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Criticality Analysis for Network Utilities Asset Management

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Abstract: The proposed work describes the main part of asset criticality analysis for Distribution Network Services Providers (DNSP), also known as Network Utilities, the severity-value factors definition. The methodology is based on the risk-based evaluation of assets, considering potential impacts of their failures on network value. Thus, it provides the capability to take maintenance management decision in terms of value and risk, considering the whole network under unique and homogeneous criteria. A hierarchy of assets ranked according to with value and risk will come out of this process, which represents a fundamental result serving as input of the subsequent steps of the asset management process. Specific attention is paid to network utilities issues, characterizing assets in these companies, and the services that they provide. In addition to this, high requirements established by the Service Level Agreements (SLA), that are characteristics of network services contracts, make this methodology especially suitable in this application. In order to illustrate method applicability, an example extracted from a real electrical network use case is included.

Keywords: Risk, Criticality Analysis, Asset Management, Network Utilities, Maintenance Optimization.

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1. INTRODUCTION

Network services management must adapt to customers demand, sustaining the contracted service level agreements (SLA), Suave et al. (1998) and Howes (2000). Network utilities are exposed to many types of hazards, such as natural hazards, component aging and failure, sharp load demand increase, climatic changes, intentional attacks. Besides, any service failure could be propagated among the network, making vulnerable the network by physical degradation, disruptions, and congestions, attacks or disasters. Furthermore, design safety margins may not be enough to cope with the expected and unexpected stresses onto the systems, emerging from small perturbations that can lead to large-scale consequences. An asset management strategy can improve the network utilities management.

If we focus on Network Utilities maintenance management models, most of the works found in literature only cover the management function for an individual and specific kind of network (water, gas, electricity and telecommunications), Al-Arfaj et al. (2007) and Amador et al. (2005). In addition, these works usually cover specific aspects of network maintenance management (reliability assessment, network risk analysis, etc.) rather than comprehensive network management models, for example Brown et and Willis (2006), Abraham et al. (1998) and Brown and Humphrey (2005). Criticality analysis, in terms that are proposed in this work, is a suitable and practical tool to deal with these aims. This includes the elicitation of objective value assessment factors and the treatment of risk assessment in value terms. To effective control of network service and business sustainability, value consequences evaluation method allows consider not only cost impacts, but also operative, reputational, environmental legal, financial, etc. The main difficulty of this methodology is to select the proper criteria to evaluate consequences, the weight of them, the consistency among them and their scale values in Crespo et al. (2016). The selection of these parameters is crucial for adjustment to the company strategy and for the complexity of the criticality evaluation process.

Based on failure events, their likelihood of occurrence provides a narrow relationship between network conservation and provided value to customers by levels of aggregation, determining the level of required maintenance actions, in order to properly sustain the service level agreements over time. In the other hand, to assess the real risk and criticality in a network, we must consider vulnerability and resilience under the dynamic complexity with interactions among nodes through link dependences (Network Topology). Therefore, network criticality should not only consider reliability but also the ability to recover from disruptions, minimizing the impact on health, safety, security, economics and social well-being.

2. SEVERITY-VALUE FACTORS DEFINITION

The number of selected severity criteria must be minimized as much as possible, not making difficult the model implementation. But, on other hand, criteria must be enough to describe accurately the reality of the network and avoiding dependence among factors. Authors recommend, from our experience in network utilities, to aggregate all the factors using four to six criteria. The final severity criteria to include have been realized in four criteria to compose the model:

- Loss Exposure Criterion (LE)

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- Safety Criterion (S)
- Network Resilience Criterion (NR)
- Social Importance Criterion (SI)

Below, the quantification method applied in four criteria will be introduced. Terms and abbreviations employed to this end are included in Table 1.

