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Simulation-based optimisation of maintenance systems: Industrial case studies

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ABSTRACT

Investigating the optimum blend of maintenance strategies for a given manufacturing system is a continuing concern amongst maintenance academics and professionals. Recent evidence suggests that little research is conducted on the simulation optimisation of maintenance in industrial systems. This study was designed to make an important contribution to the field of simulation-based optimisation of maintenance by presenting two empirical case studies: a tyre re-treading factory and a petro-chemical plant. It is one of the first to optimise various maintenance strategies simultaneously with their parameters in industrial manufacturing systems while considering production dynamics. Stochastic Discrete Event Simulation models were developed and connected to a Multi-Objective Optimisation engine. Various maintenance strategies were investigated including Corrective Maintenance, Preventive Maintenance, Opportunistic Maintenance and Condition-Based Maintenance. The results of this research suggest that over-looking the optimisation of maintenance on the strategic level may lead to sub-optimal solutions. In addition, it appears that traditional trade-offs between maintenance cost and production throughput are not present in some maintenance systems. This is an interesting observation that requires further investigation and experimentation.

1. Introduction

Investigating the optimum blend of maintenance strategies for a given manufacturing system is a continuing concern amongst maintenance academics and professionals [1]. Increased throughput, higher asset availability and cost savings are some of the benefits gained from maintenance optimisation.

Industrial systems are becoming more complex making simulation the preferred modelling choice [2–4]. The inherited uncertainty in assets behaviour is one of the main contributors to the complexity of maintenance problems. This is further increased by variations in factors such as operating conditions, production schedules, spare parts policies and dependencies between components which affect the degradation pattern or the main maintenance performance measures. Increasing the number of assets in the system or the number of applicable maintenance strategies and policies will increase the number of decision variables leading to more complexity in the maintenance optimisation problem.

Recent evidence suggests that little research is conducted on the simulation optimisation of industrial case studies [1,5]. This prospective study was designed to make an important contribution to the field of simulation-based optimisation of maintenance by presenting two empirical case studies. The research focus is on maintenance practices rather than particular simulation or optimization tools. Data is collected from a tyre re-treading factory (industrial case A) and a petro-chemical plant (industrial case B). As shown in Table 1 the two case studies were carefully selected to ensure that together they are able to validate the research results for key features in maintenance optimisation problems. The maintenance systems in the case studies vary in terms of sector, size, number of manufacturing processes and level of maintenance documentation. when considered together, the case studies ensure the generality of the research results.

This paper first outlines the methodology including data collection and analysis, the approach to modelling maintenance systems and optimisation algorithms utilised in the study. Sections 3 and 4 present the findings of the industrial case studies. Cross case

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Nomenclature

CBM	Condition based maintenance
CM	Corrective maintenance
DES	Discrete event simulation
GA	Genetic algorithms
LCU	Local currency unit
MOO	Multi-Objective optimisation
MTBF	Mean time between failures
NSGA II	Non-dominated sorting genetic algorithms II
OM	Opportunistic maintenance
PK	Zero-to-peak
PM	Preventive maintenance
SSP	Solid state polycondensation
TTF	Time to failure

List of Notations

i	A single asset in the system where i = 1...n
Labour	Number of maintenance technicians
MA	A single maintenance action resulting from a maintenance strategy
Mc_i	Machine i
MS_i	Maintenance strategy for machine i
n	Total number of assets in the system
$PMfreq_i$	Preventive maintenance frequency for machine i
Q_i	Order quantity for SP_i
s_i	Reorder level for SP_i
SMA	A scheduled maintenance action resulting from a maintenance strategy
SP_i	Spare part for machine i
T	Simulation run length

examination and analysis are conducted in Section 5 and conclusions are presented in Section 6.

2. Methodology

2.1. Data collection

During the initial visits, discussions were conducted to determine which production line will be the focus of the research. That is usually decided based on the most critical assets from the maintenance point of view where maintenance managers are faced with continuous challenges in keeping the equipment available as planned. Interviews and site visits were then scheduled with the relevant production manager to understand the manufacturing process in detail. For data confidentiality purposes, the case studies will be labelled as **industrial case A** and **industrial case B.**

The data was collected mainly from manuals and records. This was further clarified by engineers and managers in the industry. However, if the required data was not available due to poor documentation or confidentiality, approximate distributions such as Uniform or Triangular distributions are utilised by collecting available data such as maximum, mode and minimum values [6].

Collected data included a list of all equipment in the production line, the detailed record for all maintenance interventions including durations, spare parts involved, cost estimations, maintenance technicians as well as PM plans and execution.

2.2. Data analysis

Raw data needed to be analysed in order to use it as an input to the simulation optimisation process. For example, raw data included the start and finish date and time of each maintenance intervention for all assets. Therefore, the durations had to be calculated and separated for each asset. In addition, data for different maintenance strategies had to be categorised and analysed independently.

In order to capture the variability in maintenance systems, stochastic data were fitted into statistical distributions [6]. The analysis included plotting the empirical data in a histogram. A statistical software package (Stat-Fit) was used to auto-fit the empirical data into theoretical distributions. At this stage, transforming some of the input data was required in order to obtain a better fit to theoretical distributions. The suggested distribution was further confirmed via goodness of fit tests as well as various graphical approaches such as Probability – Probability Plot and Quantile – Quantile Plot.

Witness – the simulation software- does not allow imposing minimum and maximum values on some statistical distributions, which presents a risk of producing infeasible high values in the simulation model [6]. Therefore, times for maintenance actions were restricted to the minimum and maximum values found in the empirical data.

If CBM is investigated in the maintenance system, the degradation process of assets needs to be modelled. Condition of assets is monitored by measuring the vibration levels. The convention used is to measure the vibration signal zero-to-peak (PK) regularly in mm/s. It is assumed that only maintenance interventions can enhance the state of assets and that the degradation process is stochastic with independent increments. Therefore, only ascending and stationary trends from the condition monitoring data were analysed. To enable the modelling of degradation increments, the increments are calculated over five day periods. The data points with no increments were considered as 'no changes in the condition indicator'. Minimum, mode and maximum data points are used as an input to a Triangular distribution that defines the degradation of the asset.

Table 1
Main features of industrial cases.

	Industrial case A	Industrial case B
Sector	Tyre re-treading	Petro-chemicals
Company size	Small < 50 employees	Large > 300 employees
Number of manufacturing processes	11	4
Maintenance documentation	Minimal	Updated regularly in SAP
Applicable maintenance strategies	CM and PM	CM, OM and CBM
Optimisation scope	Maintenance	Maintenance
Optimisation objectives	Max throughput Min maintenance cost	Max throughput Min maintenance cost
Decision variables	Maintenance strategy PM frequency Maintenance technicians	Maintenance strategy CBM inspection frequency CBM threshold