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Kozirolek, Anne ; Happe, Lucia ; Avritzer, Alberto ; Suresh, Sindhu

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# A Common Analysis Framework for Smart Distribution Networks Applied to Survivability Analysis of Distribution Automation

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*Abstract*—Smart distribution networks shall improve the efficiency and reliability of power distribution by intelligently managing the available power and requested load. Such intelligent power networks pose challenges for information and communication technology (ICT). Their design requires a holistic assessment of traditional power system topology and ICT architecture. Existing analysis approaches focus on analyzing the power networks components separately. For example, communication simulation provides failure data for communication links, while power analysis makes predictions about the stability of the traditional power grid. However, these insights are not combined to provide a basis for design decisions for future smart distribution networks.

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*Keywords*-Distribution Automation, Modeling, Model-to-Model Transformation, Smart-Grid, Common Information Model, Survivability, Design Decisions

## I. INTRODUCTION

Power engineers are currently designing future intelligent power distribution networks. To assess these designs, they need to consider the interactions between several relevant domains such as electrical power flow, telecommunications, distribution network topology, demand side management, and failure detection, isolation, and restoration.

The Common Information Model (CIM) [2], [1] is an IEC-standardized model of power networks, capturing information about topology, power distribution, loads etc. to support interoperability of energy management systems.

In this paper, we present (1) a software engineering framework based on the CIM to support the design of future intelligent power distribution networks and (2) an application of this framework to holistic survivability analysis.

We propose a common analysis framework that employs transformations from CIM to the several models required

to perform the holistic analysis of the smart distribution network. Specifically, the power engineer will be provided with an immediate-feedback tool to edit and view the current state and associated metrics of a smart distribution network design. The design will be expressed as a CIM model that will interface to several specific analysis models.

To show the applicability of our approach, we describe its application to survivability analysis. We use a high-level model for holistic survivability analysis of failure detection, isolation, and restoration scenarios and sketch how low-level analysis results from detailed communications, power flow equations, and demand response analysis will be integrated. The high-level survivability model uses the electrical properties of the distribution automation topology for state aggregation and thus can be used to analyze large models efficiently.

In this paper, we consider the software engineering aspects that need to be considered for the proposed scalable distribution automation assessment framework. The proposed design takes advantage of analysis decomposition and separation of concerns to support the required modelling scalability while integrating the detailed communication, power, and demand response analysis results into a holistic assessment provided by the high-level survivability model.

The main contributions of this paper are the following.

**Scalable analysis framework for holistic power systems design:** We describe a common model-driven analysis framework that supports holistic design by integrating high level analysis methods with low-level, detailed analyses. In particular, we present a case study of the interactions between communication reliability, power system topology, and demand response behaviour in failure detection, isolation, and restoration scenarios. Engineers can use our approach to quantitatively evaluate design options.

**Mapping of CIM models to survivability models:** We present a mapping from CIM to a holistic survivability model. Our mapping considers power system topology, load information, available power information, demand response behaviour of customers, and communication infrastructure.

The implementation of the proposed framework as well as the mapping of detailed communication, power and demand response analysis results is subject to future work.

