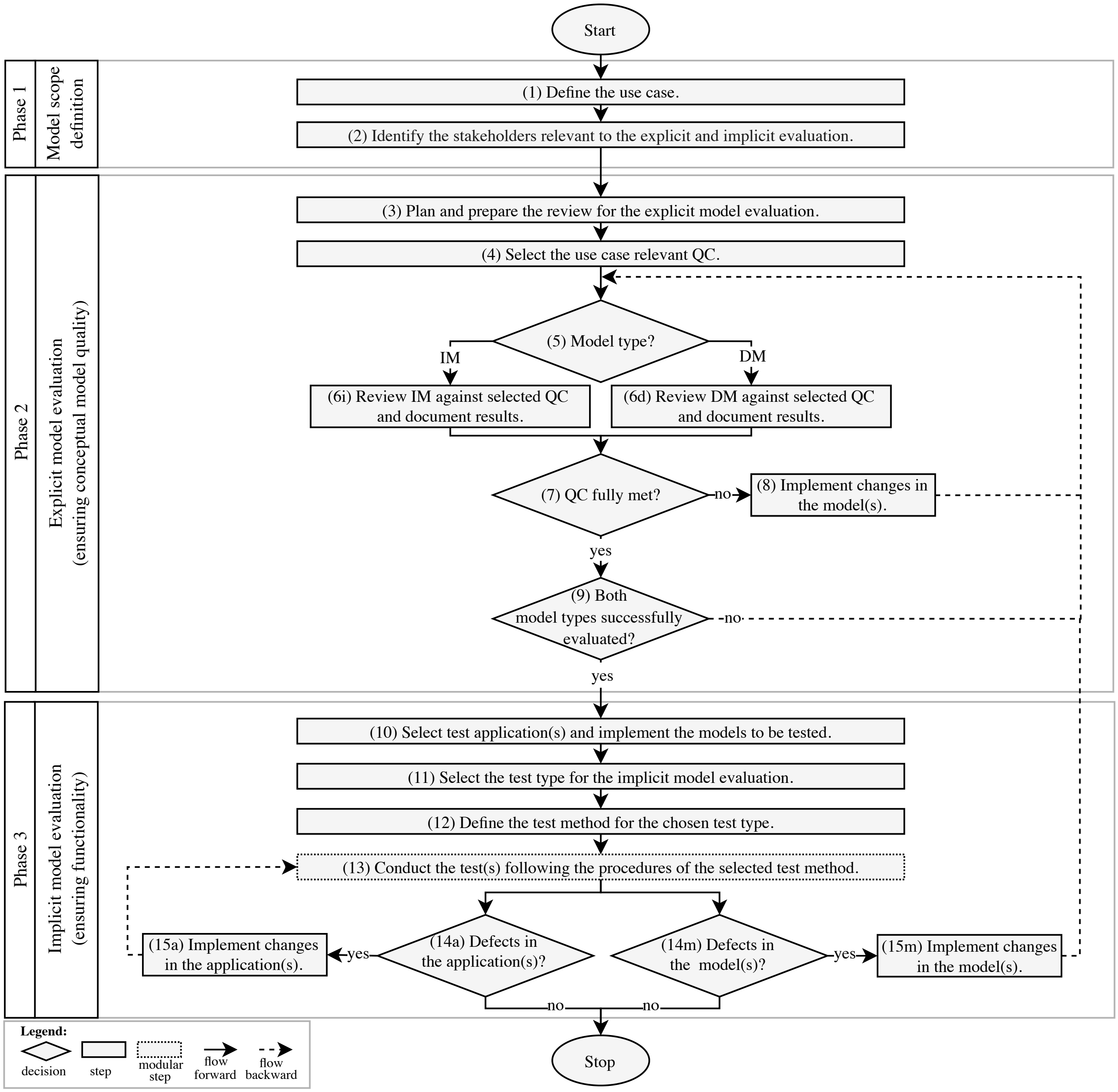

Fig. 4. Three-Phase Evaluation Approach for new IMs & DMs.

