Multidimensional Risk Assessment of Manhole Events as a Decision Tool for Ranking the Vaults of an Underground Electricity Distribution System

T. V. Garcez and A. T. de Almeida, *Member, IEEE*

***Abstract*—Even though an underground electricity distribution system is safer than an overhead system, several accidents have occurred in them. Assessing the risk of hundreds or even thousands of underground vaults is a hard task. Furthermore, given the large variability in external and internal environments and, hence, there being a wide range of possible consequences when an accident occurs, an approach to risk assessment under a multidimensional view is required. Moreover, in terms of decision making, the aggregation of the decision maker's preferences in modeling, by multiple-criteria decision-making methods, is more complete, comprehensive, and, in particular, includes considering the decision maker's desires. Therefore, this study puts forward a multidimensional assessment of the risks from underground vaults by generating a decision tool, which ranks the vaults in a risk hierarchy. Multiattribute utility theory was used to achieve this ranking. An application was generated to demonstrate the applicability of the model, under the following aspects of consequences: those that are human, financial, and operational; and disruptions to local vehicular traffic. The use of information arising from analysis of the differences between risks enabled the decision maker to make an in-depth analysis of the range of possibilities over which alternatives may be chosen in order to implement preventive actions.**

***Index Terms*—Accidents, arc discharges, decision making, manhole events, multiattribute utility theory (MAUT), multidimensional risk, risk analysis, safety, uncertainty, underground power distribution lines.**

I. Introduction

THE USE of underground electricity distribution networks is increasing worldwide due to various advantages, such as greater security for the population, greater protection from the elements of nature, and aesthetic benefits to the city. On the other hand, this requires a higher initial investment to install and it is more difficult to access such a network for maintenance purposes (e.g., to detect faults and their location [1]). Furthermore, these systems are considered a critical infrastructure, since, according to Apostolakis and Lemon [2], they are complex, interdependent, and, consequently, any disruption can lead to cascading failures with serious consequences.

Although a safer system for the population, this type of network has seen several events in underground vaults. For example, in New York City, hundreds of manhole events occur every year, such as manhole fires, explosions, smoking manholes, and burnouts [3]–[5].

These events can cause various consequences, such as fatalities and injuries to people, fires in nearby locations, disruptions in local vehicle traffic, loss of company image, financial loss, the local population being afraid (on account of the uncertainty of when and where an underground vault will explode), and other consequences which cannot be measured financially.

Thus, as shown in several studies [2], [6]–[11], an approach to risk assessment that uses only one dimension of risk (only the loss of human lives or financial loss, which are the traditional measurements), may not be sufficiently comprehensive to make the most realistic and efficient form of risk assessment. However, whereas other consequences are not as important as the risk of fatalities or human injuries, they also demand substantial attention from the decision maker (DM) [6].

Several requirements see to it that decision analysis to allocate additional investments (resources) that the company needs to make in its system have become more complex. Such requirements include:

- the increasing pressure from the population at large for greater safety;
- the great diversity of hazards that can cause accidents and different consequences;
- the demands made by regulatory agencies for electricity systems to be available for longer and more reliably, so they are taken together with the financial goals of the company (profits);
- the creation of smart grids for distributing electricity so that operations and maintenance are more online (using proactive operations and maintenance practices) [5].

Hence, with these matters in view, this paper puts forward a multidimensional (multiattribute) assessment of the risk from vaults in the underground electricity distribution system, by generating a decision tool, which ranks risk values in a risk hierarchy.

This paper is organized as follows. Section II summarizes the background to multidimensional risk decision modeling. Section III describes the main causes of manhole events. Section IV shows how the hazard zone can be estimated, based on the trajectory of manhole covers that have been blown off

Manuscript received January 19, 2013; revised June 07, 2013; accepted July 02, 2013. Date of publication July 30, 2013; date of current version March 20, 2014. This work was supported in part by research study funded by the Brazilian National Research Council (CNPq) and in part by the Pernambuco Science and Technology Research Funding Agency (FACEPE). Paper no. TPWRD-00085-2013.

The authors are with the Department of Management Engineering, Federal University of Pernambuco, Recife 50630-970, Brazil (e-mail: tvgarcez@gmail.com; almeidaatd@gmail.com).

Digital Object Identifier 10.1109/TPWRD.2013.2273083

and of the incident energy (the thermal energy released from an arcing fault). Section V discusses how to assess consequences by determining the probability functions for each dimension of the consequence. Section VI sets out a multidimensional decision model for risk assessment and for ranking underground vaults and Section VII provides a numerical application. Finally, Section VIII draws some conclusions about the model and its possible applications.

II. Multidimensional Risk Decision Modeling

In order to allocate an additional investment effectively, consideration needs to be given to different aspects, such as safety; the financial, operational, and external characteristics of the system; requirements demanded by regulatory agencies; the stance of competitors; and the demands from society.

To formalize the decision-making process and ensure that it is consistent with the goals of the company, an approach must be used that allows the various criteria involved in this process and the DM's preferences to be incorporated into it. Multicriteria decision analysis (MCDA) methodologies are well suited for such situations [12].

MCDA is a set of models for operational research that deals with decision problems in the presence of (usually conflicting) multiple objectives, the main purpose of which is to make the problem clearer for the DM [13], [14].

Among various problematics, the problem of ranking emerges from the need for the DM to build a list of the most important alternatives in order of relevance (prioritization) which, in this particular case, is a risk hierarchy, such that the alternatives (the underground vaults of the system) most likely to be the source of a manhole accident are dealt with first of all by using the available additional resources and only thereafter, other sections of the system according to their ranking if these resources are still available. Multiattribute utility theory (MAUT) achieves this ranking.

To define a hierarchy, under a risk context, a model of the consequences is needed. According to Aven [15], the most appropriate definition of risk involves defining the consequences and uncertainties.

By decision theory [16], the loss (consequence) function can be defined as the negative of the utility function of the expected consequence $[L(c) = -u(c)]$. These consequences are the outcomes of the impact of an accident in a given dimension, and can be represented by a probability distribution function $P(c|\theta, V_q)$, given knowledge of the hazard scenario $\boldsymbol{\theta}$ (the final outcome of an accident), and the underground vault analyzed V_q.

In order to determine the consequences of hazard scenarios that can lead to an accident, the first requirement is to understand what the main causes of manhole events are. Thus, the next section discusses this problem.

