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Risk assessment methodologies in maintenance decision making: A review of dependability modelling approaches

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ABSTRACT

The risk assessment process performs an important role in maintenance decision making, through structuring the process of identifying, prioritizing, and thereafter formulating effective maintenance strategies. However, the effectiveness of the implemented strategies is influenced by the extent to which asset failure dependencies are taken into account during the risk assessment process. In the literature, several risk assessment methods are discussed that vary widely depending on factors such as modelling of failure dependencies in dynamic assets, and treating uncertainties associated with sparse reliability data. These factors invariably influence the extent to which different risk assessment methods are applicable for maintenance decision making. This article reviews the state-of-the-art knowledge on risk assessment in the context of maintenance decision making, with a particular focus on dependability modelling methods. The review structures knowledge on dependability modelling approaches, treatment of uncertainty, and highlights important challenges researchers and practitioners are likely to experience when performing risk assessment in the context of maintenance decision making. The challenges highlighted include the resolution complexity of methods such as Bayesian networks, especially while assessing risks of assets with complex failure dependencies.

1. Introduction

In recent years, a wide range of methods have been developed and applied for assessing risks and safety hazards in diverse sectors such as process industries, or power plant facilities [1]. In the maintenance decision making domain, risk assessment is performed with a view of assisting practitioners systematically identify, analyse, evaluate, and mitigate failure risks in assets [2,3]. Among the most commonly applied methods in this context include the Failure Mode and Effect Analysis (FMEA), Fault Tree Analysis (FTA) and Bayesian network (BN). Of these, the FMEA is widely used for prioritizing equipment failures and selecting appropriate maintenance strategies [4]. However, the FMEA is associated with important deficiencies, and in particular, the conventional form of the risk priority number (RPN), an important metric for quantifying asset failure risk [5,6]. In addition, the FMEA ignores failure dependencies in assets, which in turn, negatively influences the risk assessment process [5].

In the literature, several state-of-the-art reviews of risk assessment methods are presented. Examples includes Li [7] where methods such as Markov models and Monte Carlo simulation are discussed in the context of assessing risks of failure of power utility systems. The reviewed methods, however, insufficiently addressed dependability modelling aspects. In the context of maintenance decision making, Fraser et al. [8] reviewed methods for assessing equipment failure risks and useful for deriving maintenance decisions. Notably the methods are evaluated considering two maintenance concepts; Risk based Maintenance (RBM) and the Reliability Centered Maintenance (RCM). The RCM embeds the FMEA which as mentioned, ignores failure dependency modelling aspects. On the other hand, the RBM approach embeds fault trees, which although models asset failure dependencies, ignores temporal aspects that are crucial for effective risk assessment, and optimal maintenance planning. More recently, Aven [9] reviews trends and advances of risk assessment methods where he evaluates foundational challenges associated with applicability of different methods for decision making. This includes aspects such as treatment of uncertainty, however, failure dependability modelling aspects are not explicitly addressed in the review. Smith [10] also reviews methods applicable for quantifying risks of operable assets characterized with sub-optimal reliability and availability. Examples of methods reviewed includes Hazard and Operability Analysis (HAZOP), and the Fault Tree Analysis (FTA). However, suitability

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Abbreviations

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
AND	AND gate for the static fault tree
BE	Basic Event
BN	Bayesian Networks
BUGS	Bayesian Inference Using Gibbs Sampling
CBM	Condition Based Maintenance
CMMS	Computerized Maintenance Management System
DAG	Directed Acyclic Graph
Dynamic BN	Dynamic Bayesian Network
DIC	Deviance Information Criterion
DSTE	Dempster-Shafer Theory of Evidence
E-M	Expectation-Maximization Algorithm
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis
HAZOP	Hazard and Operability Analysis
IVP	Interval-Valued Probability
McMC	Markov Chain Monte Carlo
MCDM	Multi-Criteria Decision Making
M-H	Metropolis-Hastings Algorithm
OR	OR gate for the static fault tree
PAND	Priority AND Gate
RBD	Reliability Block Diagrams
RBIM	Risk-Based Inspection and Maintenance
RCA	Root Cause Analysis
RCM	Reliability Centered Maintenance
RPN	Risk Priority Number
SPARE	SPARE gate for the dynamic fault tree
SPN	Stochastic Petri-net
TE	Top Event
VOTING	VOTING gate for the dynamic fault tree