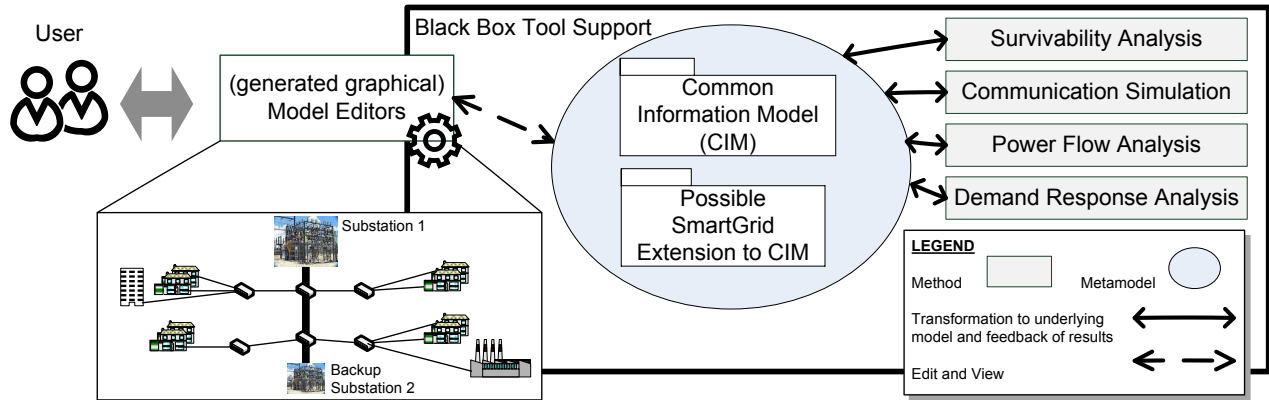


Figure 1. Envisioned Common Analysis Framework for Smart Distribution Networks

The outline of this paper is as follows. Section II sketches our envisioned common model-driven analysis framework for smart distribution networks. In Section III we present the smart failure detection, isolation, and restoration scenario and briefly describe the survivability model we build upon. In Section IV we describe the mapping of CIM models to the survivability model. In Section V we present our case study, which is based on a real distribution circuit, and describe how investment options can be supported by our analysis framework. In Section VI we present related literature before Section VII concludes.

## II. A COMMON MODEL-DRIVEN ANALYSIS FRAMEWORK FOR SMART DISTRIBUTION GRIDS

This section introduces a common analysis framework for smart distribution grids. It states basic requirements, describes our proposed conceptual approach, and finally sketches the planned technical realization. Multiple challenging *requirements* drive our common analysis framework:

**User-friendliness:** The framework shall enable engineers to express the information necessary for the analyses in an easy to learn format, ideally having illustrative and intuitive graphical model editors. The sophisticated analysis formalisms and tools shall remain transparent from the engineers, thus relieving them to deal with specific expert knowledge. Therefore, an automated feedback mechanism shall map the analysis results (e.g., reliability or survivability metrics) back to the graphical input notation.

**Extensibility:** Due to new possibilities emerging from the smart-grid distribution networks, the analysis framework shall be easily extensible for new analysis methods.

**Scalability:** As complex smart-grid distribution networks complicate sophisticated analysis methods and might even make detailed analysis infeasible due to state space explosion of the underlying models, the framework shall provide some mechanism to scale with complex distribution networks. Moreover, it shall be easy-to-use even for large models and shall not require manual interaction to transform the CIM model into the specific analysis languages.

**Reuse of existing assets:** Many analysis method and tools have already been implemented and shall be reused to not loose the expert knowledge encapsulated in their implementation.

To meet these requirements, we propose the *conceptual approach* illustrated in Fig. 1. The power engineers model the distribution circuit under study based on a common model, including information required for the analysis. Then, they can request a specific analysis (e.g., survivability, communication simulation, power flow, demand-response) directly from the tool. The transformation to the required analysis model and analysis algorithm execute in the background. Finally, our approach reports the results back into the original common model as annotations.

The approach is user-friendly as the user only needs to deal with a single notation and does not need to be aware of details of the underlying analysis methods. To further improve the usability of the approach, it offers textual and graphical editors for the common model.

The approach is extensible as it allows to implement transformations from the common model into future analysis models that provide novel analysis capabilities. Thus, for each new analysis method a transformation from common model into the specific language used for the analysis is required. If the common model does not contain required information, it is extended by adding new metamodel elements, which is transparent to the other transformations. As such, the extension of provided analysis methods is independent from other already integrated methods.