III. Main Causes of Manhole Events

In general, the frequency of accidents concerning manholes is statistically small. For example, Rudin *et al.* [3] show that there are about six to nine hundred manhole events per year in 21,000 miles of underground Manhattan's secondary electrical grid, which has approximately 51 thousand manholes and service boxes.

There are several causes for manhole events. Regular attention needs to be given to flaws in cabling of the primary and secondary network and in transformers [17]–[19]. These failures occur for several reasons, and arise from the internal and external reasons for having underground vaults. First, with regard to the internal reasons, failures can occur, for example, because of the aging process, inadequate facilities and forms of maintenance, the thermo-mechanical stress of the cable and connections, the thermal decomposition of the insulation and overloading the power grid.

As to the external reasons, consideration needs to be given to external interference, such as, the shared use of the underground space with other public and private utilities (e.g., for the distribution of natural gas, a telecommunications system, water and sewage systems, drainage system and the network of subways), or the flooding of underground vaults, or drains and manhole covers being clogged or blocked [1], [18]. Moreover, in many urban areas originally developed along waterways where a large amount of organic material was covered over to make streets and other infrastructure, the fuel gases from this organic material that decomposes outside the vault often accumulate in the manholes, and result in explosions when they are ignited.

An arcing fault is linked with the main causes of manhole events, such as, fire, smoke and explosion in underground vaults of the secondary distribution system [17], [18], [20].

An arc flash releases large amounts of energy (about 10 000 kW cycle) in a very short period of time at high temperatures and at a high noise level. The incident energy depends on the voltage, current and duration of the arc [21], [22].

The sudden release of a large amount of energy can beget a considerable pressure wave, causing both the projection (hurling) of equipment at people many meters away, and an explosion inside the underground vault, given that it is a confined space; it can cause high-degree burns (from jets of very-high-temperature vapors and ionized gases); it can produce toxic, corrosive and fuel gases (because of the melting and evaporation of insulation materials and/or electrolysis, or because of thermal degradation—pyrolysis—of nearby organic materials) [18], [20], [21], [23]–[26]. The occurrence of fire inside an underground vault can generate a large amount of smoke due either to materials burning, or water or sewage on site evaporating, or combustion being incomplete [17], [27].

Other causes of explosions in underground vaults arise from external events from third-party systems, such as, leaks in the natural gas distribution system, or because of groundwater contamination (fuel products) from gas stations or other sources of contamination, or because organic material in the vault has decomposed. These fuel gases may accumulate due to the confined space, and, should there be an ignition source, this could result in an internal explosion.

As the internal structure of the underground vault is rigid, the energy generated by an internal explosion will be released through the weakest points of the system, which are the manhole covers [21], [23]. In more extreme cases, the roof of the underground vault may be blown off.

In conclusion, the main hazard scenarios, considering only the failure mode of an arc flash, are summarized in an event tree analysis, as shown in Fig. 1.

Fault	Initial Event (Failure Mode)	Presence of fuel gases	Possible Hazard Scenarios (θ)
Manhole Events	Electrical Arc	Yes	Internal Explosion with displacement of manhole cover Internal Explosion without displacement of manhole cover Flash Fire Fire Intense Light and Noise Smoke
		No	Internal Explosion with displacement of manhole cover Internal Explosion without displacement of manhole cover Flash Fire Fire Intense Light and Noise Smoke Shock and Heat Wave

Fig. 1. Event tree analysis for underground manhole events caused by arcing fault.

IV. Estimating the Area of the Hazard Zone

The surrounding environment, in turn, influences the intensity of consequences, because of the characteristics and conditions that form part of the hazard zone (e.g., presence of the third-party installations; density of the local population or pedestrians; the level of vehicular traffic; and if the area is residential, commercial, or industrial).

Furthermore, the consequences can directly affect the quality and level of the operation of the supply of electric energy (e.g., loss of revenue or fines because the power supply was interrupted, or because the quality of the supplied power deteriorated; costs of repair, downtime, and it is likely to impact in the company's image being impaired).

To simplify, the hazard zone above ground can be determined, mainly, by two factors. The first is with regard to the trajectory (projection) of manhole covers and where they crash land, and the second is associated with the incident energy from an arc flash, only taking into account the occurrence of a hazard scenario due to an electrical arc.

According to Walsh and Black [21], the vertical height to which a manhole cover is projected is a relative measure of the danger of the manhole event. They modeled the forces that act on a manhole cover, such that it could be displaced from its seat.

The measure of the first external hazard zone is estimated by the distance that the manhole cover can be projected. In this study, the distance is estimated by defining a projection angle (α_c) along which the cover can travel and fall. This angle is related to the vertical projection component. It is the result of several forces on the displacement of the manhole cover, such as those of the wind, convection, or projection of the horizontal component.

It is assumed that the crash site of the manhole cover, inside the hazard zone, follows a uniform probability distribution. Hence, the radius of the hazard zone $r_{hz(\text{cover})}(m)$ is given by:

$$r_{hz(\text{cover})} = x \cdot \tan(\alpha_c) + \frac{d}{2} \tag{1}$$

where x is height of the vertical projection of the manhole cover (m) determined by [21]; and, d is the diameter of the manhole cover (m).

The second hazard zone, also known as the Flash Protection Boundary, can be calculated as the minimum distance from the arc flash at which people could be safely exposed to incident energy without suffering second-degree burns. This distance is calculated by IEEE Standard 1584 [28].

In a system for urban underground power distribution, two possible locations of manhole covers should be considered. The first is to locate them on the sidewalk, and the second to do so on the street. Moreover, it is considered that manhole covers can only be located in the center of the sidewalk or in the center of the lane of a street, respectively. Furthermore, it is considered that pedestrians transit only sidewalks. Thus the impacts on human beings that are not on a sidewalk are disregarded, that is, impacts on people inside cars were not considered. Bearing these matters in mind, the diagram, given in Fig. 2, shows how the consequences with respect to the localization of manhole covers are determined.

V. Assessment of Consequences

Multidimensional risk has some advantages such as its providing a broader analysis, which makes it more realistic and complete, and it also deals with conflicting objectives, the different parties involved, and uncertainties. Several studies have tackled the context of risk analysis from a multidimensional view, such as, for natural gas pipelines [6], [8]; for hydrogen pipelines [7], [9]; for infrastructure vulnerabilities due to terrorism [2], [29]; for management of contaminated materials, sediments and related areas [30]; and, for nuclear emergency management and planning [31]. Some dimensions addressed are human safety, finance, the environment, property, the impact of stakeholders and the impact on a distribution company's external public image.