TABLE 1
TERMS AND ABBREVIATIONS EMPLOYED

Term/ Abbre.	Definition
o	$1 \ldots k$ element or asset analysed,
C_o	$S_o \cdot f_o$: Criticality of element *o*,
$CNPV$	Customer Net Present Value,
$\overline{cc_o}$	All costs in materials, human resources and supplies to solve the failure in the asset o,
n_{co}	Concerned customers per failure of element o,
CC_o	Corrective costs of node o,
UC_o	Loss of earnings by service unavailability in node o,
LE_o	Loss of earnings of node o,
BP_o	Bad propaganda effects over current customers in node o,
RF_o	Recover Fair Market Value,
NR_o	Network Resilience Criterion Cost of element o,
T	Mean life time cycle of CNPV,
$\overline{t_{ro}}$	Average reestablishment time of the element *r*, and T_r is defined reestablishment time per contract,
$\bar{t}$	Average reestablishment time in all the elements of the network,
$P_{abo}(t_{ro})$	Abandon probability per customer related to the offered reestablishment time by the contract,
LE_o	Loss Exposure Criterion Cost of element *o*,
l_{So}	S / Safety consequences level of the element o,
l_{RFo}	Recover FMV consequences level of the element o,
P_{aco}	Probability of occurrence of an S / Safety accident due to a failure of element o,
S_o	Safety Criterion Cost of element o,
SI_o	Social Importance Criterion Cost of element o,
LCCDC	Local clustering coefficient-based degree centrality,
$LC\dot{C}DC$	maximum LCCDC number of graph nodes,
g_o	Degree centrality
LCC_o	Local clustering coefficient
x_o	Remaining capacity in terms of customers of element *o*,
n_f	Number of failures with service interruption in the network,

2.1 Loss Exposure Criterion (LE)

This criterion concretes the number of economic losses due to functional breakage, Rubio-Loyola et al. (2015), not only the direct losses by corrective costs, but also the lost earnings due to service interruption time. Equations (1) and (2) represent the consequences caused by a failure in the network as a part of the Customer Net Present Value for the company (CNPV). CNPV includes total income from a customer during a period minus all the costs required to serve that customer, such as Gupta and Lehman (2005). This concept is key to translate consequences in terms of customer and business impacts.

- Corrective costs (CC_o) in a node-o: They include all costs in materials, human resources and supplies to solve the failure in the asset. They are measured as a percentage of the CNPV. Then for an asset, these costs are concretized as a ratio between the mean corrective cost ($\overline{cc_o}$) per failure in the asset per each concerned customer (n_{co} in total), and the CNPV. This cost depends on the maintainability characteristics of the asset, the higher involved resources and supplies, the higher corrective costs are.

$$CC_o = CNPV \cdot n_{co} \cdot \frac{\overline{cc_o}}{CNPV} \tag{1}$$

- Loss of earnings by service unavailability (UC_o): It represents the amount of money that the provider loses because of an interruption in the service it provides. The impact of a functional loss of an asset is reflected by the service interruption, being proportional to time, to the unavailability of the service per failure related to the service re-establishment time ($\overline{t_{ro}}$) against the total time (T) of customer life-cycle, and so determining the discounting Customer Net Present Value (CNPV) per each concerned customer (n_{co} in total) and failure. This cost depends on the asset maintainability, mainly in the time to repair.

$$UC_o = CNPV \cdot n_{co} \cdot \frac{\overline{t_{ro}}}{T} \tag{2}$$

Consequently, for each asset, the Loss Exposure costs are the sum of direct and indirect costs.

$$LE_o = CC_o + UC_o = CNPV \cdot n_{co} \cdot \left[\left(\frac{\overline{cc_o}}{CNPV} + \frac{\overline{t_{ro}}}{T} \right) \right] \tag{3}$$

2.2 Safety Criterion (E)

Based on Legal parameters, safety consequences of an asset (node-o) can be evaluated based on Wireman (1998) method, which has been widely used to evaluate these risks, reducing the consequences categories in the following levels l_{So}:

- Catastrophe; numerous fatalities; damage or penalty over \$500,000.
- Critical fatality, damage or penalty \$100,000 to \$500,000.
- Extremely serious injury (amputation, permanent disability); damage or penalty \$10,000 to \$100,000.
- Minor cuts, bruises, bumps; minor damage or penalty 1,000 to \$10,000.

In a failure event, the risk about safety penalty could appear or not, that is, there is a probability that the accident occurs once the failure has occurred (P_{aco}). Therefore, the reduced and modified levels of probability for this risk are four:

- Quite possible (has an even 50% chance) with a P_{aco} =0.5.
- Remotely possible with a P_{aco} =0.1.
- Conceivable (has never happened after many years of exposure) with a P_{aco} =0.05.
- Practically impossible (has never happened) with a P_{aco} =0.01.

$$S_o = l_{So} \cdot P_{aco} \tag{4}$$

2.3 Social Importance Criterion (SI)

The social perspective is crucial in network utilities. In this line, failures decrease customer satisfaction, transmitting bad propaganda into the market (up to 10 partners in Goodman (1986)), modifying customer perception of service quality. Then for an asset (node-o), bad propaganda due to failures could have effects on current customers or potential customer. In addition, critical and strategic customers are usually more exigent in-service performance and quality, and we should consider the indirect costs due to their dissatisfaction. Impacts go beyond the repair costs and penalties, because it has to consider the impact on earnings and market value, and so if the continuity of supplied services is crucial facing catastrophes.

