A Review of Simulation-based Optimization in Maintenance Operations

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***Abstract*— This paper aims to report the state of the art of research in simulation-based optimisation of maintenance operations by systematically classifying the published literature and outlining various tools and techniques used by researchers to model and optimise maintenance operations. The authors investigate the critical elements and aspects of maintenance systems and how well they are represented in the literature as well as various approaches to problem formulation. On this basis, the paper identifies the current gapsanddiscussesfutureprospects.Itisobservedthatdiscrete event is the most widely used simulation technique while non-traditional optimisation algorithms such as genetic algorithms and simulated annealing are the most reported optimisation techniques. Little attention has been paid to the discussion and analysis of different elements in the maintenance environment andtheireffectonthemaintenancesystembehaviour.Thereis a need for verifying suggested models through real life case studies.**

Keywords- maintenance; simulation; moedlling; optimisation

I. Introduction

As competition is increasing and the financial crisis is hitting businesses around the globe, manufacturers strive to operate more efficiently in order to sustain. This usually means producing more with the same resources or less. Increasingtheefficiencyofmaintenanceoperationsisoneof the potential areas that received growing attention throughout theyears.

Although research on maintenance optimisationwas established decades ago [1], the area of simulation-based optimisationin maintenance is becoming an emerging trend [2;3].Roger[4]definessimulationbasedoptimisationasan approachwherebyanoptimisationengineprovidestheinput factors for the simulation program. The simulation will run and provide the results of the optimisation objective function. This process will continue iteratively between the simulation program and the optimisation engine until it results in a satisfied solution or a termination due to prescribedconditions.

Dekker [1] provided a comprehensive view andanalysis of maintenance optimisation models and applications. It is interesting to note that in his work, simulation has not been mentioned and the emphasis was on mathematical models only.Morerecently,Sharmaetal.[2]observedthatthereisa potentialaswellasagrowinginterestamongstresearchersto utilise simulation in optimising maintenance systems. The advancement in technology enabled researches to use powerful computers and software in continuous decreasing costs. Simulation delivers an advantage over analytical approaches because many maintenance policies are not analytically traceable [3; 5]. Furthermore, it allows experimentation and better understanding of complex systems[6].

On the other hand, Andijani and Duffuaa [7] evaluated simulation studies in maintenance systems in terms of adherence to sound modelling principles such as program verificationandvalidation.Alabdulkarimetal.[8]reviewed the applications of simulation in maintenance systems and categorised it according to the purpose of the study. Their researchconfirmsthatresearchonmaintenancesimulationis steadily rising. Additionally, they observed that research on thecombineduseofsimulationandoptimisationislimited.

It is evident that previous reviews focused either on maintenance optimisation or maintenance simulation. Considering the potential of simulation based optimisation technique in improving maintenance systems, this work is the first to analyse and describe available literature on the combineduseofsimulationandoptimisationinmaintenance operations.

II. Literature ReviewMethodology

A. Research Aim andScope

This research aims to identify and summarise available literature on simulation-based optimisation of maintenance operations. Thus the scope is focused on research that includes building a simulation model of maintenance operations and then connecting the simulation model to an optimisation algorithm.

Research that aims to identify optimal solutions based solely on design of experiments and response surface methodology lies outside the research scope. Similarly, researchthatfocusesonthetechnicalaspectsofmaintenance as opposed to operational aspects is considered irrelevant. There have been attempts to simulate maintenance operations through static system models, usually using monte-carlo simulation [9; 10]. As time is a significant variableinmaintenanceoperations,onlyattemptstomodelit through dynamic system models are within the scope of this research.

B. Research Methodology andResults

A systematic research was conducted by searching for the following keywords in article titles: (maintain* and optim* and simulat*) and (maintenance and optim* and simulat*). The search covered relevant scholarly databases such as Scopus, ABI Inform Complete (ProQuest) and Business Source Complete (EBSCO). After removing duplicate records, the search resulted in 83 documents. Resulting literature was screened first through titles and abstracts to remove irrelevant documents. A further comprehensive screening was conducted through the full documents which yielded 28 articles [11-38].

III. OVERVIEW OFRESULTS

Simulation-based optimisation studies covered a wide range of applications. Roux et al. [23] studied a simple unrepairable system where replacement policies are only applicable. Xiang et al. [11] studied a repairable system where preventive maintenance and condition-based maintenance policies where investigated. The focus ofHani et al. [28] and Allaoui and Artiba [36] research was on maintenanceschedulingbyevaluatingvariouspriorityrules and heuristics. Rezg et al. [31] main focus was on determining the preventive maintenance frequency and buffer size that allows the application of just-in-time configuration efficiently in the production system. Sarkerand Haque [37] examined maintenance spare provisioning policies and its impact on the effectiveness of maintenance operations.However,onthewholetheresearchislimitedin terms of covering main maintenance decisions such as comparing and selecting the optimum maintenance policies in multi-component systems and determining the optimum maintenanceresources.

