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Foreword

Any organization is interested in having a structured decision process for its strategic success. This is particularly relevant when the decision context involves technological risk, reliability or maintenance issues. In general these issues may often be associated with potential threats to human life (e.g. safety) and the environment. They may also affect the strategic results of any organization. All these matters may be integrated into a single decision problem in many systems, for example an electrical supply system. Service interruptions or accidents in this kind of system may affect health and other emergency services, traffic in big cities, air traffic control, and many other issues that society has become increasingly aware of as a result of media reports of major accidents that had or could well have had a very serious impact on human safety. These interruptions are often related to the decisions in a system involving Risk, Reliability and Maintenance (RRM). Usually, these decisions include more than one objective that need to be dealt with simultaneously, with appropriate support from multicriteria and multi-objective models. These multicriteria models become even more relevant for the example of electrical supply system with smart grids conception.

"Multicriteria and Multi-objective Models for Risk, Reliability and Maintenance Decision Analysis" is a book that enables the reader to have a better understanding of and guidelines on integrating important application areas of operations research and management science. This is done by discussing means of structured process for model building that incorporate RRM issues. This integration is based on the combination of concepts and foundations related to RRM areas within multicriteria methods.

The authors represent a group of active members of scientific societies in operations research and RRM areas. They set out to build a bridge between these areas with this book; They have had more than 20 years' experience of engaging on such research and have had many articles published both in journals of distinction in the areas of operations research and also in specialized journals related to risk, reliability and maintenance, since the 1990s. Many of these articles also consider real problems found in business organizations.

As the current IFORS (International Federation of Operational Research Societies) President, it is with great pleasure that I present a book that reports outstanding academic research results in operational research and management science, thus bridging these relevant areas in order to support the decision process related to issues of the utmost importance to society.

Nelson Maculan Filho
Prof Emeritus of Universidade Federal do Rio de Janeiro
President of IFORS (International Federation of Operational Research Societies)

Preface

Many decision problems have more than one objective that need to be dealt with simultaneously. Risk, Reliability and Maintenance (RRM) are contexts in which decision problems with multiple objectives have been on the increase in recent years. The importance of having a better structured decision process is essential for the success of any organization. Additionally, decisions on RRM matters may affect the strategic results of any organization, as well as, human life (e.g. safety) and the environment.

RRM influences society and organizations in many ways, since companies and governments must satisfy several expectations related to the everyday lifestyle inherent in modern society, such as safeguarding the safety of their employees, their customers and the community they are part of. Such a lifestyle includes new paradigms for judging what level of risk is acceptable and this requires multi-dimensional risks to be evaluated in order to meet society's and regulatory bodies' expectations. Reliability and maintenance have become more important also, since such expectations are extended to the demands that services are constantly available and that products are of a consistently high quality. Therefore, companies strive to reduce costs and simultaneously improve their performance with regard to meeting their strategic objectives. These are affected by reliability and maintenance and include implications for risk, namely that the analysis of risk and reliability demands a more conservative approach as do maintenance policies since failures may have serious implications regarding safety and environmental losses. As a result, MCDM/A approaches are becoming inevitable when modeling strategic problems that involve the RRM context.

This book integrates multiple criteria concepts and methods for problems within the RRM context. The concepts and foundations related to RRM are considered for this integration with multicriteria approaches. In the book, a general framework for building decision models is presented and this is illustrated in various chapters by discussing many different decision models related to the RRM context.

In general, a decision process or problem in the multicriteria context is related to the acronyms MCDM (Multi-Criteria Decision Making) and MCDA (Multi-Criteria Decision Aiding; also known as Multi-Criteria Decision Analysis). The distinctions between these acronyms are not emphasized in this text. Without loss of generality, the acronym MCDM/A is applied throughout the text to represent a variety of approaches associated with MCDM and MCDA (decision making, decision analysis and decision aiding).

The scope of the book is related to ways of how to integrate Applied Probability and Decision Making. In Applied Probability, this mainly includes: decision analysis and reliability theory, amongst other topics closely related to risk analysis and maintenance. In Decision Making, it includes a broad range of topics

in MCDM/A. In addition to decision analysis, some of the topics related to Mathematical Programming area are briefly considered, such as multiobjective optimization, since methods related to these topics have been applied to the context of RRM.