- Bad propaganda effects over current customers (BP_o). It represents the loss of earnings that the company would suffer due to the abandonment of dissatisfied customers for the service provided. In this case, current customers (that have suffering failures) could decide to abandon the service with a probability $P_{abo}(t_{ro})$ related to the service re-establishment time ($\overline{t_{ro}}$) against the offered by the contract or existing standard market service level agreements (T_r). The probability to abandon relies on a Weibull distribution and Maximum Likelihood Estimation (MLE) to obtain the Weibull equation that reflects the probability to abandon per current customer and per each failure based on the mean service re-establishment time. In this case, the study supports the quantitative estimation of this probability, simplifying by a 2-parameters Weibull equation.

$$BP_o = CNPV \cdot n_{co} \cdot P_{abo}\left(\frac{t_{ro}}{T_r}\right) \tag{5}$$

- Recover FMV (RF_o). The associated consequences costs to this criterion, have been related to the amount of earnings in risk plus the necessary publicity to recover the fair market value (FMV) due to bad reputation and the losses in the capital stock during a year (up to 15% consistent with Knight and Pretty (1997)). Failures in an asset (node-o) can harm the FMV, and to evaluate this we have employed the same categories of ES criterion (l_{ESo}) with a remote probability P_{aco} = 50% of chance, obtaining (l_{RFo}):
    - More than three social sites or large enterprises, failure impact estimated over $250,000. Social Sites: such as public administrations, hospitals, fire station, transport stations, airports, military buildings, ports, etc.
    - Less than three social sites or large enterprises with failure impact between $50,000 to $250,000.
    - More than 10 Medium and Small enterprises with failure impact between $5,000 to $50,000.
    - Less than 10 Medium and Small enterprises or regular customers with failure impact less than $5,000.

$$RF_o = l_{RFo} \tag{6}$$

Consequently, for each asset, the Social Importance criterion (SI_o). is the sum of the bad propaganda effects over current customers (BP_o), bad reputation effects over potential customers (BR_o), and the Recover FMV (RF_o).

$$SI_o = BP_o + RF_o = CNPV \cdot n_{co} \cdot P_{abo}\left(\frac{t_{ro}}{T_{ro}}\right) + l_{RFo} \tag{7}$$

2.4 Network Resilience Criterion (NR)

This criterion summarizes the possible impacts of cascading service outages and the possible effects on surrounding assets or infrastructures. For this purpose, this criterion correlates them with parameters about network topology, since that networks are dynamic and suffer several configuration and operational changes. Network topology is the logical representation of the network as a combination of nodes linked by edges (distances among nodes).

Local clustering coefficient-based degree centrality (LCCDC) of a node is defined as the product of the degree centrality (g_o) of the node and one minus the local clustering coefficient (LCC_o) of the node, Meghanathan (2016). The LCCDC of a node can be computed based on just the knowledge of the two-hop neighborhood of a node and would take significantly lower time. The LCCDC is a coefficient that roughly represents the centrality of a node, practically the same as the betweenness coefficient. The biggest difference is that the computational time of the LCCDC is much less than the betweenness coefficient, especially for large networks. This coefficient is based on communication flow and with this parameter, we search how a node can assist to others or to be assisted by the neighbors to deliver services in case of failures and, evaluating cascade failures, and how its neighbors can survive receiving services from it. It is a good measure of the centrality in a network and the capability to route services from other nodes in emergency cases.

We propose the network resilience criterion based on LCCDC in a normalized way, using the maximum LCCDC number of graph nodes ($LC\dot{C}DC$). This coefficient can be calculated as follows:

$$LCCDC(o) = (g_o * (1 - LCC_o))/LC\dot{C}DC \tag{8}$$

In order to show the properties of this coefficient, the following Fig. 1 presents the values of $LC\dot{C}DC$ in typical network topologies, Fig. 1-a, 1-b and 1-c respectively;

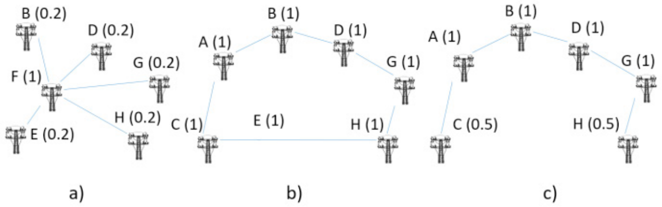

Fig. 1. LCCDC coefficients example.