A. Phase 1 - Model scope definition

This phase consists of two steps, as illustrated in Fig. 4. In step (1), the model developer(s) define the intended use case for the model being evaluated. Use cases establish a shared understanding among stakeholders, which is crucial in complex systems like the smart grid [44], [60]. They provide the basis for selecting suitable QCs in Phase 2 (see Section V-B) and defining the test cases [44] in Phase 3 (see Section V-C). Use case templates, such as the one defined in IEC 62559-2, provide a uniform specification [61]. Its use saves effort and enables comparability between descriptions. In the context of smart grids, the standardisation bodies CEN, CENELEC and ETSI provide a checklist based on IEC 62559-2 [9]. In step (2), the model developer(s) identify participants for the evaluation execution, selecting individuals from the stakeholder groups identified in step (1). Involving stakeholders ensures capturing various perspectives and interests during the evaluation process [17], [39].

B. Phase 2 - Explicit model evaluation

This phase consists of five steps, as illustrated in Fig. 4. In step (3), the model developer(s) plan and prepare the review of the model(s). Review types, mentioned in connection with model/standard evaluations, include inspections [6], [17], [37] and walk-throughs [6], [62]. [62] specifies for the review of standards: the involvement of experts without a direct role in the specification development; the specification of a chair that leads the review sessions; the provision of the specification to the reviewers before the review sessions; a presentation of the specification in the beginning of the review session and a line-by-line review. [17] mentions the rating of the model for each QC on a scale of 1-5 prior to the review sessions. In addition to the organisational planning, the model developer(s) select the QCs in step (4) relevant to the use case defined in step (1). We provide an overview of a consolidated set of QCs in Table II. This list contains a mapping to the two model types (i.e. IM & DM). Next, the model developer(s) and stakeholder(s) decide which model type to evaluate (see decision 5). The evaluation process begins with the evaluation of the IM. In step (6i), the model developer(s) and stakeholder(s) review the IM against the chosen QCs specific to IMs and document the results. In turn, if the model developer(s) and stakeholder(s) decide to review the DM, they do this in step (6d). The procedure for the review process depends on the review method defined in step (3). The evaluation against QCs in steps (6i) and (6d) can also be carried out in rounds. In addition to human inspection, model developer(s) and stakeholder(s) may use tools for defect detection [37]. For the documentation of the review results, [17] proposes a quality issues matrix. If not all QCs relevant to the evaluated model type are met (see decision 9) and model developer(s) and stakeholder(s) identify defects, they implement changes to the model in step (8) and start the re-evaluation with the decision (5). This process repeats until all QCs are satisfied. Once one model type is successfully evaluated, the same process is applied to the other model type. Once both model types are successfully evaluated (i.e. all QCs are met) (see decision 11), the model developer(s) and stakeholder(s) will proceed with the evaluation in Phase 3.

C. Phase 3 - Implicit model evaluation

This phase consists of four steps, as illustrated in Fig. 4. In step (10), the model developer(s) and stakeholder(s) select the test application(s) according to the models' scope defined in Phase 1 and implement the models to be tested. If no application exists, the model developer(s) and stakeholder(s) can either develop a test application or use the conceptual formulation of a test application provided in the use case defined in step (1).

In step (11), the model developer(s) and stakeholder(s) select a test type for the implicit model evaluation. We distinguish between two types of tests: formal and informal. On the one hand, formal tests define established test procedures. An advantage of using established formal test procedures is their usage beyond the model design phase. The use of the Interoperability Test Bed [54], for example, enables the description and provision of test cases. These could be made available to users of the finalised developed IM & DM to test their implementations. However, the suitability of formal methods at the respective development stage needs to be assessed in model development projects in terms of required effort and time [6]. On the other hand, informal tests define individual test procedures. This includes a simplified version of a formal test procedure or conceptual testing. Simplified tests can be useful if test applications are not yet advanced enough to support automated testing. Conceptual tests can be used if test applications do not yet exist and in step (10) were formulated conceptually. This type of test might be suitable, especially at the beginning of a model development project.