This study evaluates the consequences (c) from four dimensions: human impacts, financial impacts, operational impacts and disruptions to vehicular traffic.

The human dimension (c_H) deals with the possibility of injuries caused by projection of the manhole covers and where they crash land, and burns of at least the second degree due to exposure to incident energy from an arc flash. The occurrences of injuries alone are considered because estimates for injuries are more conservative than those for fatalities.

The financial dimension (c_F) is about any kind of monetary compensation related to an accident occurring. As shown in Brito and Almeida [6], these consequences can be monetary estimates, which include those that arise from: the expected loss due to the supply being interrupted; probable refunds to customers because of disruptions in supply; expected expenses on labor, equipment and raw material to restore the system; and maintenance costs. There are, also, other expenses linked to fines established by regulatory bodies and government authorities. Furthermore, financial expenses incurred on compensation for human injuries or fatalities, and to restore a third-party's system, which may be affected by such accidents, must be taken into account.

The operational dimension (c_O) corresponds to the impact on the supply operation of the electricity distribution company. To estimate these consequences, the downtime parameter of the system will be used. This time is time that the electricity distribution system will be unavailable to consumers, until it is restored to the standards required by the regulatory agencies. A lognormal probability density function may be used to calculate the consequence function, which represents the maintainability of the system.

Finally, the dimension of disruption to traffic (c_T) is evaluated by the process of how traffic jams form on the streets around the accident area. This can be modeled by Queueing theory. The impact of traffic jams, for the DM, can be a negative point for society and for the company's image. This dimension can be measured by average waiting time in a queue or the average number of vehicles that are in the queue, during the traffic jam.

A. Probability Function for the Consequences

In the intra-criteria probabilistic assessment of the consequences, the probability functions for each dimension of the consequence need to be determined separately. However, there may be cases, in some dimensions, in which these consequences will almost certainly occur, in a deterministic view (also, justified as a way to simplify the modeling of consequences). Thus, this consequence function is expressed by $P(c|\theta, V_q) = 1$.

In this specific study, if the state of nature θ is adversely affected, there will almost certainly be consequences for the financial and for the disruptions to traffic dimensions. Thus, the disruptions to traffic dimension can be modeled by D/D/1 queue and financial consequences can be estimated by

$$c_F(\theta_i, V_q) = \sum_i \mathrm{R}(V_q)(FI(V_q) + Pf(V_q) + RC(V_q) + FM(V_q)) \quad (2)$$

where $R(V_q)$ is the revenue from each underground vault, which can be estimated as a percentage of total revenues from the local system. Normally, this percentage is directly influenced by the network type, its magnitude and the distribution of the type of clients served; $FI(V_q)$ is the total of fines imposed by the national regulatory agency; $Pf(V_q)$ is the total of fines arising from loss of performance (quality) of the power supply, applied by the regulatory agency; and $RC(V_q)$ is the percentage of revenue spent to restore the system to its normal electricity supply level. This may include amounts spent to recover a third-party system; and $FM(V_q)$ is due to fines imposed by the public prosecutor when an accident has occurred that has had an adverse impact on society.

Depending on the physical configuration of the distribution network, and on whether there are alternative ways to isolate the system affected (the one that has crashed), it is likely that the financial consequences will be lower due to the lower impact on revenue, fines and the performance of the system.

As mentioned previously, the human consequence is measured by the number of people injured. Also, it depends on the location of the manhole cover in relation to the sidewalk or street, as summarized in Fig. 2. The number of people c_H within the hazard zone can be modeled by Queueing theory, because the retention of the flow of people on a sidewalk can be considered as a queuing process, in which the number of people who are at instant t is influenced by the rate of the arrivals of people λ, the service time μ, and number of servers s.

This study assumes that the rate of arrival (λ) of people on the sidewalk follows a Poisson process, and μ is a parameter of the exponential distribution for the service times. Further, it is considered that the number of servers (s) is determined by the width of sidewalk inside the hazard zone. Thus, the M/M/s model set out in Queueing theory can be applied.

Since it is considered that the stability condition $\rho = \lambda/(s\mu) < 1$ is mandatory, then there is a finite number of people in a queue and, therefore, in this specific case, it can be considered there is a finite number of people within the hazard zone.

Using the concepts of Queuing theory, the probability of exactly c_H people being within the hazard zone, when the system reaches the steady-state condition is given by

$$P(c_H|\theta, r_{hz(\text{cover})}, V_q) = \begin{cases} P_0, & \text{if } c_H = 0 \\ \begin{cases} (1-\rho)\rho^{c_H}, & \text{if } s = 1 \\ \begin{cases} \frac{P_0(\lambda/\mu)^{c_H}}{c_H!}, & \text{if } s \geq c_H \\ \frac{P_0(\lambda/\mu)^{c_H}}{s! s^{c_H - s}}, & \text{if } s < c_H \end{cases} & \text{if } s > 1 \end{cases} & \text{if } c_H > 0 \end{cases} \quad (3)$$

where c_H is the number of people that are within the hazard zone; λ is the arrival rate of people on the sidewalk (people/s);μ is the parameter of the service time; and P_0 is the probability of no one being within the danger zone, which is expressed by

$$P_0 = \frac{1}{\sum_{c_H=0}^{s-1} \frac{(\lambda/\mu)^{c_H}}{c_H!} + \frac{(\lambda/\mu)^s}{s!}\frac{1}{1-\lambda/(s\mu)}} \quad \text{if } \lambda < s\mu. \quad (4)$$

The probability that one or more people suffers injuries can be modeled by, first, considering someone being hit by a manhole cover, and, subsequently, by considering the exposure of people to incident energy.

First of all, as the size of the manhole cover is restricted, the possibility of its injuring people is also restricted. The modeling of the number of people who suffer injuries can be modeled as a Poisson Process. The probability of a designated number of people with injuries per unit interval is given by:

$$P\left(c_H|\theta_i, r_{hz(\text{cover})}, V_q\right) = \frac{(\lambda_{Hi})^{c_H}}{c_H!} e^{-\lambda_{Hi}} \quad (5)$$

where c_H is the total number of people injured by the manhole cover; and λ_{Hi} is the average number of people injured when an accident involving a manhole cover occurs.