To be scalable the approach allows to feed results from different analysis approaches into one another. Thus, results from analysis methods on lower abstraction levels can be condensed and then used on higher abstraction levels to analyze complex systems. For example, the result from low-level reliability simulation of a single communication link can be annotated to the common model as a failure probability, which is used by the transformation to the high-level survivability model. Because of this decomposition of the

analyses, state space explosion is avoided and system-wide properties on a higher abstraction level can be analyzed.

Finally, the approach is designed to reuse existing assets; existing analysis models and tools can be connected via model transformations from the common model. This way, our approach allows easy reuse of existing tools through their integration as one of the backend analysis methods.

We plan the *technical realization* of our conceptual approach based on a number of existing technologies. The model edited by the users will be based on the CIM. Because the CIM models many aspects of power systems, it unifies the information required by different analyses, and thus serves as good foundation for our analysis framework. CIM models can also be imported and exported by several power analysis tools from ABB and Siemens [6], thus facilitating the reuse of existing tools. However, because the CIM does not yet support all concepts needed for smart grids [8], it possibly needs to be extended for some analyses, such as the analysis of demand response application.

### III. FOUNDATIONS: SCENARIO AND ANALYSIS

This section briefly describes the smart failure detection, isolation, and restoration scenario (III-A) and the existing holistic survivability analysis (III-B). For more detail on the distribution automation challenges, we refer to [7].

#### A. Failure Isolation and Restoration

To convey our envisioned approach, we focus on a future failure isolation and restoration scenario in smart sectionalized circuits, described in the following. Fig. 2 shows a distribution circuit that is sectionalized into 7 sections. Between the sections, reclosers can interrupt the connection if a failure in an adjacent section is detected.

In normal operation, a circuit is powered by a dedicated substation. In our figure, sections S1 to S7 are powered by subsection Sb1 in normal operation. If a failure occurs in a section  $i$ , the downstream sections can quickly be recovered by isolating them from the faulty section and powering them from the normal substation (green in Fig. 2).

If a backup substation is connected to the other end of the circuit and has enough available spare power, the distribution automation can restore the upstream sections (red in Fig. 2). If the backup power does not suffice, demand response might be called for to reduce the requested load so that backup power suffices. Signals (price signals or mandatory control signals) will be sent to smart meters at the energy consumers, which can switch off non-critical devices, such as fridges or air conditioning for a while.

#### B. Survivability Model

To predict the survivability of a distribution circuit as described in the previous subsection, we build upon a holistic survivability analysis model [3]. It takes into account

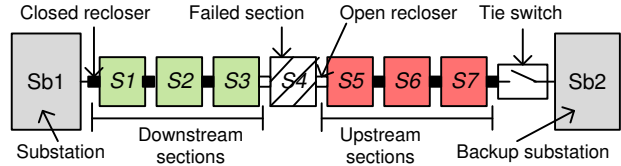


Figure 2. Failure Isolation and Restoration in Sectionalized Circuits

Table I  
SURVIVABILITY MODEL PARAMETERS FROM [3]

Parameter	Description
$p$	probability that communication works after failure
$q$	probability that backup power suffices to supply isolated sections
$r$	probability that demand response is effective after failure
$ENS/h_s$	energy not supplied per hour for model state $s$
$\gamma$	communication repair rate in events/hour

the topology of the distribution circuit, the communication availability, and the demand response capabilities.

Table I shows the input parameters of the survivability model. The model takes as an input the probabilities that communication is available  $p$ , that backup power is sufficient  $q$ , and that demand response is effective  $r$ , as well as the duration to repair communication as a rate  $\gamma$  and the measure “energy not supplied” for each of the model states. The model states and transitions reflect the behaviour of the system after a fault. Initially, all sections upstream of the failure are without power, then, depending on the availability and the communication, the upstream sections may recover with different rates. Eventually, the system completely recovers if the cause of the section failure is manually repaired. The survivability can be calculated in terms of the “accumulated energy not supplied up to full system recovery metric (AENS).