The book addresses the needs of two specific audiences and these include practitioners and researchers of both areas:

- Those dealing with Risk analysis, Reliability and Maintenance areas, who are interested in using multicriteria decision methods;
- Those related to multiobjective and MCDM/A, who are interested in making applications in the contexts of RRM.

Those, who are dealing with decision problems related to the RRM context, in general need to improve their knowledge of multiobjective and multicriteria methods so they can build more appropriate decision models. Also, those dealing with multiobjective and multicriteria decision making area, require to improve their knowledge of the concepts and methods related to the contexts of RRM, so that they can approach decision problems on RRM in a more appropriate way.

The book addresses an innovative treatment for the decision making in RRM, thereby improving the integration of fundamental concepts from the areas of both RRM and decision making. This is accomplished by presenting an overview of the literature on decision making in RRM. Some pitfalls of decision models when applying them to RRM in practice are discussed and guidance on overcoming these drawbacks is offered. The procedure enables multicriteria models to be built for the RRM context, including guidance on choosing an appropriate multicriteria method for a particular problem faced in the RRM context. The book also includes many research advances in these topics. Most of the multicriteria decision models that are described are specific applications that have been influenced by this research and the advances in this field.

The book is not strictly for research and reference by researchers and practitioners. It has potential for use as an advanced textbook for one of the three topics: reliability, maintenance and risk management. That is, it could usefully complement a basic textbook on one of those topics.

The book is implicitly structured in three parts, with 12 chapters. The first part deals with MCDM/A concepts methods and decision processes (Chaps. 1 and 2). The second part corresponds to Chap. 3, in which the main concepts and foundations of RRM are presented. Then, comes the third part, which forms the greatest section of the book (Chap 4 to Chap. 12) and deals with specific decision problems in the RRM context approached with MCDM/A models.

Chap. 1 gives a first view on decision problems with multiple objectives, with a description of the basic elements needed to build decision models. This Chapter is directly integrated with Chap. 2, which focuses on the decision process and MCDM/A methods. Although the description and concepts are given in a general sense, they are focused on the main problems and situations found in the context

that this book explores: risk, reliability and maintenance, although they can be applied to any other context. Therefore, an explanation is given as to why and how MCDM/A arises in the RRM context.

Chap. 2 deals with MCDM/A methods and the decision process. A procedure for building an MCDM/A decision model is presented. Some concerns on the choice of MCDM/A methods are presented, discussing the compensatory and non-compensatory approaches. Although this procedure may be applied to any context, some particular considerations are given to the RRM one. A few MCDM/A methods are presented, the focus being on deterministic additive methods (MAVT) and methods for aggregation in probabilistic context, with a focus on MAUT. Outranking methods are also presented, with some emphasis to ELECTRE and PROMETHEE methods.

Chap. 3 presents concepts of RRM. These concepts should be considered when building RRM decision models in order to indicate procedures and techniques that can be used to calculate and estimate consequences. This allows aspects related to the state of nature and particularities of RRM to be incorporated when modeling a decision problem. Chap. 3 includes techniques for dealing with risk analysis such as the HAZOP, FMEA, FTA, ETA, QRA and ALARP principle; cost effectiveness; and risk visualization. Reliability and maintenance aspects presented in Chap. 3 include random failure modeling, reliability and failure functions, maintenance and reliability interactions, FMEA/FMECA, redundant systems, repairable and non-repairable systems, maintenance goals and maintenance management techniques (TPM, RCM). Additionally Chap. 3 presents techniques for eliciting expert's prior knowledge.

Chaps. 4 to 12 present an integration of the first and second part when considering RRM decision problems structured within an MCDM/A approach, for which formulation and insights for decision problems are given. Chap. 4 presents a multidimensional risk analysis perspective by introducing a general structure for building a multidimensional risk analysis decision model. Based on the structure provided, Chap. 4 presents examples of multidimensional risk evaluation models for natural gas pipelines and an underground electricity distribution system. Other contexts are discussed, the purpose of which is to offer insights on how to evaluate multidimensional risks, such as in power electricity systems, for natural hazards, counter-terrorism and nuclear power.