By assumption, it is considered that about 1% of people within the danger zone are injured, that is, $\lambda_{Hi} = 0.01 \cdot nc_{H\,\max}$. This $nc_{H\,\max}$ parameter is the maximum number of the people inside the hazard area $A_{hz(\text{cover})}$, which is the sidewalk area that is included in the hazard zone.

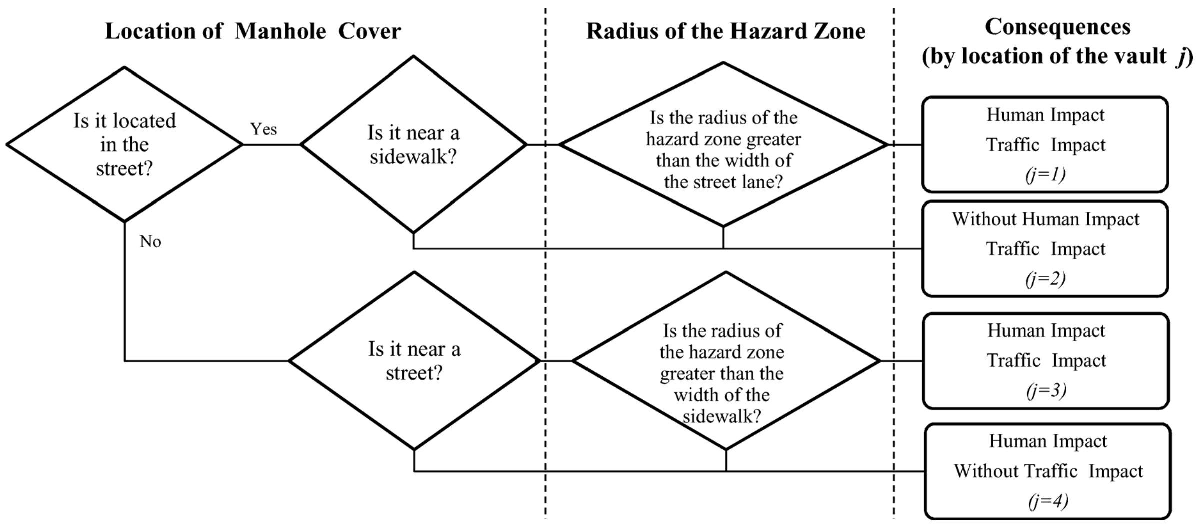

Fig. 2. Diagram to determine the consequences considering the localization of the manhole cover.

Second, exposure to accident in the hazard zone as a consequence of incident energy is considered. In this case, anyone who is within the hazard zone $A_{hz(\text{energy})}$ is likely to get a second-degree burn, and the calculation for this hazard area takes this consequence into account, hence

$$P\left(c_H|\theta, r_{hz(\text{energy})}, V_q\right) = 1. \tag{6}$$

Hence, the probability function of the consequence that one or more people are in the hazard zone and that they are injured because of the trajectory and landing of a manhole cover is given by

$$P_{\text{cover}}(c_H|\theta_i, V_q) = \sum_{i=0}^{nc_{H\max}} \begin{pmatrix} P[N_{\text{injuries}} = c_H] \\ \cdot[1 - P[N_{\text{inside}A_{\text{HZ}}} < c_H - 1]] \end{pmatrix}. \tag{7}$$

Similarly, the probability function of the consequence that one or more people are in the hazard zone and that they are injured because of the incident energy from an arc flash is determined.

Finally, the consequence probability function that one or more people are in the hazard zone and that they are injured because of an accident, considering both possibilities for the causes of their injuries (a falling manhole cover or incident energy), is given by

$$P_{\text{overall}}(c_H|\theta_i, V_q) = \sum_i \begin{bmatrix} \begin{pmatrix} P_{\text{energy}}(c_H|\theta_i, V_q) \\ +P_{\text{cover}}(c_H|\theta_i, V_q) \end{pmatrix} - \\ -\begin{pmatrix} P_{\text{energy}}(c_H|\theta_i, V_q) \\ \cdot P_{\text{cover}}(c_H|\theta_i, V_q) \end{pmatrix} \end{bmatrix} \tag{8}$$

where i indicates different hazard scenarios (θ_i).

VI. Multidimensional Decision Model for Risk Assessment and for Risk Ranking

As previously mentioned in Section II, the loss function is defined as the negative of the utility function of the expected consequence. The utility function is calculated by

$$u(\theta, V_q) = \int_c u(c)P(c|\theta, V_q)\text{dc} \tag{9}$$

thus

$$L(\theta, V_q) = -\int_c u(c)P(c|\theta, V_q)\text{dc}. \tag{10}$$

The measurement of risk $r(V_q)$ in an underground vault is the expected value of loss function $L(\theta, V_q)$ [16]. This can be represented by:

$$r(V_q) = \sum_\theta \pi(\theta)L(\theta, V_q) = -\sum_\theta \pi(\theta)\int_c u(c)P(c|\theta, V_q)\text{dc} + (-1)\pi(\theta_N) \tag{11}$$

where $\pi(\theta)$ is the probability distribution over the states of nature (hazard scenarios); and the state of nature θ_N represents the scenario of the normality, in which there is no occurrence of accidental scenario and, consequently, no negative consequences in the system, that is, $\int_c u(c)P(c|\theta_N, V_q)\text{dc} = -1$ (the system is operating normally). The range of risk values is $[-1, 0]$, where the value -1 is related to the "lowest risk" and the value 0 to the "highest risk."

Multiatribute utility theory, which lies within the concepts of MCDA, enables the values of the DM's preferences to be aggregated (through the utility function) from multiple attributes, together with the uncertainty inherent in their consequences $P(c|\theta, V_q)$ and hazard scenarios $\pi(\theta)$, in a unique synthesis criterion function. This is a compensatory method [12].