### IV. MAPPING THE CIM TO SURVIVABILITY ANALYSIS

In this work, we show the feasibility of our approach by mapping a subset of the CIM to the survivability analysis. In Section IV-A, we describe the subset of the CIM required to model the power system topology. Section IV-B sketches how the load data is modelled. The mapping of the chosen CIM model elements to the model parameters of the survivability analysis are described in Section IV-C.

#### A. Relevant CIM Subset

In this work, we use CIM concepts from the core standard IEC 61970-301:2011 [2] (UML model version 13v19, packages Core, Topology, Wires, SCADA, Meas) and the extension for distribution management, IEC 61968-11:2010(E) [1] (UML model version 10v31, package Assets) as available from IEC. Additionally, we use the yet unstable `Informative::InfAssets::--ReliabilityInfo` concept, which is available in the IEC 61968-11 UML model version 10v31 [4] but not described in the official IEC publication.

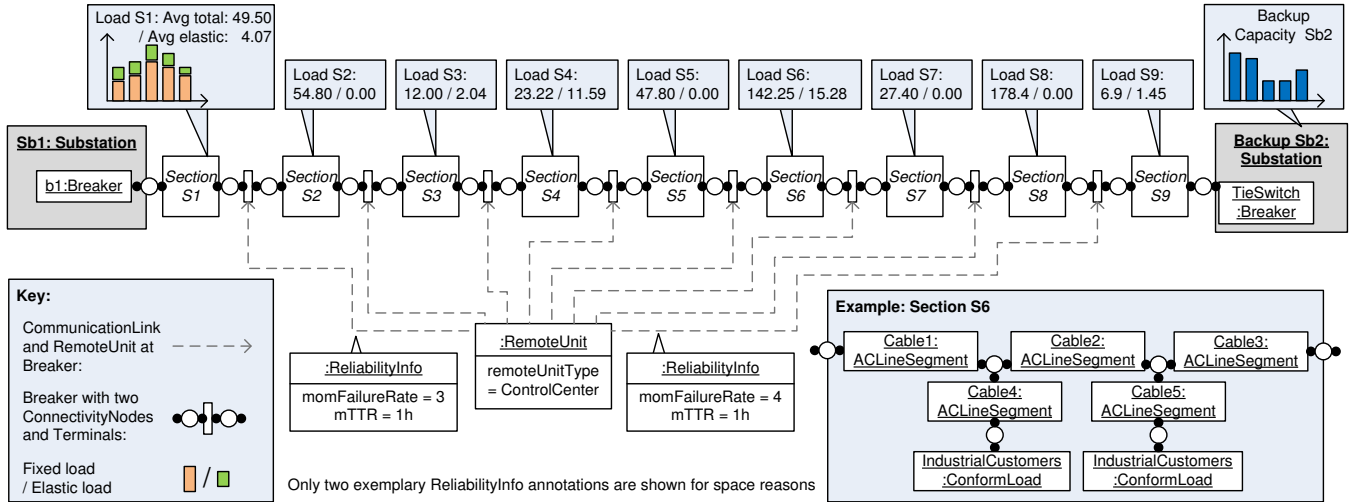


Figure 3. Case Study CIM Model (Simplified View)

To convey the relevant subset of the CIM, Figure 3 shows the CIM model of a distribution circuit between two substations (also used later in our case study, Section V). The used model elements are explained in the figure’s key and in more detail on the accompanying website<sup>1</sup>. In between the Substations, the distribution circuit is assumed to be a sequence of sections separated by Breakers (i.e. reclosers). Within a section, any type of other `Core::ConductingEquipment` can be placed: `ConductingEquipment` is the superclass for “parts of the power system that are designed to carry current or that are conductively connected therewith” [2], for example `Wires::ACLineSegments`, which represent cables, or `LoadModel::ConformLoads`. The lower right of Fig. 3 shows an example section with two industrial customers.