Preventive maintenance decisions are presented in Chap. 5 with regard to how to go about selecting which is the most suitable time interval for scheduling preventive maintenance actions. This chapter explores the classical optimization approach for preventive maintenance modeling and gives insights on the implications of considering an MCDM/A approach by discussing illustrative applications of two kinds of MCDM/A approaches based on the general procedure for building MCDM/A models presented in Chap. 2.

Condition-based maintenance (CBM) is tackled in Chap. 6, including a discussion of MCDM/A models in CBM. An MCDM/A model is presented including delay time concepts followed by a case study conducted in a power distribution company, thereby illustrating the advantages of considering an MCDM/A perspective.

Chap. 7 presents maintenance outsourcing decisions regarding supplier and contract selection. Throughout this chapter, several criteria for such problems are discussed and five MCDM/A decision models are presented.

Spare part planning models are discussed in Chap. 8. General aspects of approaches to sizing spare parts are presented which gives insights into how an MCDM/A model considers the state of nature over reliability and maintainability, based on the probability of stockout and cost. Another MCDM/A decision model grounded on the same objectives is presented for sizing the need for multiple spare parts for which the case study uses a multiobjective genetic algorithm. Additionally, a spare parts model integrated with CBM is shown.

The allocation of redundancy is discussed in Chap. 9, and takes the combinatorial complexity of these problems into account. Therefore, multiobjective formulations for these problems, found in the literature are presented and the tradeoffs in redundancy allocation are emphasized. An MCDM/A model is presented for a standby system in the context of a telecommunications system of an electric power company with a 2-unit standby redundant system. The model takes interruption time and cost into account.

Design selection decisions are explored in Chap. 10 with a discussion on the roles of reliability, maintainability and risk in system design. Based on these aspects, this chapter includes an MCDM/A model for selecting the design of a car and an MCDM/A model for risk evaluation in design selection and gives illustrative applications.

Chap. 11 consists of MCDM/A models for priority assignment in maintenance planning. An MCDM/A model is presented within the RCM structure to establish critical failure modes considering a multidimensional perspective and this is followed by an illustrative example. The second MCDM/A model presented in this chapter considers the problem of identifying critical devices in an industrial plant. TPM aspects are also mentioned in this chapter and briefly discussed in order to emphasize potential MCDM/A problems that may be addressed.

Chap. 12 presents other RRM decision problems including the location of backup transformers, sequencing of maintenance activities, evaluating the risk of natural disasters, reliability in power systems, integrated production and maintenance scheduling, maintenance team sizing and reliability acceptance testing.

Depending on the reader's background and experience regarding MCDM/A and RRM concepts, a thorough understanding of the first and second parts of the book, respectively, may be required in order to understand the decision models presented in the third part (Chaps. 4 to 12). Otherwise, the reader may dip into Part 3 directly and choose to read any Chapter (Chaps. 4 to 12) without having read

the first three Chapters. However, Chap. 2 is required, if the reader wants to use the procedure for building an MCDM/A decision model even though the reader has good knowledge of MCDM/A concepts.

We would like to thank our colleagues, students and professionals from industry, who jointly worked with us on modeling MCDM/A problems in the RRM context, integrated to the Center for Decision Systems and Information Development (CDSID). In addition, we are grateful to our sponsors (especially CNPq - the Brazilian Research Council) and the business organizations that have supported our research and activities since the 1990s. We would also like to thank the editors of Springer for their professional help and cooperation, and finally, but most of all, our families, who constantly supported and encouraged us in our research work.