MAUT enables issues, such as ranking, o be tackled. The details of the process of assessing the multiattribute utility function are given in more detail in Keeney and Raiffa [12]. They

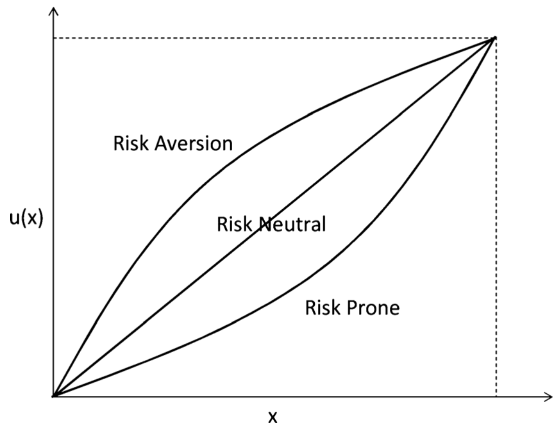

Fig. 3. Attitude of the decision maker toward risk [12].

summarize the process into five steps: 1) introducing the terminology and idea; 2) identifying relevant assumptions of independence; 3) evaluating the utility functions conditionally; 4) evaluating the scale constants; and 5) checking consistency.

In this model, the multiattribute utility function is considered additive, implying additive independence in the DM's preference amongst the attributes. Therefore, the multiattribute utility function can be obtained by

$$U(c_H, c_F, c_O, c_T) = k_H U(c_H) + k_F U(c_F) + k_O U(c_O) + k_T U(c_T) \quad (12)$$

where k represents the scale constants, those being $k_{c_H} + k_{c_F} + k_{c_O} + k_{c_T} = 1$, and $U(c)$ as the 1-D utility functions of each attribute considered. The scale constants are related to the gain compensation in one criterion, when it loses out in another. Scale constants depend on the range of values considered to define the consequences.

The DM can have different basic attitudes (behavior), such as: risk aversion, risk neutral, or risk prone. If the DM is risk averse, then the expected utility value is greater than the value of the certainty equivalent $(u[E(\tilde{x})] > E[u(\tilde{x})])$. If the DM is risk-neutral, the expected utility value is equal to the certainty equivalent $(u[E(\tilde{x})] = E[u(\tilde{x})])$. Should the DM be risk prone, the expected utility value is less than the certainty equivalent $(u[E(\tilde{x})] < E[u(\tilde{x})])$. These behaviors can be expressed graphically as shown in Fig. 3 [12].

By adding the concepts of the MAUT into the risk measure (14), based on Brito and Almeida [6], and by taking the probability independence of the consequences into account, the risk measure is expressed by:

$$r(V_q) = \sum_i \left(\sum_\theta \left(\pi(\theta) \left(- \int_c u(c) P(c|\theta, V_q) \mathrm{d}c \right) \right) \right) + (-1)\pi(\theta_N) \quad (13)$$

where θ represents the several hazard scenarios considered; i represents the several dimensions of the analysis, that is, the dimensions of the consequence (c_H, c_F, c_O, c_T), when a hazard scenario (θ) occurs.

These risks measure form a top-down hierarchy of the risk from the underground vaults evaluated. Consequently, they serve as a support tool for decision making and risk management.

VII. Applying the Model

A numerical application of the proposed multicriteria decision model is presented, with a view to assessing and ranking the risks from underground vaults. This is a hypothetical study, although the situation is a realistic one that was based on an underground system of an electricity distribution company.

For all decision models, the DM must be identified. In this case, one can consider the DM to be the company's senior manager for safety and operations. The outcomes of the analysis (ranking of the underground vaults) must reflect his elicited preferences. Consequently, it is believed that this preference structure reflects the preference structure of the company whom the DM represents. Furthermore, the DM must have some experience and knowledge of this type of analysis; otherwise, a team of experts on the context must support him.

For this specific study, ten underground vaults $(V_1, \ldots, V_q, \ldots, V_{10})$ will be analyzed, which represent a wide range of possible scenarios found in electricity distribution companies. Each of the underground vaults analyzed has the same internal standard volume of 25 m^3. The main features of these vaults are summarized in Table I, where C. Area means the commercial area, R. Area means residential area, and I. Area means the industrial area.

The study was supported by computational tools, using Matlab software. Some simulations were performed. Four main dimensions of consequence were considered: 1) the consequences on human impacts, 2) financial impacts, 3) operational impacts, and 4) traffic disruptions.

For this study, conservatively, only one hazard scenario was considered: an internal explosion caused by an arc flash, which is considered the greatest impact, and causes the manhole cover to be blown off and projected.

Estimating the projection of the manhole cover is the hardest task because this involves several complex parameters. However, in this study, a different approach is used, which combines the main characteristics that influence the projection of the cover, as defined by the study of Walsh and Black [21], with the experts' knowledge.

The elicitation method, called Equiprobable Intervals, was used. This method is defined in Raiffa [32], and is expressed as an a *priori* distribution probability using subjective probabilities. Subjective probability refers to the degree of belief in a proposition. At one extreme there is $\Pr(A) = 1$, if A is trusted to be true. At the other, there is $\Pr(A) = 0$, if A is trusted to be false, so the points in the range (0,1) express intermediate beliefs between $\Pr(A) = 1$ and $\Pr(A) = 0$; in other words, true and false. This method is based on successive subdivisions of equiprobable intervals (percentiles) through interviews with the expert.

After estimating the size of the hazard areas, the consequences are estimated by means of probability density functions $(P(c|\theta_i, V_i))$.

TABLE I
FEATURES OF THE VAULTS ANALYZED AND THEIR SURROUNDINGS

Vq	Description of the external vicinity	Location of the manhole cover	Dist. from the manhole cover center on sidewalk to street (m)	Dist. from the manhole cover center on street to sidewalk (m)	Diameter of the Manhole Cover (m)	kV of the bus	Total Arcing Fault Current (kA)	λ Arrival Rate of people (*people/s*)	% of revenue local electricity distribution	Downtime (h)	Number of the street lanes	λ_T Arrival rate of the vehicles (*vehicles/h*)
V_1	C. Area 1	Sidewalk	2.50	-	1.0	13.8	10.66	0.25	1.0%	4	2	500
V_2	C. Area 2	Street	-	4.25	1.5	0.48	11.85	0.30	1.0%	4	2	650
V_3	C. Area 3	Sidewalk	2.25	-	1.5	0.48	25.93	0.25	1.0%	4	0	0
V_4	R. Area 1	Sidewalk	2.50	-	1.0	0.48	25.93	0.05	0.5%	5	2	200
V_5	R. Area 2	Street	-	3.5	1.0	0.48	25.93	0.05	0.5%	5	2	200
V_6	R. Area 3	Sidewalk	3.25	-	1.5	0.48	25.93	0.15	0.5%	5	0	0
V_7	I. Area 1	Street	-	6.5	1.0	0.48	13.82	0.05	1.0%	2	2	900
V_8	I. Area 2	Street	-	6.25	1.5	0.48	7.75	0.10	1.5%	2.5	2	100
V_9	C. Area 4	Street	-	8.5	1.0	0.48	9.86	0.25	1.5%	4	3	3200
V_{10}	C. Area 5	Street	-	8.5	1.0	0.48	7.28	0.20	1.0%	3	2	1800

To estimate the consequences to the dimension of the disruptions to vehicular traffic, first, it is necessary to check the exposure consequences of this dimension with respect to the location of the manhole cover, as shown in Fig. 2. It was supposed that the arrival rate λ_T and service time μ_T are constant, and that there is only one server $(s_T = 1)$, and so, it can be modeled by a queueing model of the D/D/1 kind.