After selecting the test type, the model developer(s) and the stakeholder(s) define in step (12) a suitable test method according to the previously chosen test type. We provide an overview of test methods and test tools for conformance and interoperability testing in Section III-D. For informal tests (i.e. simplified or conceptual), the model developer(s) and stakeholder(s) have to define their own method. In the case of conceptual testing, the data are mapped with the IM & DM to be tested according to the conceptually formulated test application in step (10).

In step (13), the model developer(s) and stakeholder(s) conduct the test according to the chosen test method. This step is replaced by the procedures defined in the test method previously selected or defined. We highlight this modularity in Fig. 4 with a dotted line. It addresses the tailoring of the validation according to the model's scope and the status of the development.

If the model developer(s) and stakeholder(s) identify defects in the application(s) (see decision 14a), the model developer(s) implement changes to the model in step (15a) and re-conduct the test in step (13). If the model developer(s) and stakeholder(s) identify defects in the model(s) (see decision 14m), the model developer(s) implement changes to the model(s) in step (15m) and start the re-evaluation of the model(s) with the decision (5) in Phase 2. This process repeats until no defects are identified in steps (14a) and (14m). Once the model developer(s) and stakeholder(s) have successfully conducted all relevant tests, the evaluation of both IM and DM is deemed successful, and the model development process concludes.

VI. Our proposed consolidated quality characteristics list

In Table II, we list the set of 21 QCs resulting from the consolidation process described in Section IV-B. This list is intended as a supplement to the explicit model evaluation in Phase 2 of our proposed evaluation approach (see Section V-B). We describe each QC with an evaluation question based on the referenced literature and list an example of observed defects during the application of our evaluation approach to the EFIM and EFDM evaluation (see also Section VII), where applicable. In addition,

TABLE II
SUPPORTIVE LIST OF QC FOR THE EVALUATION OF IMS AND DATA MODELS (DMS).

QC	Model type	Evaluation question	Observed defect example	Based on referenced QC
Semantic correctness	IM	Does the model correctly specify entities/ attributes for the intended purpose?	Attributes with incorrect unit.	relevance [10]; semantic correctness [OBA] [3]
Completeness	IM / DM [2]	Does the model consider all entities/attributes required for the intended application?	Entity missing.	completeness [17]; complete [14] comprehensiveness [10]
Unambigiousness	IM	Are all definitions clear and without the possibility of misinterpretation?	Description of entities unclear.	unambiguous definitions [10]; unambiguous [14]; unambiguity [OBA] [3]
Understandability	IM / DM [1]	Are all entities/attributes easily understandable by all stakeholders?	Data type not human-readable.	understandability [17]; increase usability [OBA] [3]
Value obtainability	IM	Are values for all entities/attributes sufficiently accessible?	n/a	obtainability of values [10]
Simplicity	IM	Are only entities/attributes specified that are relevant for the intended application?	n/a	essentialness [10]; simplicity [17]
Attribute granularity	IM	Is the granularity of entity/ attribute specifications achievable and justifiable?	Entity requires min and max attributes.	attribute granularity [10]
Precision	IM / DM [2]	Does the specified accuracy of the attribute values fulfil the requirements of the domain/application?	Incorrect number of decimals for attributes.	domain precision [10]; precise [14]
Naturalness	IM	Do all entities/attributes have a real counterpart, and do attributes represent a single fact?	n/a	naturalness [10]
Identifiability	IM / DM [2]	Are individual entities identifiable and distinct from one another?	Identical attribute names and enumerations.	occurrence identifiability [10]; sharable [14]
Homogeneity	IM / DM [2]	Do all attributes of a given type apply to all entities of that type?	Two attributes define variants of an attribute.	homogeneity [10]
Semantic consistency	IM / DM [2]	Are all entities/attributes consistently defined between related components and across related models?	n/a	semantic consistency [10]; integration [17]
Structural consistency	IM / DM [2]	Are entities/attributes consistently structured?	Inconsistent hierarchical structure of attributes.	structural consistency [10]; well-structured [14]
Robustness	IM / DM [2]	Are all entities/ attributes stable against changing requirements?	n/a	robustness [10]; stable [14]
Extensibility	IM / DM [2]	Is the model easily adaptable to incorporate changes?	n/a	flexibility [10], [17]; extensible [14]
Implementability	IM	Can the model be implemented within the project requirements?	not considered	implementatbility [17]
Integrity	IM	Are all business rules that apply to the data incorporated?	not considered	integrity [17]
Syntactic correctness	IM / DM [2]	Are modelling conventions met?	Undesirable behaviour of numeric types.	correctness [17]
Singularity	IM / DM [2]	Does every entity/attribute describe distinct information?	Redundant attributes for model version.	**proposed in this paper**
Instance uniqueness	IM	Does the model specify an attribute to distinguish model instances?	No ID attribute for model schema.	**proposed in this paper**
Essentialness	IM / DM [2]	Are only entities/attributes specified as mandatory that are necessary for all intended use cases?	All attributes are mandatory by default.	**proposed in this paper**