In the CIM, communication links are represented by `SCADA::RemoteUnits` and `SCADA::CommunicationLinks`. One `RemoteUnit` models the central control unit (`remoteUnitType = ControlCenter`). For this work, we express the reliability of the communication with the `Informative::InfAssets::ReliabilityInfo` concept. A `ReliabilityInfo` annotates any asset with a failure rate (as expected number of failures per year `momFailureRate`) and a mean time to repair (in hours as `mTTR`). This reliability information could be derived, for example, by running detailed communication simulations for a communication link.

### B. Load information

The load information is assumed to be aggregated per section. For each time of the day  $t$  for a given day type  $d$  (e.g. Sundays in winter), the amount of power requested by all consumers in a section  $i$  need to be imported into the CIM model. In Fig. 3, the load model of each section

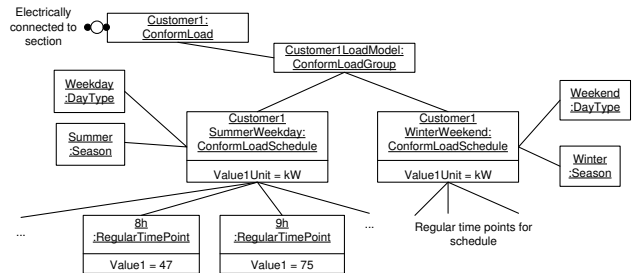


Figure 4. Load Model Example

is simplified and shown as a histogram for one day type for section S1, and is even further aggregated for the other sections for brevity. Figure 4 shows a more detailed CIM model with load information. In the following, we denote this total load of a section  $i$  at time  $t$  of day type  $d$  with a function of day and time  $L_i(t, d)$ .

Additionally, the share of this load which is susceptible to demand response mechanisms (i.e., the elastic load) needs to be modelled for each section  $i$  (shown as the green parts of the load histograms in Fig. 3). While this is not intended by the CIM elements, we can use the `LoadModel` elements to model this type of load. We denote the elastic load as a function of day and time as  $E_i(t, d)$ .

Furthermore, we model the available backup power of the backup substation  $B(t, d)$  for each time of the day  $t$  for a given day type  $d$  with the `LoadModel` elements (blue in the load histograms in Fig. 3).

### C. Deriving the Model Parameters

From a CIM model that corresponds to the previous subsection, we can derive the dependent variables of the survivability model presented in Table I as follows. Let  $D$  be the distribution circuit with  $n$  sections, simplified denoted as  $D = \{1, \dots, n\}$ . For a section  $i \in D$ , we denote all upstream sections by  $u(i)$ :  $u(i) = \{j \in D \mid j > i\}$ . We derive

<sup>1</sup>[http://sdqweb.ipd.kit.edu/wiki/Smart\\_Distribution/SE4SG/CIM\\_Subset](http://sdqweb.ipd.kit.edu/wiki/Smart_Distribution/SE4SG/CIM_Subset)

the model parameters for a fixed day type  $d$  and a section that fails  $i$ , i.e. we derive the parameters  $p_i$ ,  $\gamma_i$  (both independent of the day type),  $q(i, d)$ , and  $r(i, d)$ . The model can be solved for every section in a circuit to obtain the average AENS metric if any section fails.

**Communication  $p$ :** Assuming that the CIM model has been annotated with reliability information (e.g., as derived from detailed communication simulation), we can derive the communication availability as follows. By  $f(c)$ , we denote the probability that a single `CommunicationLink`  $c$  in the set of all communication links  $C$  of the circuit has failed at any point in time. It is the number of failures per year (`momFailureRate`) times the length of each failure (`mTTR`) divided by the number of hours in a year:

$$f(c) = \frac{\text{momFailureRate}_c * \text{mTTR}_c}{365 * 24}$$

In our simple model, if a section  $i$  fails, the two `CommunicationLinks`  $c_i$  and  $c_{i+1}$  connected to the two `Breakers`  $b_i$  and  $b_{i+1}$  need to be operational to successfully assess the situation. Then, the probability that the required `CommunicationLinks` for assessing the failure of section  $i$  are available is the product of the probabilities that the adjacent communication links are available:

$$p(i) = (1 - f(c_i))(1 - f(c_{i+1}))$$

Note that in this work we assume that sections and the required communication fail independently (i.e. they do not fail due to common causes). If this is not the case (e.g. because wireless senders are mounted on a power line pole and thus are subject to the same weather conditions as the line itself), a correlation factor has to be added, which is subject to future work.