The LCCDC coefficient ranks the nodes according to their influence in the neighbors, higher values (near to 1) indicate multiple redundant paths to be reconfigured to support their neighbors in case of node failures, see in Fig. 2.

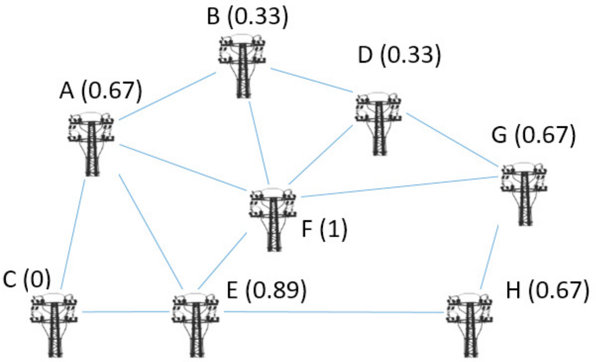

Fig. 2. Practical case Electrical Network Topology and LCCDC coefficients.

The cost of consequences due to bad redundant paths configuration is considered an opportunity cost because these could be utilized in emergency cases to support failures of their neighbors. Therefore, the remaining node capacity (x_o) in terms of possible customers (CNPV) could support other nodes in the mean re-establishment time $\bar{t}$ against the total time (T) of customer life-cycle for all the failures with service interruption (n_f) in the network. In a failure event, the support of other node could appear or not, that is, there is a probability that the support occurs once the failure has occurred in the node, so betweenness coefficient is as a probability for the occurrence of this support due to redundancy by paths.

$$NS_o = CNPV \cdot LCCDC(o) \cdot x_o \cdot n_f \cdot \frac{\overline{t_{ro}}}{T} \tag{9}$$

3. SCALE DEFINITION OF SEVERITY FACTORS

In a second step, the levels inside each criterion must be established in the used scale in this model, from 0 to 100. Although, firstly, it is necessary to define the "non-admissible" effects for some criteria which represent those consequences, referred to a specifically defined criterion that is considered unacceptable by the organization. Therefore, this level of impact can be identified as that saturate severity assessment, thus those assets where "non-admissible" effects can appear will have the maximum severity 100 (the top level of this criterion). Besides, in any criterion, we could consider as the lower level "No Affection (N/A)" effect if it is needed.
With these considerations, description of levels of the four severity criteria are included below:

Loss Exposure Criterion (LE$_o$): We have developed 4 costs categories depending on the cost distribution based on Pareto analysis:

- Very High (10%)
- High (20%)
- Medium (20%)
- Low (50%).

Safety Criterion (S$_o$): Based on William T. Fine (1971) factors, where the risk score is defined in three levels: Immediate (correction required; activity should be discontinued until hazard is reduced), Urgent (requires attention as soon as possible), and Possible or acceptable (hazard should be eliminated without delay, but the situation is not an emergency). As a result, we have developed the following levels:

- Non-admissible with $ES_o = l_{ESo} \cdot P_{aco}$ equals or higher than $250,000.
- Urgent with ES_o between $50,000 and $250,000.
- Possible with ES_o between $5,000 and $50,000.
- N/A with ES_o equals or minor than $5,000.

Social Importance Criterion (SI$_o$): Accordingly, our four types of customers which are described below, the classification level in this effect criterion are the following:

- More than three social sites or large enterprises, failure impact estimated over $250,000, valuing the impact as "non-admissible".
- High impact with less than three social sites or large enterprises with failure impact between $50,000 to $250,000.
- Medium impact with more than 10 Medium and Small enterprises with failure impact between $5,000 to $50,000.
- Low impact with less than 10 Medium and Small enterprises or regular customers with failure impact less than $5,000.

Network Resilience Criterion (NR$_o$): By virtue of translating the impact to a term of cost, and once the Pareto analysis has been utilized searching the distribution on 4 costs categories with their averages costs following the corresponding developed levels for the Loss Exposure Criterion (LE).

- Very High (10%)
- High (20%)
- Medium (20%)
- Low (50%)

The relative values for the different effects for each criterion are presented in a matrix (see Table 2), where units for these relative values are based on cost.

Assuming that the weight of the severity factors is 20%, 35%, 20% and 25% respectively, Table 2 shows the effects' severity per functional loss in scale 0-100 corresponding to the levels selected for the severity factors.