Case studies were conducted in semiconductor manufacturing systems [13; 16; 35], automotive parts industry [24], plastic industry [26] and train maintenance facilities [22; 28]. It is however, important to note thatmost researchers tended to use academic case studies [17; 19-21; 23; 31; 36;37].

While most studies examined maintenance in a production context, few researchers examined maintenance operations for working products such as ships or aircrafts. Johansson and Jagstam [15] examined military equipment while Gupta and Lawsirirat [29] examined a general multi-component system. Both studies reported the shift towards product service system as the main motivation for their research.ElHayeketal.[30]demonstratedtheeffectiveness of simulation based optimisation for planning maintenance operationsforanaircraftgas-turbine.Itisobservedthatthere areseveraldifferencesbetweenmaintenanceinaproduction contextandmaintenanceinaproductservicesystemcontext. In the former issues such as bottle necks, buffer size and parts waiting in progress have an impact on maintenance planning [12]. In contrast, logistics and transportation are main issues in product servicesystems.

IV. RESEARCH TRENDS IN SIMULATION USEDWITH OPTIMISATION

A. SimulationTechniques

Discrete event simulation dominates the literature as it wasusedaloneorcombinedwithothermodellingtechniques bymorethan70%ofresearchers(seeFigure1).Thisshould notcomeasasurprisesinceitisthemostpopulartechnique in modelling manufacturing systems [39]. Someresearchers combined discrete event simulation with other modellingtechniques to gain further advantages [14]. Xiang et al.[11] and Gharbi and Kenne [32] built a discrete event model to representthegeneralmanufacturingsystemwiththemachine degradation process modelled as a continuous element to reflect the fact that machines age as time passes by. On the other hand, other simulation techniques such as dynamic programming [13; 35], continuous simulation [29], markov chains[33]andpetri-nets[17]werereportedinfewarticles.

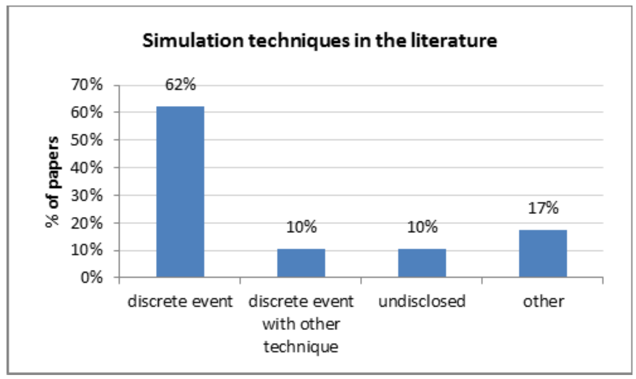

Figure 1. Simulation techniques in the literature (28 papers)

B. Elements Modelled in theSimulation

Modelling maintenance operations was approached differently amongst researchers as they tried to balance between mimicking the behaviour of the real system and makingreasonablesimplifyingassumptions.Thedecisionof including an element should depend on the level of effect it has on the desired simulation output [40]. In general, appropriate discussion and analysis of elements and their effect on the system wasinsignificant.

Figure 2 illustrates the wide range of variances in terms ofelementsconsideredinthesimulationmodel.Theworkof Hennequin et al. [21] proved novel in terms of modellinguncertainty.Fuzzylogicwasincludedinthemodeltor eflect the uncertainty associated with maintenance crew skillsand experiences.

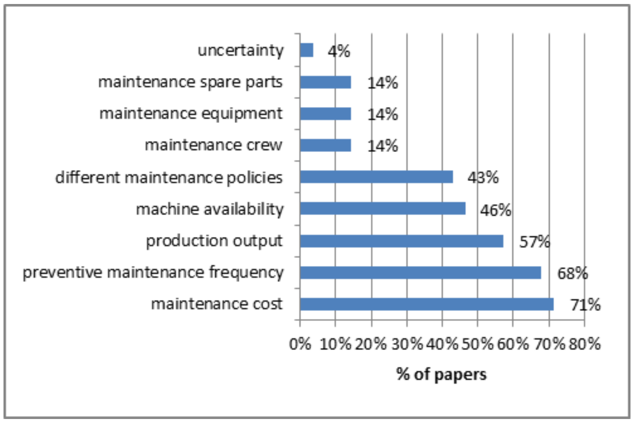

Figure 2. Elements modelled in the simulation (28 papers)

Although maintenance resources such as technicians, spare parts and equipment have a direct effect on maintenance cost and scheduling [41-43], only few researchers incorporated them in the simulation model. In fact, the assumption of readily available maintenance resources is fairly common [12; 14; 23; 31; 36].