[1] Defect observed.
[2] Analytical explanation.
[3] OBA being observation-based approach.

we map QCs to the DM type in cases where we observed a defect or when the definitions in the IM concerning the respective QC require verification of the implementation in the DM. An example where verification is not required is *naturalness*. Once all entities and attributes are defined as having a real counterpart, this will not change in the realisation of the DM. The allocation illustrates that all QCs should be used for the evaluation of IMs and 12 of them for DMs (provided that an associated IM has been evaluated beforehand). The proposed supportive set of consolidated QCs also includes three new items: *singularity*, *instance uniqueness*, and *essentialness*. These stem from the observation-based approach and are based on specific defects that did not align with the existing QCs. They address the practical aspect of our evaluation approach. Since explanations of the consolidated QCs can be found in the referenced literature, we will focus on the three new ones in the following:

Singularity refers to the absence of redundant elements, which helps to maintain a single point of truth and is essential to prevent the processing of contradictory information. [17] decided to include redundancy within the QC *correctness*. However, since technical modelling experts may not always be involved in the development of domain models, we see the risk that *singularity* might not be directly associated with *correctness*. Therefore, we include singularity in our supportive set of QCs to reduce the risk of this criterion being overlooked.

Uniqueness refers to the requirement that model instances must have unique identifiers, ensuring they are distinguishable once automatically exchanged, stored and processed. By specifying identifiers directly in IMs, IT systems do not have to assign their own ones, thereby reducing the risk of errors caused by misidentification of data objects.

Essentialness refers to the minimum specification of mandatory entities and attributes. This helps prevent the inclusion of intentionally false information into DM instances. Once incorrect information is exchanged between information systems, it can be challenging to detect and correct it. Default values can be specified for entities and attributes that are not mandatory. These also support the model's expandability and ensure downward compatibility with older model versions.

VII. Exemplary use of our evaluation approach

We used the development process of a new IM and DM to test and refine our evaluation approach based on feedback from the model developers who used it. The newly designed IM and DM are the EFIM and EFDM [63] respectively. The team of model developers comprised a group of experts from research and industry, specialising in the energy sector, manufacturing, and IT. Consequently, we describe hereafter the exemplary use of our final evaluation approach proposed in Section V to the EFIM and EFDM.

A. Evaluated model

The EFIM and EFDM are developed to define descriptions of industrial energy flexibility. The models are designed to be applicable across various industrial sectors and to reduce interoperability challenges associated with information exchange [64]. The EFIM consists of two main classes: The `flexibilitySpace` class describes the potential (i.e. possible options) of an industrial company to adjust their planned power consumption. The `flexibleLoadMeasuresPackage` class describes the schedule (i.e. one specific option) of an industrial company to adjust their planned power consumption. The EFIM is described in natural language, and the EFDM in JSON schemas (i.e. one schema for each class). The complete model specifications can be found in a Git repository [63].

B. How did we apply our evaluation approach?

In Phase 1, model developers started by defining the use case in step (1). To enhance the readability, we describe the use case in a narrative form instead of adhering to a use case template (see Section V-A). The use case consists of two information systems exchanging information as illustrated in Fig. 5: An industrial company sends information (i.e. EFDM instance) from their digital company platform (System A) [64] to an energy service (System B) called the Flex-Tool [65]. Afterwards, the energy service (System B) sends a response to the digital company platform (System A) of the industrial company. Both information systems (i.e. digital company platform and energy service) have implemented the EFIM and EFDM in their application programming interfaces (APIs). Next, in step (2), the model developers identified three additional stakeholders for the evaluation, including developers of the energy service and experts in manufacturing and IT.