At the time that an accident in the underground vault occurs, it is assumed that all lanes of the street become completely blocked. Some time (t_1 hours) after the accident has occurred, the lanes not directly affected by the accident are re-opened, and only t_2 hours after the accident has occurred is the street completely reopened to traffic. Hence, the average size of the queue of vehicles formed is given by:

$$L_{V_q} = \frac{W_T}{W} \tag{14}$$

where W_T is the total waiting time (*vehicles.h*), which is formed by the area between the curves of arrival and service time; and, W is the time spent in the queue (h) by each vehicle individually.

Subsequently, a risk measure is made from the perspective of Decision theory. At the same time, the multiattribute utility function $U(c_H, c_F, c_O, c_T)$ is elicited from the DM. As it is supposed that the DM's preference structure is additive independent between the criteria, the utility functions from the perspective of a one-dimensional utility $(U(c_H), U(c_F), U(c_O), U(c_T))$ can be elicited separately. To do so, the procedures described in Keeney and Raiffa [12] were followed.

It is considered that the DM is risk averse in the human dimension and risk prone in the remaining dimensions.

Likewise, by considering the preference independence, and using the consequence matrix, the scale constants $(k_{c_H}, k_{c_F}, k_{c_O}, k_{c_T})$ are obtained. More details about these procedures are also given in Keeney and Raiffa [12]. The values obtained were $k_{c_H} = 0.3386, k_{c_F} = 0.4423, K_{c_O} = 0.0944$ and $k_{c_T} = 0.1247$.

The multiattribute utility functions are combined with the probability density function. Hence, the multidimensional risk measure is calculated.

TABLE II
RESULTS OF THE RANKING OF THE MULTIDIMENSIONAL RISK ASSESSMENT

Rank	V_q	Risk value	Risk difference	Risk ratio
1st	V_3	-0.99221631107	0.0028157169	0.020
2nd	V_1	-0.99221912679	0.1405724794	0.229
3rd	V_6	-0.99235969926	0.6143075709	0.478
4th	V_4	-0.99297400684	1.2847738118	2.430
5th	V_5	-0.99425878065	0.5286859778	19.728
6th	V_7	-0.99478746662	0.0267993196	0.909
7th	V_{10}	-0.99481426594	0.0294889692	26.448
8th	V_2	-0.99484375491	0.0011149576	0.013
9th	V_8	-0.99484486987	0.0875532687	
10th	V_9	-0.99493242314		

A. Results and Discussions

The results from ranking the risks are shown in Table II. The values of the 3rd column present the risk values ranked $r_i(V_q)$; the 4th column contains the differences between the risks, and is calculated by $(r_{i+1}(V_q) - r_i(V_q)) \cdot 10^{-3}$; and, in the 5th column, the value of the Risk ratio $((r_i(V_q) - r_{i+1}(V_q))/(r_{i+1}(V_q) - r_{i+2}(V_q)))$ is shown.

Notice that the values of risks (Table II, 3rd column) are close to -1. This is due to the greatest contribution being from the scenario of normal operation (θ_N), since the occurrence of manhole events is rare, so the probability of the scenario of normal operation $\pi(\theta_N)$ is close to 1, and its loss function is -1.

The conclusion should be drawn that underground vault V_3 is at the top of the ranking; consequently, it should receive the greatest attention when additional resources are available for allocating to safety measures and system improvements, that is, it should receive the greatest priority when allocating resources. Furthermore, it is possible to make comparisons of the increments of risks, by examining the difference between the risks of the vaults ranked, since the results are given on an interval scale (due to the utility function), as shown in Table II (fourth column).

Since the radius of the danger zone is around a few units of meters, and as per the diagram shown in Fig. 2 with the simulation results, it was found that the consequences for

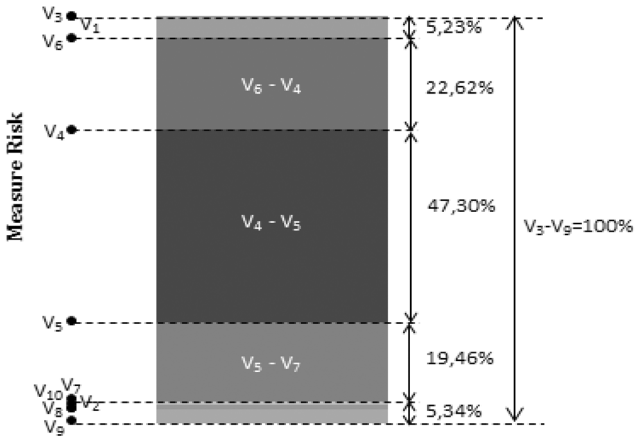

Fig. 4. Analysis of the differences of the risks.

the human dimension are given only for underground vaults $(V_1, V_3, V_4, V_5, V_6, V_7)$, even although alternatives V_5 and V_7 are not located on sidewalks (where it is considered that pedestrians are located). Moreover, the underground vaults located on sidewalks caused no impact on the disruption to traffic dimension, due to the small size of the area of the hazard zone. For all alternatives analyzed, consequences in the financial and operational dimensions were observed.

By analyzing the differences between the risks (see Fig. 4), the conclusion may be drawn that the difference between the risk values of vaults V_4 and V_5 corresponds to about 47% of the total range of risk $((V_4 - V_5)/(V_3 - V_9) = 47.30\%)$, which indicates a large increase in the risk between these vaults. The same occurs with the increases in risk from V_4 to V_6 and from V_7 to V_5, approximately 20% each.