Anequallysignificantaspectisthemodellingofmachine aging process. Some researchers simplified it by designing only two states for the machine, either working or broken [26]. Additionally, the machine is regarded as good as new after undertaking maintenance tasks. On the other hand, El Hayek et al [30] considered an improvement factor that incorporates imperfect maintenance. Therefore the machine statusaftermaintenancetaskswillnotberegardedasgoodas new,ratheritliessomewherebetweenabrokenmachineand a new machine depending on the random improvement factor. Furthermore, the duration between preventive maintenancetasksisreducedasthemachineages.

Accurate modelling of machine degradation process becomes essential for examining condition-based maintenance where an inspection is conducted periodically todecidewhichmaintenancetasksshouldbeexecuted[44]. Alternatively,sensorscouldprovideindicatorsonmachines' health such as vibration magnitude and temperature in real time [11]. When indicators' reading exceed a specific threshold, a maintenance task is triggered. Guizzi et al. [20] simulated condition based maintenance via discrete event simulationwiththeaimofinvestigatinghowinspectioncost affects the optimum inspection intervals. In their study, the limitation of discrete event simulation is overcome by triggering special events that increase the machine wear at predetermined intervals. Xiang et al. [11] conducted a comparison between preventive maintenance and condition based maintenance for a single component. Although the applications of condition based maintenance are increasing in the industry [44], it is evident that it is poorly covered in theliterature.

V. RESEARCHTRENSINOPTIMISATION

A. OptimisationTechniques

Similar to simulation techniques, not all researchers disclosed the optimisation technique they used [16; 35; 37]. Manual optimisation was reported extensively where simulation runs were conducted whilst changing variables valuesmanuallyingradualsteps[17;18;31;33].Ascanbe expected, manual search is limited in terms of search space and number of variables. On the other hand, direct search methods such as Nelder-Mead method [14; 23] and cyclic coordinate method [11] were applied to simple manufacturingsystems.

As the complexity of maintenance systems increased[3; 5], non-traditional optimisation algorithms emerged as a betteroptimisationtechnique[38;45].AsshowninFigure3, Non-traditional algorithms such as genetic algorithms [12; 27; 28; 34] and simulated annealing [36] were the most reportedoptimisationtechniques.Alietal.[25]andGuuizzi et al. [20] approach has a significant advantage. In their studytheyconnectedthesimulationsoftwaretoaspecialisedopt imisationtool that allowed the utilisation of multiple optimisationalgorithms including Non-traditional algorithms.

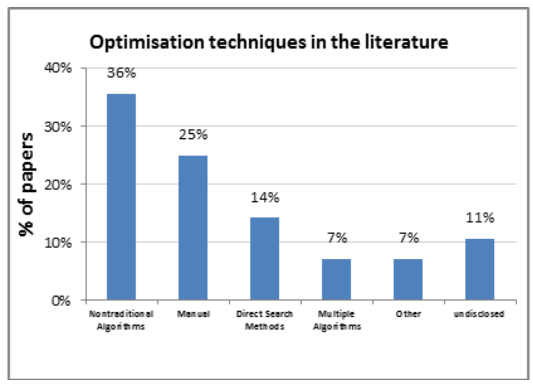

Figure 3.optimisation techniques in the literature (28 papers)

B. Optimisation ProblemFormation

Minimising maintenance cost was reported as an objective in more than 70% of the studies (see Figure 4). In factitwastheonlyoptimisationobjectiveinaroundthirdof thestudies,seeforexample:[11;23;29;34].Arabetal.[12] correctly argues that maintenance is a part of the manufacturing system and considering maintenance cost aloneisnotsufficient.Rouxetal.[14]andBouletetal.[18] included maximising machines availability as an optimisation objective. However, maximum machine availability does not necessarily lead to maximum productionthroughput,whichisanoptimisationobjectivein severalrecentstudies[12;16;17;25].Oyarbide-Zubillagaet al. [24] considered a holistic approach where the total cost and profit of the system is evaluated. The costs of maintenancetasksaswellasdefectiveproductscontributeto thecostfunctionwhereastheprofitiscalculatedbythe number of non-defective items produced. Azadivar and Shu [38] optimised a maintenance system with the objective of maximisingthepercentageofjobsdeliveredontime.