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Acronyms

AHP	Analytic Hierarchy Process
ALARP	As Low As Reasonably Practicable
Aneel	Brazilian government agency responsible for regulating the generation of electrical power
ANP	Analytic Network Process
BLEVE	Boiling Liquid Expanding Vapor Explosion
CB	Cost benefit ratio
CBM	Condition-based maintenance
CBR	Case Based Reasoning
CDR	Composite dispatching rule
CDRNRGA	Non ranking genetic algorithm with composite dispatching rule
CDRNSGA-II	Non dominated sort genetic algorithm with composite dispatching rule
CRA	Comparative Risk Assessment
CSE	Concept Safety Evaluation
CVCE	Confined Vapor Cloud Explosion
DEA	Data Envelopment Analysis
DEC	Equivalent to System Average Interruption Duration Index
DM	Decision Maker
DSS	Decision Support System
DT	Delay Time
EC-JRC	European Commission - Joint Research Centre
EHS	Environmental Health Safety
ELECTRE	Elimination Et Choix Traduisant la Réalité
EPDC	Electric Power Distribution Company
ET	Event Tree
ETA	Event Tree Analysis
FAR	Fatality Accident Rate
FEC	Equivalent to System Average Interruption Frequency Index
FFA	Functional failure analysis
FMEA	Failure Modes and Effects Analysis
FMECA	Failure modes, effects, and criticality analysis
FT	Fault Tree
FTA	Fault Tree Analysis
GA	Genetic Algorithm
GD	Group Decision Making
GDN	Group Decision and Negotiation
GIS	Geographic Information System
GIT	Geo Information Technology
GPSIA	Genetic Pareto set identification algorithm
HAZID	Hazard Identification

HAZOP	Hazard and Operability Study
I	Indifference relation of preference
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
J	Incomparability relation of preference
JIPM	Japan Institute of Plant Maintenance
LPP	Linear Programming Problems
M/M/s	A system where arrivals form a single queue, there are s servers and job service times are exponentially distributed
MACBETH	Measuring Attractiveness by a Categorical Based Evaluation Technique
MAU	Multi-Attribute Utility
MAUT	Multi Attribute Utility Theory
MAVT	Multi-Attribute Value Theory
MCDA	Multi-Criteria Decision Aiding; may also be applied to Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision Making
MCDM/A	Indiscriminately applied to MCDM or MCDA
MOCBA	Multiobjective Computing Budget Allocation
MOEA	Multiobjective Evolutionary Algorithm
MOGA	Multiobjective Genetic Algorithm
MOLP	Multi-Objective Linear Problems
MOPSO	Multiobjective Particle Swarm Optimization
MTBF	Mean Time Between Failures
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
Natech	REPRESENTS a simultaneous occurrence of a natural disaster event and a technological accident, both requiring simultaneous response efforts
NCAP	New Car Assessment Program
NORSOK	NORSOK standards developed by the Norwegian petroleum industry
NPD	Norwegian Petroleum Directorate
NPRD	Non-electronic Parts Reliability Data
NRGA	Non ranking Genetic Algorithm
NSGA-II	Non dominated Sort Genetic Algorithm
OEE	Overall Equipment Effectiveness
OREDA	Offshore Reliability Data Handbook
P	Strict Preference Relation
PHA	Preliminary Hazard Analysis
PHM	Proportional Hazards Modelling
PM	Preventive Maintenance
PRA	Probabilistic Risk Assessment
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation

PSA	Probabilistic Safety Assessment
PSM	Problem Structuring Methods
PSO	Particle Swarm Optimization
Q	Week Preference Relation
QRA	Quantitative Risk Analysis
RCM	Reliability Centered Maintenance
RDU	Rank-Dependent Utility
ROC	Rank Order Centroid
RPN	Risk Priority Number
RRM	Risk, Reliability and Maintenance
RUL	Residual Useful Life
S	Outranking Relation
SAFOP	Safety and Operability Study
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SEMOPS	Sequential Multiple-Objective Problem-Solving Technique
SJA	Safe Job Analysis
SMART	Simple Multi-Attribute Rating Technique
SMARTER	Simple Multi-Attribute Rating Technique Exploiting Ranks
SMARTS	Simple Multi-Attribute Rating Technique with Swing
SPEA2	Strength Pareto Evolutionary Algorithm
TPM	Total Productive Maintenance
TTR	Time To Repair
VCE	Vapor Cloud Explosion
VIP	Variable Interdependent Parameters
VTTF	Variance of Time to Failure

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Chapter 1
Multiobjective and Multicriteria Problems and Decision Models