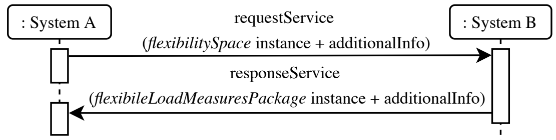

Fig. 5. Sequence diagram of the information exchange of the use case.

In Phase 2, the model developers and stakeholders began by planning and preparing the review in step (3). They decided to conduct the review session with one of the model developers as the chair, who leads the discussions. Even though having a model developer as the chair is not recommended by ETSI for reviewing standards, this decision was taken due to resource limitations. Next, following step (4), the model developers and stakeholders selected 19 out of the 21 QCs listed in Table II based on the use case defined in step (1). They excluded the QCs *integrity* and *implementability*. Since the EFIM and EFDM do not address specific company applications, the evaluation of compliance with business rules and project requirements is not of interest. During the first evaluation iteration, the model developers and stakeholders selected the EFIM for evaluation (see decision 5). They evaluated the EFIM against the 19 QCs and documented any identified defects in step (6i) by human inspection. In such cases where at least one QC was not met (see decision 7), they implemented the necessary changes in the model in step (8). This iterative evaluation process continued until the EFIM met all QCs (see decision 7). Afterwards, the process continued with the evaluation of the EFDM in steps (6d) to (8). From steps (6i/6d), developers identified defects such as missing price elements (*QC completeness*), incorrect units (*QC semantic correctness*), redundant information such as two elements referring to the model version (*QC singularity*) and absence of IDs (*QC instance uniqueness*). Once both EFIM and EFDM were successfully evaluated (see decision 9), the evaluation proceeded with Phase 3.

In Phase 3, model developers and stakeholders selected a test application in step (10). They chose the Flex-Tool (i.e. System B according to Fig. 5) and implemented both EFIM and EFDM. Due to limited available resources and the status of the research project, the model developers and stakeholders decided, in step (11), to select the informal test type and conduct a simplified form of a conformance test. As an informal test was chosen, the model developers and stakeholders defined the testing method in step (12) based on the formal conformity testing method specified by [49], resulting in five steps replacing the modular step (13).

In step (13.1), the model developers and stakeholders specified the test case. Following our use case, an industrial company sends `flexibilitySpace` instances from their digital company platform (System A) to the energy service (System B) (see Fig. 5). The expected responses are `flexibleLoadMeasuresPackage` instances that the energy service (System B) sends to the digital company platform (System A). In step (13.2), the model developers and stakeholders selected the syntax and semantics test criteria. The syntax test criteria ensured that serialised class instances were compliant with the corresponding class schema specifications. The semantics test criteria ensured that the values specified in the response (i.e. `flexibleLoadMeasuresPackage` instances) sent from the energy service (System B) to the digital company platform (System A) are compliant with the value ranges (e.g. minimum and maximum values) of the request (i.e. `flexibilitySpace` instances). In step (13.3), the model developers and stakeholders selected the test environment. For the syntax test, they opted to write test scripts in Python. For the semantics test, they decided on a manual test execution (i.e. manually comparing the values in the response with the semantics test criteria) due to time constraints. In step (13.4), the industrial company defined the `flexibilitySpace` instances and implemented the information exchange with the model developers using an API client before executing the tests in step (13.5).

If the syntax or semantic tests failed (see decision 14a/14m), the model developers and stakeholders implemented changes following steps (15a)/(15m) in the application or the model. Defects identified after failed syntax tests were ascribed to incorrect EFDM implementation in the test application. Defects identified after failed semantic tests could, for example, be ascribed to the missing specification of units in the EFDM, resulting in differing magnitudes of values. Depending on where the changes were implemented (15a)/ (15m), the following re-evaluation started in step (13) or step (5). Once both the syntax and semantics tests passed, the model evaluation process for the considered model development stage was considered complete. The model versions before and after the evaluations are accessible in a Git repository [63].