**Backup energy sufficient  $q$ :** For a given section  $i$  that fails at a given time of the day  $t$  on a day type  $d$ , the total load  $T_i$  requested by the upstream sections  $u(i)$  is

$$T_i(t, d) = \sum_{j \in u(i)} L_j(t, d)$$

Then, the backup power  $B$  is sufficient if the total requested load is lower than the backup power:

$$q(i, t, d) = \begin{cases} 1 & \text{if } T(i, t, d) \leq B(t, d) \\ 0 & \text{else} \end{cases}$$

Then, if the load information is provided per hour, the probability that the backup power is sufficient at any time of the day of day type  $d$  is

$$q(i, d) = \frac{1}{24} \sum_{0 \leq t < 24} q(i, t, d)$$

**Demand response effective  $r$ :** The load that can be reduced using demand-response mechanisms can be analogously derived from the data. For each section, the orange parts of the histograms in Fig. 3 represent this fixed load: It is obtained by subtracting the elastic load  $E$ , i.e. the load amendable to demand response, from the total load  $T$ . Thus,

the fixed load of all subsections upstream of a failed section  $i$  is

$$F_i(t, d) = T_i(t, d) - \sum_{j \in u(i)} E_j(t, d)$$

Demand response is only needed if the total load is higher than the backup power. In that case, demand response is effective if the fixed load is lower than the backup power:

$$r(i, t, d) = \begin{cases} \text{undef} & \text{if } q(i, t, d) = 1 \\ 1 & \text{if } q(i, t, d) = 0 \wedge F_i(t, d) \leq B(t, d) \\ 0 & \text{otherwise} \end{cases}$$

Let  $H(j, d)$  denote the hours in which backup power is not sufficient if section  $j$  fails:

$$H(j, d) = \{t \in 0, \dots, 24 \mid q(j, t, d) = 0\}$$

The probability that demand response is effective at any time during the day given that backup power is not sufficient is

$$r(i, d) = \frac{1}{|H(i, d)|} \sum_{t \in H(i, d)} r(i, t, d)$$

**Communication repair rate  $\gamma$ :** The average time needed to restore failed communication can be derived from the CIM `mTTR` attribute of a `ReliabilityInfo` as follows. The average time needed to restore failed communication if section  $i$  fails, denoted  $\gamma_i$ , is the average of the mean time to repair of the two adjacent communication links  $c_i$  and  $c_{i+1}$ . Let  $mTTR_c$  denote the repair rate of communication link  $c$ . Then,

$$\gamma_i = \frac{1}{2}(mTTR_{c_i} + mTTR_{c_{i+1}})$$

**State reward rates: Energy not supplied:** The energy not supplied per hour (`ENSh` in kilowatt, short `ENSh` in formulas) in each of the system states (simplified here compared to [3]) can be derived as follows. After a failure (state 1), energy is only supplied to the sections downstream of the failed section  $i$ . Let  $d(i)$  denote the downstream sections  $d(i) = \{j \in D \mid j < i\}$ . Thus, the energy supplied in these state is the total load of the the failed section ( $L_i$ ) and the total load of the upstream sections ( $T_i$ ) averaged over the day:

$$ENSh_1(i, d) = \frac{1}{24} \sum_{0 \leq t < 24} L_i(t, d) + \frac{1}{24} \sum_{0 \leq t < 24} T_i(t, d)$$

