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Development of a novel methodology for root cause analysis and selection of maintenance strategy for a thermal power plant: A data exploration approach

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ABSTRACT

Performing root cause analysis in technical systems is usually challenging owing to the complex failure associations which often exist between inter-connected system components. The recent adoption of maintenance management systems in industry has enhanced the collection of maintenance data which could assist practitioners derive meaningful failure associations embedded in the data. However, root cause analysis in the maintenance domain is dominated by the use of qualitative and semi-quantitative approaches. Such approaches, however, rely on expert elicitations whereof this elicitation process often introduces bias in the root cause analysis process. On the other hand, quantitative techniques for root cause analysis, for instance, fault trees and Bayesian networks are often limited to analyzing root causes in fairly simple systems. Moreover, the quantitative techniques seldom model the failure dependencies linked to the empirical failure events. Hence, to address these challenges, a novel data exploration methodology for root cause analysis is proposed which consists of four steps: 1) data collection and standardization step; 2) data exploration framework incorporating multivariate and cluster analysis; 3) causal mapping; and 4) maintenance strategy selection. The methodology is demonstrated in the application case of thermal power maintenance data. Moreover, the methodology is compared with two conventional qualitative root cause analysis techniques – Ishikawa cause-and-effect diagram, and the '5-whys' analysis. A detailed discussion is presented whereof the added value of the methodology for maintenance decision support is demonstrated.

1. Introduction

1.1. Background

In maintenance decision making, root cause analysis (RCA) refers to a class of problem solving methods which are aimed at identifying the focal root causes of recurrent equipment failures in technical assets. Empirical studies show that, depending on the operating context, the cost of mitigating failures and their associated impacts often constitute a significant proportion of the total cost of asset ownership [1,2]. For this reason, identifying the root causes of equipment failure is rather important

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because, once identified, maintenance strategies could be implemented more effectively, thereby maximizing equipment availability. In this context, maintenance strategy refers to activities implemented with the objective of maximizing the equipment reliability and availability [3]. Examples of such strategies include the time-based maintenance (TBM), condition-based maintenance (CBM) and design-out maintenance (DOM).

Analyzing root causes of failure in technical systems is, however, challenging for several reasons. Firstly, many technical system consists of intricately interlinked sub-systems and components' and as a result, linking the failure event to the specific root causes is hence challenging [4]. In recent years, however, the increased adoption of maintenance management systems (MMS) has facilitated the collection of maintenance data which could be useful for root cause analysis [5]. Despite the data availability, the root cause analysis process is largely delinked from failure associations embedded in the empirical failure events. Importantly, few data-driven methodologies are reported in the literature which leverage on maintenance data for decision support in root cause analysis [6,7].

By contrast, many techniques reported in the literature for aiding decision support in root cause analysis are largely expert-driven, for instance, qualitative frameworks for root cause analysis, e.g. the Ishikawa cause-and-effect diagram, and the '5-whys' analysis. On the other hand, quantitative techniques such as the fault trees and Bayesian networks are limited to fairly simple system consisting of few interacting components, or logical failure associations. Moreover, the complex failure associations or mechanisms underlying the empirical failure events limits the extent to which conventional statistical approaches such as correlation analysis could be applied for root cause analysis [5].

In recent years, the wide adoption of maintenance management systems, hence the availability of maintenance data has enhanced the potential for applying multivariate analysis and clustering data mining techniques for causal analysis [8]. Indeed, the use of data exploration approaches is reported in the literature in different domains such as, marketing, medical research, and environmental research [9–11]. Their use is also reported for fault diagnosis in condition monitoring signal data, for instance, in vibration signal data collected through sensors attached to mechanical drives [12,13]. However, the application of data exploration approaches is under-reported in the literature, more so, where such approaches are applied with a view of exploring failure associations embedded in the maintenance data. This motivates the work reported in this paper.

1.2. Study aim and motivation for the research

Hence this study is motivated by the need for alternative approaches or methodologies for decision support in root cause analysis. More importantly, this study is motivated by need for data-driven approach which leverages on maintenance data with the objective of deriving meaningful association in the data. Hence from the derived associations, the cause-and-effect relations linked to equipment failure could be mapped, and as a result, the focal root causes of failure identified. Consequently, more effective maintenance strategies could be formulated and targeted at these focal causes.

The proposed methodology starts with data standardization step in which, taxonomical descriptions for failure modes and component failures are adopted from the ISO 14224. Hence, from the standardization, the unstructured maintenance data at the case power plant are interpreted into a more simplified and coherent data structure. Hence, from the simplified data structure, the analysis of failure distribution for the failure modes, component failures, and maintenance activities is performed.

Next, multivariate and cluster analysis is applied to the structured maintenance data. For multivariate analysis, the principal component analysis (PCA) is performed, and here, the PCA explores the failure associations through reducing the dimensionality of the multivariate data [14]. Hence, from the dimensional reduction, the failure associations embedded in the structured data are evaluated through covariance or correlation statistical measures [14]. Four cluster analysis techniques are also incorporated into the data exploration framework: the hierarchical agglomerative, K-means, Fuzzy c-means and self-organizing means (SOM). From the cluster analysis, correlated failure associations embedded in the maintenance data are grouped into distinct clusters, and subsequently interpreted for logic from the operational perspective of the understudied engines at the case power plant.

Thereafter, the interpreted associations forms the input for the causal mapping step where, in this step, the cause-and-effect relations linked to the equipment failure are mapped, and the resulting focal root causes identified. Consequently, appropriate maintenance strategies are assigned to the focal root causes, and here, three strategies are suggested – failure-based maintenance, condition-based maintenance, and design-out maintenance.

The remaining sections of this paper are organized as follows: Section 2 reviews related studies in which techniques for root cause analysis are reported. From the review, gaps in the existing studies are highlighted, hence justifying the need for the methodology proposed in this study. Section 3 enumerates the proposed methodological steps, starting with the rationale for data standardization, data exploration analysis, causal mapping and finally, maintenance strategy selection. Section 4 presents the results derived from the proposed methodology as applied in the application case of maintenance data describing engine failures in thermal power plant. Section 5 reports the results of root cause analysis based on two conventional techniques for root cause analysis – the Ishikawa diagram, and the '5-whys' analysis. Section 6 discusses insights derived from the proposed methodology, with emphasis placed on decision support aspects for root cause analysis and maintenance strategy selection. In addition, the added value for decision support of the proposed methodology as compared to the qualitative conventional techniques is discussed. Section 7 draws important conclusions, study implications and possible directions for future work.

2. Review of related literature

Techniques for root cause analysis for decision support in the maintenance may be classified into three broad categories; qualitative, semi-quantitative and quantitative techniques [7].