VIII. Discussion

During the iterative design process of our evaluation approach for newly designed IMs and DMs, we captured lessons learned through discussions with EFIM and EFDM modelling experts, which we summarise hereafter.

The explicit model evaluation phase of our evaluation approach to ensure conceptual quality, allows model developers to review the IMs & DMs against a set of QCs. Our proposed set of QCs includes both rather generic and more specific ones. The generic ones are based on a consolidation of the literature. The specific ones are QCs observed during the evaluation of EFIM and EFDM that we could not map with the existing QCs. For a practical application, specific QCs are considered more useful compared to general ones, subsuming them [40]. Consequently, with the expected emerging IMs & DMs in the smart grid, we expect this QC list not to be static and to further emerge.

In applying our approach, we have not identified defects for every general QC (see n/a in Table II). While this observation may be model-specific, we assume some QCs such as *naturalness* or *value obtainability* to be fundamental in the design of models intended for practical use and thus will be addressed already in the model design phase. However, in order to assess which QCs can be considered fundamental for practical models and therefore may not need to be considered in the evaluation process, a more detailed analysis would be required.

During the application of our evaluation approach, we also learnt about the influences between QCs. Although such positive and negative influences among QCs have been discussed in prior work by [10], [42], our observations relate to the newly proposed one *singularity*. We learnt that an increase in *understandability* may lead to a trade-off with *singularity*. Such influences indicate that the evaluation process remains a creative process that often relies on intuition and experience [12], [42] and cannot be fully automated. Future research could explore how such interdependencies might be systematically addressed within the evaluation process.

Moreover, we also learnt that by engaging with QCs during the evaluation, the model developers began to consider them during the subsequent design process. This suggests that our evaluation approach not only supports the evaluation of models but also positively fosters quality-conscious design practices.

In the implicit model evaluation phase of our evaluation approach, model developers have the possibility to select an established method for testing the model implementation. During the application to the EFIM and EFDM, we identified fewer defects than in the explicit model evaluation phase. We see two possible explanations for it. On the one hand, we were unable to conduct formal interoperability testing due to the development status of the information systems that use the EFIM and EFDM. On the other hand, we anticipate that the learning outcome in this phase will be less extensive due to its modular structure and the resulting possibility to apply established methods.

In general, our evaluation approach was found to be useful by the EFIM and EFDM experts. They emphasised its potential applicability beyond the initial development phase, particularly in contexts involving model expansion. Additionally, they suggested its integration into application lifecycle management as a method for evaluating IMs & DMs. These findings support the suitability of our approach for assessing the EFIM and EFDM within the smart grid domain. Given its foundation in both general and smart grid-specific evaluation methods, we anticipate that our evaluation approach is generalisable. However, this has not yet been validated. Future research should investigate its generalisability by applying it to a broader range of IMs & DMs and engaging a larger group of modelling experts through interviews or focus groups. Such a practical validation will require a dedicated study, which we leave for future work.

IX. Conclusion

To address the need for evaluation methods for newly emerging IMs & DMs in the smart grid, we designed a three-phase evaluation approach using DSR. Our evaluation approach combines both explicit and implicit validation methods. It is step-oriented and tailored for models in their design phase. To support the explicit model evaluation phase, we proposed a consolidated list of QCs. We introduced in this list three new QCs based on an observation-based approach that focus on the practical applicability of the IMs & DMs. To support the incorporation of established methods in the implicit model evaluation phase, we adopted a modular structure. This modularity enables model developers to incorporate conformance and interoperability testing and ensures that potential flaws in interoperable information exchanges can be identified and addressed early in the design process. Overall, our evaluation approach supports the design of IMs & DMs used in the smart grid and ensures their conceptual quality and functionality.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly, ChatGPT, Copilot and DeepL to improve the clarity and readability of the text. After using these tools, the authors carefully reviewed and edited the content to ensure that the original meaning was preserved. The authors take full responsibility for the content of the publication.

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