If demand response is called for (state 2), the energy demand has been lowered to the fixed load  $F$  of the upstream sections, so that the energy not supplied is reduced to

$$ENSh_2(i, d) = \frac{1}{24} \sum_{0 \leq t < 24} L_i(t, d) + \frac{1}{24} \sum_{0 \leq t < 24} F_i(t, d)$$

Eventually, energy is supplied to all sections except the failed section (state 3), resulting in

$$ENSh_3(i, d) = \frac{1}{24} \sum_{0 \leq t < 24} L_i(t, d)$$

Table II

AVERAGE TOTAL LOAD  $L$ , AVERAGE ELASTIC LOAD  $E$  IN THE BASE MODEL, AVERAGE ELASTIC LOAD  $E$  WHEN IMPLEMENTING OPTION 3

Section $i$	1	2	3	4	5	6	7	8	9
$\varnothing L_i$	49.5	54.8	12	23.22	47.8	142.25	27.4	178.4	6.9
$\varnothing E_i$ base	2.04	0	4.07	11.59	0	15.28	0	0	1.45
$\varnothing E_i$ opt. 3	9.16	0	5.26	13.33	0	34.32	0	0	2.27

## V. CASE STUDY

This section presents the application of our method to survivability analysis of an adaptation of a real-world distribution circuit located in Virginia, USA. In addition to the real topological information and the real load information from [11], we estimated failure rates and demand response behaviour. Section V-A describes the CIM model we created for analyzing the survivability of this distribution circuit and the investment options engineers want to consider. Then, Section V-B presents the survivability analysis results.

### A. CIM Model

Figure 3 shows a simplified view of the CIM model we created for the described distribution circuit. We study three investment options, which can be reflected in the CIM as follows. Each option represents a class of design decisions: Power topological changes, communication network changes, and demand response mechanism changes.

Option 1 - install another breaker: A breaker can be installed to split the largest section 6, where several industrial customers are connected to the distribution network. After the split, the two `ConformLoads` are in separate sections 6a and 6b. How the load is distributed among the two sections can be determined e.g. based on billing data. Here we assume that both fixed an elastic load are split in the ratio 0.55/0.45 for sections 6a/6b, respectively.

Option 2 - Improve communication reliability: A more reliable communication technology could be used. Detailed communication simulation can be used to assess different communication technology. For this example, let us assume that the failure rate of all communication can be decreased by 50% by adding cell phone network communication to all breakers in the section, so that communication links are redundant. In the CIM model, we reflect this by changing the `momFailureRate` to half its value (another option would be to add a second communication link model element to each breaker with a separate reliability annotation, and extending our derivation of  $p$  to consider redundant links).

Option 3 - Increase available elastic load: The conversion of 15% of the fixed load into elastic load can be modelled by updating the `ConformLoad` model elements as shown in Table II. Note that some sections do not support demand response, e.g. because they power a hospital (section 8). These sections are not updated and have 0 elastic load.

The input parameters to the survivability analysis are derived as described in Section IV-C. The resulting parameters for the three options are shown in Table III.

Table III

INPUT PARAMETERS FOR SURVIVABILITY MODEL

$i$	base model			option 1		option 2	option 3
	$p$	$q$	$r$	$p$	$q$	$p$	$r$
1	0.933	0	0.042	0.933	0	0.966	0.167
2	0.933	0	0.167	0.933	0	0.966	0.250
3	0.922	0.042	0.130	0.922	0.042	0.960	0.261
4	0.922	0.125	0.048	0.922	0.125	0.960	0.286
5	0.922	0.292	0.471	0.922	0.292	0.960	0.941
6	0.911	1	NA	0.911	1	0.955	NA
6b				0.911	1		
7	0.922	1	NA	0.922	1	0.960	NA
8	0.922	1	NA	0.922	1	0.960	NA
9	0.911	1	NA	0.911	1	0.911	NA
$\varnothing$	0.922	0.495	0.171	0.921	0.546	0.960	0.381
				-0.12%	10.19%	4.21%	122.23%