of these methods for failure dependability modelling, and maintenance decision support is not sufficiently addressed. Modarres, Zhou et al. [11] evaluates advances in probabilistic risk assessment of safety-critical installations, where the importance of methods such as fault trees and Bayesian belief networks are highlighted for modelling failure dependencies. Similarly, suitability of the reviewed approaches for maintenance decision making is not clearly addressed. A review of fault tree analysis and its application for modelling failure dependencies in complex assets is presented in Kabir [12], likewise, applicability for maintenance decision making is not clearly discussed.

Evaluating the above reviews highlights several limitations or gaps which motivates this review article. Firstly, the reviews tend to focus on specific application contexts such as safety or risk assessment in process industries. However, since risks are domain specific, application of specific risk assessment methods varies depending on the application context [13]. For instance, risks in civil engineering structures such as bridge collapse are rare and periodic, unlike technical failures of mechanical systems, which occurs more frequently over the operational lifetime of the equipment, e.g. bearing wear. Secondly, the reviews insufficiently evaluates the suitability of the reviewed risk assessment methods for failure dependability modelling, especially in the context of maintenance decision making. The decision making aspects may include aiding root cause analysis, or selecting appropriate maintenance strategies.

Hence, this article attempts to bridge the aforementioned gaps by reviewing risk assessment methods discussed in the literature, while focusing on their applicability for maintenance decision support in view of modelling failure dependencies in assets. The review also evaluates how the methods address aspects such as treatment of uncertainty, which in maintenance decision making, is associated with availability and sufficiency of maintenance data. Fig. 1 illustrates the organization of this review. Section 2 reviews dependability modelling concepts where methods such as Fault trees, Bayesian networks, and Stochastic Petri-nets are evaluated. Section 3 reviews concepts for treating aleatory and epistemic uncertainty while Section 4 reviews different Bayesian inferencing methods associated with Bayesian networks. Examples here include methods such as analytic approximation, data augmentation, and Markov chain Monte Carlo simulation. Section 5 reviews methods for quantifying epistemic uncertainties in the context of dependability modelling where methods such as Fuzzy theory, Interval analysis, and the Dempster-Shafer Theory of Belief (DSTE) are discussed. Section 6 discusses the implications of the review for theory and practice, and further points out directions for future research. Section 7 draws important conclusions.

2. Dependability modelling in risk assessment

Technical assets are usually characterized by complex dependencies between system components, which in turn, influences the extent to which asset failure risks are assessed, and maintenance decisions reached [14]. In absence of system dependencies, the risk assessment problem reduces a single component analysis where failure events are assumed as independent. For complex systems dependencies, Weber et al. [15] suggest that dependability modelling should consider the following aspects:

- Complexity and system size,
- Inclusion of temporal aspects and failure propagation in specific time instances,
- Inclusion of empirical and/or qualitative knowledge on failure events at different abstraction levels.
- Inclusion of failure dependencies and treating uncertainties related to data availability, and estimation of model parameters.

Weber et al. [15] further describe several examples of dependability-modelling methods which includes among others:

- Fault trees, further classified into Static and Dynamic fault trees;
- Bayesian networks, classified into Static and Dynamic Bayesian networks;
- Combined Fault trees and Bayesian network models, and
- Stochastic Petri-nets

The following sections reviews the suitability of the above mentioned methods for assessing asset failure risks in the context of dependability modelling and maintenance decision support.

2.1. Fault trees

Primarily, the fault tree models failure dependencies in a hierarchical form, with a top failure event (TE) at the system level, intermediate failure events (IE) at the sub-system levels, and basic failure events (BE) at the component level. The dependencies are modelled through logical AND OR gates. Assuming failure events as statistically independent, the probability of occurrence of the TE modelled through the AND gate is expressed as follows:

$$P(TE) = \prod_{i=1}^{n} P_i \tag{1}$$

The OR gate, on the other hand, presumes occurrence of two or more failure events prior to observing the TE. The probability of occurrence of the TE is hence expressed as the sum of input probabilities of independent BE denoted as:

$$P(TE) = \sum_{i=1}^{n} P_i \tag{2}$$