Therefore, additional resources applied to any of the first three vaults (V_3, V_6, V_1) in the ranking may generate outcomes as efficient (decreased risk) as those applied to V_3, the first alternative ranked, under an overview of the system. Hence, it should be more efficient to deal with the risks offered by the first three underground vaults than with those arising from V_4 but, at the same time, the risk from V_4 is significantly higher than that of V_5, that is, if the risks it poses are attended to, this is likely to generate significantly more benefits than those that would come from attending to those of V_5. This kind of information can be strategic to financial, resource, and risk management.

Another important analysis arises from there being some underground vaults with different characteristics and distinct areas (such as the commercial area and the residential area) in the areas of the vaults ranked in the top three positions of the ranking, as can be seen in the specific study (V_3, V_1, V_6). The conclusion is drawn that by simply choosing to designate a given specific (commercial, residential or industrial) area to be the most critical, one cannot accurately reflect the risk hierarchy in line with the DM's preferences.

VIII. Conclusion

When it comes to making allocations (investments) of additional resources, an approach that ranks the risks is the most appropriate one because this enables the DM to make a ranked list of underground vaults and, thus, to allocate resources to those at the top of the list until all resources are consumed.

Given the large variability in external and internal environments, and, hence, there being a wide range of possible consequences when an accident occurs, there is a need for an approach to risk assessment from a multidimensional view. Moreover, in terms of decision making, aggregating the DM's preferences in the modeling is made more complete and comprehensive and particularly given that this best meets the DM's desires.

Thus, this study examined the multidimensional risks from vaults in an underground electricity distribution system, under several aspects of consequences, which deals with their uncertainties and accident scenarios, and also considers the DM's preferences, by using the utility function.

The hypothetical application demonstrated the applicability of the model and the possible results. One can conclude that a risk hierarchy may well be an important tool for setting priorities when allocating additional investments in such a system.

The use of information arising from an analysis of the differences between risks enabled the DM to make an in-depth analysis of the range of possibilities over which alternatives may be chosen to implement preventive actions. Analyzing the difference between risks enables alternatives which have near risk values together with the ranked risks to be identified and thus to evaluate what the set of alternatives at the top of the list of alternatives should be.

With this information, the DM can carry out more detailed studies on what resources (monetary, time, manpower, equipment and technology) can be allocated to the alternative of the set of the close risks, with a view to meeting the goals in each criterion (dimension) of consequence for each alternative, which will bring a better return on reducing the multidimensional risk. Hence, these considerations make this model an important tool for decision making.

An aspect to be noted is that in the proposed model, the modeling of consequence functions is tackled in a process that involves the generation of alternatives. Thus, the model is designed in such a way that it does not depend on specific alternatives. It can be applied to any set of alternatives, even when different alternatives involving different structures are used, due to the peculiarities of each alternative. Only to aggregate these peculiarities in the consequence functions makes the model proposed broader. Thus, more specific in-depth future studies for each characteristic and for each dimension can be undertaken to model the functions consequence, in accordance with the wants that the company considers are important to evaluate.

References

[1] T. S. Sidhu and Z. Xu, "Detection of incipient faults in distribution underground cables," *IEEE Trans. Power Del.*, vol. 25, no. 3, pp. 1363–1371, Jul. 2010.

[2] G. E. Apostolakis and D. M. Lemon, "A screening methodology for the identification and ranking of infrastructure vulnerabilities due to terrorism.," *Risk analysis?: An Official Publication of the Society for Risk Analysis*, vol. 25, no. 2, pp. 361–376, Apr. 2005.

[3] C. Rudin, R. J. Passonneau, A. Radeva, H. Dutta, S. Ierome, and D. Isaac, "A process for predicting manhole events in Manhattan," *Mach. Learn.*, vol. 80, no. 1, pp. 1–31, Jan. 2010.

[4] C. Rudin, R. J. Passonneau, A. Radeva, S. Ierome, and D. F. Isaac, "21st-century data miners meet 19th-century electrical cables," *Computer*, vol. 44, no. 6, pp. 103–105, Jun. 2011.

[5] C. Rudin, D. Waltz, R. N. Anderson, A. Boulanger, A. Salleb-Aouissi, M. Chow, H. Dutta, P. N. Gross, B. Huang, S. Ierome, D. F. Isaac, A. Kressner, R. J. Passonneau, A. Radeva, and L. Wu, "Machine learning for the new york city power grid," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 34, no. 2, pp. 328–345, Feb. 2012.

[6] A. J. Brito and A. T. de Almeida, "Multi-attribute risk assessment for risk ranking of natural gas pipelines," *Rel. Eng. Syst. Safety*, vol. 94, no. 2, pp. 187–198, Feb. 2009.

[7] M. H. Alencar and A. T. de Almeida, "Assigning priorities to actions in a pipeline transporting hydrogen based on a multicriteria decision model," *Int. J. Hydrogen Energy*, vol. 35, no. 8, pp. 3610–3619, Apr. 2010.

[8] A. J. Brito, A. T. de Almeida, and C. M. M. Mota, "A multicriteria model for risk sorting of natural gas pipelines based on ELECTRE TRI integrating utility theory," *Eur. J. Oper. Res.*, vol. 200, no. 3, pp. 812–821, Feb. 2010.

[9] P. H. C. Lins and A. T. de Almeida, "Multidimensional risk analysis of hydrogen pipelines," *Int. J. Hydrogen Energy*, vol. 37, no. 18, pp. 13545–13554, Sep. 2012.

[10] M. G. Morgan, H. K. Florig, M. L. DeKay, and P. Fischbeck, "Categorizing risks for risk ranking.," *Risk Analysis?: An Official Publication of the Society for Risk Analysis*, vol. 20, no. 1, pp. 49–58, Feb. 2000.

[11] H. H. Willis, M. L. DeKay, B. Fischhoff, and M. G. Morgan, "Aggregate, disaggregate, and hybrid analyses of ecological risk perceptions," *Risk analysis?: An Official Publication of the Society for Risk Analysis*, vol. 25, no. 2, pp. 405–28, Apr. 2005.

[12] R. L. Keeney and H. Raiffa, *Decisions With Multiple Objectives: Preferences and Value Trade-Offs*. New York: Wiley, 1976, pp. 592–.

[13] P. Vincke, *Multicriteria Decision-Aid*. New York: Wiley, 1992.

[14] V. Belton and V. B. T. J. Stewart, *Multiple Criteria Decision Analysis: An Integrated Approach*. Berlin, Germany: Springer-Verlag, 2002.