Abstract: The decision-making process for any organization may be a key factor for its success. Many decision problems have more than one objective that need to be dealt with simultaneously. This chapter introduces decision problems with multiple objectives, with a description of the basic elements needed to build decision models and focuses on multicriteria methods (MCDM; MCDA; MCDM/A), in which the DM's preference structure is considered. An overview for classification of MCDM/A methods is given, including a discussion on the DM's compensatory and non-compensatory rationality and on multi-objective and multicriteria approaches. The concepts and basic elements of MCDM/A methods are presented, including preference structures in a multi-attribute context, and intra-criterion and inter-criteria evaluation. The basic elements of a decision process for building decision models and the actors in this process are also presented. Differences between the descriptive, normative, prescriptive and constructivism decision approaches are discussed, considering the decision process. Although these concepts are presented in a general sense, this description deals mainly with the main context that this book explores: Risk, Reliability and Maintenance (RRM). Decision problems in a RRM context may affect the strategic results of any organization, as well as, human life (e.g. safety) and the environment. Therefore, an explanation is given as to why and how a MCDM/A arises in the RRM context. In particular, some peculiarities of service producing systems for MCDM/A models are presented, as well as for goods producing systems.

1.1 Introduction

In order to choose an alternative, from a set of possible alternatives, in a classical optimization problem, there is an objective function to be maximized or minimized, whether this function represents gains or losses, respectively. In a multiobjective or multicriteria problem, there is more than one objective to be dealt with. In many situations these objectives may be conflicting. These objectives are associated with the possible consequences (or outcomes) that will result from choosing an alternative. Therefore, these problems have more than one

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objective function to be dealt with simultaneously. In some particular situations, this means that these objectives are comprehensively optimized. Each objective is represented by a variable, in which its performance for a given alternative can be evaluated. This variable may be called a criterion or an attribute, depending on the multicriteria method used.

The acronyms MCDM (Multi-Criteria Decision Making) and MCDA (Multi-Criteria Decision Aiding) are applied to indicate a decision process or problem in the multicriteria context. MCDA may also be found as standing for Multi-Criteria Decision Analysis. Without loss of generality, the acronym MCDM/A is applied throughout the text to represent a number of approaches associated with MCDM and MCDA (decision making, decision analysis and decision aiding).

The perception of a decision process involving a tradeoff amongst several criteria was put forward since centuries ago.

A text of 1722, by Benjamin Franklin, is regularly quoted to indicate the nature of a multicriteria evaluation for a specific kind of decision problem, which consists of only one alternative, with either of two options: implement it or do not. He expressed this in a letter proposing a decision procedure (Hammond et al. 1998; Hammond et al. 1999; Figueira et al. 2005), as follows:

> "In the affair of so much importance to you, wherein you ask my advice, ... [...], my way is to divide half a sheet of paper by a line into two columns; writing over the one Pro, and over the other Con. [...] When I have thus got them all together in one view, I endeavor to estimate their respective weights; and where I find two, one on each side, that seem equal, I strike them both out. If I find a reason pro equal to some two reasons con, I strike out the three. If I judge some two reasons con, equal to three reasons pro, I strike out the five; and thus proceeding I find at length where the balance lies; and if, after a day or two of further consideration, nothing new that is of importance occurs on either side, I come to a determination accordingly."

Benjamin Franklin called this procedure prudential algebra. Much later on an MCDM/A method, called even swaps, was proposed based on this procedure (Hammond et al. 1998a; Hammond et al. 1999).

An identical perception of evaluation by tradeoff between two set of criteria for choosing a course of action, was made around 300 B.C., by Plato, a Greek philosopher, in the Protagoras dialogue. He proposed putting into the balance the two previous types of criteria Pro (pleasures) and the Con (pains), as follows:

> "I should reply: And do they differ in anything but in pleasure and pain? There can be no other measure of them. And do you, like a skilful weigher, put into the balance the pleasures and the pains, and their nearness and distance, and weigh them, and then say which outweighs the other. If you weigh pleasures against pleasures, you of course take the more and greater; or if you weigh pains against pains, you take the fewer and the less; or if pleasures against pains, then you choose that course of action in which the painful is exceeded by the pleasant, whether the distant by the near or the near by the distant; and you avoid that course of action in which the pleasant is exceeded by the painful. Would you not admit, my friends, that this is true? I am confident that they cannot deny this."