TABLE 2
CRITERIA TO MEASURE SEVERITY

Criteria to measure Severity			
LE (20%)	S (35%)	NR (20%)	SI (25%)
Category of effects per criteria and functional loss			
25,000 (20)	**Non admissible**	25,000 (20)	**Non admissible**
10,000 (8)	20,000 (35)	10,000 (8)	50,000 (25)
2,000 (2)	2,000 (4)	1,000 (2)	5,000 (2)
0	0	0	0

4. STUDY CASE

The details for severity and criticality (Severity*Frequency) calculation of each node are described hereafter, in our case about an electrical company with the following average values for all the elements:

- CNPV=2,120€ with T=2 years or 17,520 hours of lifetime cycle,
- n_{co}=60 concerned customers per failure of the 2,000 total possible customers of capacity per node,
- The corrective cost per failure is 8,950 €, then $\frac{\overline{cc_o}}{CNPV}$ = 7%,
- T_r=12h and for all of them $t_{ro}> T_r$ then ρ=1,
- n_{mo}=28% market coverage ratio of customers in the area,
- The publicity cost per influenced potential customer $\overline{cp_o}$ =90 €, then $\frac{\overline{cp_o}}{CNPV}$ =4.24%,
- $P_{abo}(t)$ obtained by Weibull analysis with parameters β=1.67, α=96 as abandon probability per customer related to the offered reestablishment time by the contract,
- x_o=300 customers in terms of average remaining capacity of the element for all nodes.

In Table 3, the reader can find the calculus in which are based each severity criterion and its correspondent severity level. The sum of all is multiplied by the supposed frequency level to obtain the criticality per element. This methodology allows us to rank the nodes from the most critical to the least critical, allowing us to design better maintenance strategies, applying the time and resources needed to those assets that have a greater impact on the company's objectives.

In view of Table 3 we could conclude that the most critical node of the network of the study case is the node G, with a Criticality of 900 (100 * 9). Therefore, this should be the first node in which maintenance resources are focused, since it is the one that costs the most money to the company. In the second place would be nodes H, C and A, also above the mean. On the other hand, nodes such as B, E or D with a low criticality should be analyzed and see if they are applying the necessary resources, or if instead they are applying more resources than they should, and the company is losing resources that could be applied in other nodes. From the ranking of criticality, therefore, maintenance strategies can be established for each one of the nodes, thus achieving a more efficient maintenance of the network.

4. CONCLUSIONS

The purpose of this methodology is to align assets management to business value, not only from a hierarchical point of view, but also evaluating the network topology implications (considering the network graph). Network utilities are companies that provide essential services to customers were reputational impacts are higher than operational impacts. Consequently, infrastructure must be analyzed with a risk-based methodology that considered these kinds of impacts in the risk assessment.

This methodology allows maintenance managers guiding the evolution of the life cycle of their infrastructure according to the business value, and at the same time to adapt their actions according to online data of in-service complex engineering

TABLE 3
CRITICALITY AND SEVERITY DETAILS PER ASSET

Node Ele-ment	**Fre-quency**	Criteria to measure Severity														**Critica-lity (FxS)**
		Loss Exposure 20%			Safety Importance 35%				Network Resilience 20%			Social Importance 25%			Severity	
	FE	t_{ro}	Total €	PE1	l_{ESo}	P_{aco}	Total €	PE2	LCCDC	Total €	PE3	l_{RFo}	Total €	PE4	Total	
A	**6**	17	9,073.4	2	150,000	0.1	15,000	4	0.67	14,885	8	50,000	56,869	25	**39**	**234**
B	**1**	13	9,044.4	2	50,000	0.5	25,000	4	0.33	5,606	2	20,000	24,433	2	**10**	**10**
C	**4**	19	9,087.9	2	100,000	0.5	50,000	35	0.00	0	0	50,000	58,225	25	**62**	**248**
D	**6**	16	9,066.2	2	50,000	0.01	500	0	0.33	6,900	2	15,000	21,224	2	**6**	**36**
E	**1**	15	9,058.9	2	20,000	0.05	40	0	0.89	17,446	8	75,000	80,603	25	**35**	**35**
F	**3**	21	9,102.5	2	5,000	0.1	500	0	1.00	27,444	20	50,000	59,663	25	**47**	**141**
G	**9**	14	9,051.6	2	10,000	0.5	5,000	4	0.67	12,258	8	250,000	255,005	100	**100**	**900**
H	**6**	18	9,080.7	2	100,000	0.1	10,000	4	0.67	15,761	8	250,000	257,537	100	**100**	**600**

assets. This makes this methodology especially suitable for supporting new challenging scenarios of maintenance management characterized for a high technological level, great interaction between assets and system and high rate of changing of demand and requirements of services. In addition, it will generate a great amount of data and information for the decision making.

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