Nearly half of the studies focused on determining the optimum preventive maintenance frequency. Usually reactivemaintenanceisfixedatahighercostthanpreventive maintenance and the optimum preventive maintenance frequency that reduces the total maintenance cost is sought [16; 19; 21; 24]. The work of several authors [17; 31; 38] show that buffer size have an impact on the performance of maintenance operations. Another significant variable that received little attention is maintenance queuing and priority rules.Thismaybeduetothefactthatmaintenanceresources were not considered in the simulation model as shown above. However, it is evident that assigning different priorities to machines when maintenance resources are occupied have a direct effect on maintenance performance [13;17].

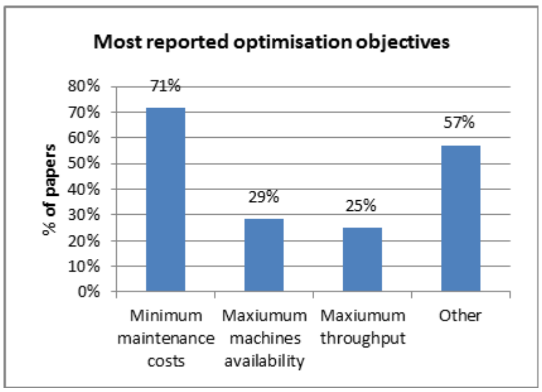

Figure 4. Most reported optimisation objectives (28 papers)

It can be seen from the above analysis that optimal problemformulationvariedsignificantly.Thismightbedue to the nature and purpose of the study. For instance, Ramírez-Hernandez and Fernandez [13] formulated the optimisationobjective purely on production measures namely to minimise both machine cycle time and wait in progress. The purpose of their study could have been to support a quality initiative without a particular interest in cutting maintenance resources in the factory. On the contrary, Hani et al. [22] examined a train maintenance facility where the focus was on minimising the parts immobilization time as well as minimising occupation rates formaintenanceworkshops.Nevertheless,limiteddiscussion of the optimal problem formulation was observed in the literature.

VI. Summary of KeyFindings

Thesystematicliteraturereviewhighlightedanumber of key findings summarisedbelow:

1- Arangeofsimulationbasedoptimisationapplications in maintenance systems across various industries were covered such as semiconductor manufacturing, automotive parts,plasticindustry,trainmaintenancefacilitiesand product service systems such as aircraft gas-turbine and military equipment.

2- Limited research is directed towards supporting maintenancedecisionsattheoperationallevel.Forinstance, comparingandselectingtheoptimummaintenancepolicy.

3- Simulation based optimisation has a significant advantage over mathematical approaches as it is more capable of representing complex systems such as maintenancesystems.

4- Fewreallifecasestudieswerereported.Theacademic cases that dominate the literature such as a single machine producing a single product are oversimplified and do not reflectthecomplexityandinteractionsinrealsystems.

5- A vast majority of researchers used discrete event simulation to model maintenance operations whereas non-traditional optimisation algorithms were the most reported optimisationtechniques.

6- Simulationandoptimisationtoolsandtechniqueswere not alwaysdetailed.

7- Investigating condition based maintenance as a maintenance policy for multi-component systems in a productioncontextispoorlycoveredintheliterature.

8- Successful implementation of simulation based optimisationrequires appropriate discussion and analysis of elements surrounding maintenance operations and their effect on the desiredoutput.

9- Incorporatingmaintenanceresourcesinthesimulation model islimited.

10- A considerable effort wasdirectedtowardsdeterminingtheoptimumpreventivemaintenancefrequency.11- Littleattentionhasbeenpaidtotheutilisationof multipleoptimisation algorithms.

12- The formulation of optimisation problems including choosing the objective function, decision variables and constraints is rarely discussed.

VII. Conclusions and FutureResearch

Theaimofthisresearchistoreportthestateoftheartof research in simulation-based optimisationof maintenance operations by systematically classifying the published literature, outlining research gaps and guiding future research. Simulation based optimisation has been successfully applied to maintenance operations. Despite the limited research in the developing field, it appears to havea high potential due to its ability to model complex maintenancesystems.

The findings outlined in this research provide direction for future work. There seems to be a need for a detailed analysis of factors that have a significant impact on maintenance performance both in a production context and in product-service systems. Similarly, there is a need for a framework that allows experimenting with different maintenance policies, especially condition based maintenance whilst utilising advanced tools that offer multiple optimisation algorithms. More applications can be conducted on real life case studies.

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