[15] T. Aven, "The risk concept—Historical and recent development trends," *Rel. Eng. Syst. Safety*, vol. 99, no. 0951, pp. 33–44, Mar. 2012.

[16] J. Berger, *Statistical Decision Theory and Bayesian Analysis (Springer Series in Statistics)*, 2nd ed. New York: Springer, 1985.

[17] B. Koch and Y. Carpentier, "Manhole explosions due to arcing faults on underground secondary distribution cables in ducts," *IEEE Trans. Power Del.*, vol. 7, no. 3, pp. 1425–1433, Jul. 1992.

[18] J. Cultrera and W. Charytoniuk, "Arcing fault detection in underground distribution networks-feasibility study," *IEEE Trans. Ind. Appl.*, vol. 36, no. 6, pp. 1756–1761, Nov./Dec. 2000.

[19] L. Zhang, S. Boggs, and G. Murray, "Effect of limiting airflow in mitigating combustion-driven manhole events," *IEEE Elect. Insul. Mag.*, vol. 27, no. 6, pp. 37–44, Nov. 2011.

[20] A. Hamel, A. Gaudreau, and M. Cote, "Intermittent arcing fault on underground low-voltage cables," *IEEE Trans. Power Del.*, vol. 19, no. 4, pp. 1862–1868, Oct. 2004.

[21] B. P. Walsh and W. Z. Black, "Thermodynamic and mechanical analysis of short circuit events in an underground vault," *IEEE Trans. Power Del.*, vol. 20, no. 3, pp. 2235–2240, Jul. 2005.

[22] T. Gammon and J. Matthews, "The historical evolution of arcing-fault models for low-voltage systems," in *Proc. IEEE Ind. Commercial Power Syst. Tech. Conf.*, 1999, p. 6.

[23] B. P. Walsh and W. Z. Black, "Thermodynamic and mechanical analysis of gas explosions in underground vaults," *IEEE Trans. Power Del.*, vol. 17, no. 1, pp. 8–12, Jan. 2002.

[24] B. Koch and P. Christophe, "Arc voltage for arcing faults on 25(28)-kV cables and splices," *IEEE Trans. Power Del.*, vol. 8, no. 3, pp. 779–788, Jul. 1993.

[25] A. Hamel, A. Gaudreau, and Y. Brissette, "Attenuation of sound and temperature caused by faulted distribution cable joints," *IEEE Trans. Power Del.*, vol. 20, no. 3, pp. 2327–2333, Jul. 2005.

[26] G. Pietsch and E. Gockenbach, "Fundamental investigation on the thermal transfer coefficient due to arc faults," *IEEE Trans. Plasma Sci.*, vol. 34, no. 3, pp. 1038–1045, Jun. 2006.

[27] L. Zhang, S. Boggs, S. Livanos, G. Varela, and A. Prazan, "The electrochemical basis of manhole events," *IEEE Elect. Insul. Mag.*, vol. 25, no. 5, pp. 25–30, Sep. 2009.

[28] *IEEE Guide for Performing Arc-Flash Hazard Calculations*, IEEE Standard 1584-2002, 2002, IEEE1584, i–113.

[29] Y. Y. Haimes, "On the complex quantification of risk: Systems-based perspective on terrorism.," *Risk Analysis?: An Official Publication of the Society for Risk Analysis*, vol. 31, no. 8, pp. 1175–1186, Aug. 2011.

[30] I. Linkov, F. K. Satterstrom, G. Kiker, T. P. Seager, T. Bridges, K. H. Gardner, S. H. Rogers, D. A. Belluck, and A. Meyer, "Multicriteria decision analysis: A comprehensive decision approach for management of contaminated sediments," *Risk Analysis?: An Official Publication of the Society for Risk Analysis*, vol. 26, no. 1, pp. 61–78, Feb. 2006.

[31] R. P. Hämäläinen, M. R. Lindstedt, and K. Sinkko, "Multiattribute risk analysis in nuclear emergency management.," *Risk Analysis?: An Official Publication of the Society for Risk Analysis*, vol. 20, no. 4, pp. 455–467, Aug. 2000.

[32] H. Raiffa, *Decision Analysis: Introductory Lectures on Choices Under Uncertainty*. Reading, MA: Addison-Wesley, 1968.

T. V. Garcez received the B.Sc. degree in electronic engineering from Federal University of Sergipe (UFS), Aracaju, Brazil, in 2007, and the M.Sc. and Ph.D. degrees in management engineering from Federal University of Pernambuco (UFPE), Recife, Brazil, in 2009 and 2013, respectively.

Currently, he is an Assistant Professor at UFPE and is a Research Assistant at the Center for Decision Systems and Information Development (CDSID/UFPE) and Risk and at Decision Analysis in Operations and Maintenance (RANDOM/UFPE).

A. T. de Almeida (M'95) received the B.Sc. and M.Sc. degrees in electronic engineering from Federal University of Pernambuco, Recife, Brazil, in 1980 and 1985, respectively, and the Ph.D. degree in management engineering from The University of Birmingham, Birmingham, U.K., in 1994.

Currently, he is Full Professor of Management Engineering, Federal University of Pernambuco, Recife, Brazil. His research interests are in decision making related to multiple objectives and group decision problems, including methodological issues and applications. He has applied decision models in many contexts, such as risk analysis, reliability and maintenance, project portfolio, project management, strategic modeling, outsourcing, R&D project portfolio, information systems portfolios, supply chain, and water management. In the past, he worked in a business organization, related to power electricity, as Engineer and Manager, including Project Manager and Program Manager of R&D projects.

Prof. de Almeida is on the Editorial Board of a number of journals, such as *Group Decision and Negotiation*, *IMA Journal of Management Mathematics*, and *Journal of Quality and Reliability Engineering*, and has served as a reviewer for many other journals. He has authored various scientific papers in several journals, such as IEEE TRANSACTIONS ON RELIABILITY, *Reliability Engineering & Systems Safety*, *Group Decision and Negotiation*, *European Journal of Operational Research*, *Omega (Management Science)*, *IMA Journal of Management Mathematics*, *Computers and Operations Research*, *Annals of Operations Research*, *Journal of Decision Systems*, and *Quality and Reliability Engineering International*, *International Journal of Hydrogen Energy*, *Water Resources Management*, and *Resources Conservation and Recycling*. He has a research grantee for Productivity in Research from the Brazilian NRC (CNPq) since 1996.