Table IV

RESULTING AVERAGE ACCUMULATED ENERGY NOT SUPPLIED UP TO FULL SYSTEM RECOVERY FOR THE INVESTMENT OPTIONS

	$\varnothing$ AAENS	Improvement
base model	481.4 KWh	
option 1	435.9 KWh	-9.44%
option 2	474.4 KWh	-1.46%
option 3	371.8 KWh	-22.76%

### B. Analyses

To assess the investment options, we assume that sections fail with equal probability, so that we can aggregate the survivability measures over which section fails. Furthermore, we assume a fixed day type  $d^*$  describing an average day. Then, we calculate the average AAENS ("accumulated energy not supplied up to full system recovery) given that any section fails, denotes AAENS. Table IV shows the resulting AAENS for the base model and the three investment options.

The base model has an AAENS of 481.4 KWh if any section fails. If we implement option 1 (split section 6 into two new sections), we can reduce the AAENS by 9.44% to 435.9 KWh. Improving the communication reliability leads to a reduction of the AAENS by 1.46%. Finally, the most improvement is achieved by increasing the available elastic load, here the AAENS can be reduced by 22.76% to 371.8 KWh. As a result, engineers can choose to implement option 3 to improve the circuit's availability if the costs of option 3 are not too high compared to the costs of option 1.

In addition to the analysis shown here, engineers may as well study the combination of several investment options. Automated design space exploration as described in [5] for software architecture models could be extended to operate on CIM models and automatically determine the best trade-off with respect to several metrics such as a survivability measure and costs.

## VI. RELATED WORK

In this section, we briefly discuss related uses of the CIM for power network analyses.

Several approaches use the CIM as a common model to combine several traditional power system analyses. For example, Uslar et al. [9] propose the application of the

CIM for the interoperability of different energy management subsystems. They discuss how load forecast, disposition management, and net simulation can be integrated by feeding results from one into the other. However, the CIM here serves as a data exchange format only and is not the modelling formalism based on which cross-cutting design decisions are made. As an example from the smart distribution network area, Vukmirovic et al. [10] present a CIM-based integration of smart meter data management with control centres, translating messages from smart meters into CIM for use in different control centre applications. However, in both examples the CIM is used as a data exchange format to achieve interoperability and exchange messages, not to store the power system model itself.

McMorran et al. [6] describe a power systems analysis framework based on CIM as the core model. Their work focusses on the technical implementation of such a core model, discussing the storage of the inevitably large object models and how to support possible extensions of the CIM. In this paper, we focus on the use of a CIM in a framework for the power engineer, its ability to integrate several analysis approaches each focussed on specific power system aspects. Moreover, we sketch how design decisions are supported by this framework. Thus, their solution could be used in our approach as part of the framework responsible for storage of the CIM model instances.

Although the CIM is recognized to have great importance for smart networks due to the interoperability it enables [7], to the best of our knowledge, it has not been applied to survivability analysis of smart distribution networks before.

## VII. CONCLUSIONS

In this paper, we have presented a scalable CIM-based common model-driven analysis framework for future smart distribution networks, enabling power engineers to assess design decisions. In particular, we have presented a mapping from CIM to a holistic survivability analysis which allows to predict the survivability of a distribution circuit with respect to power equipment failures, communication failures, and demand response applications.

In a case study based on a real distribution circuit, we showed how our approach can be used to support engineers to make investment decisions, without requiring them to have detailed knowledge about the underlying analysis models. When realized in a tool, our approach will provide the power engineers with an immediate-feedback tool to assess smart distribution network.

In future research, we plan to implement the proposed common analysis framework, to describe transformation and feedback to detailed analysis models, such as communication simulation, thus to realize the scalable multi-level survivability analysis. Furthermore, we plan to apply our framework to other quality attributes of the smart distribution network. In particular, cost modelling will be a valuable

decisions to assess cost-benefit of design options. Finally, we will research how the very rich CIM model can be efficiently shown to and edited by engineers by providing different views on the CIM.

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