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Applications of Simulation in Maintenance Research

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ABSTRACT

The area of asset maintenance is becoming increasingly important as greater asset availability is demanded. This is evident in increasingly automated and more tightly integrated production systems as well as in service contracts where the provider is contracted to provide high levels of availability. Simulation techniques are able to model complex systems such as those involving maintenance and can be used to aid performance improvement. This paper examines engineering maintenance simulation research and applications in order to identify apparent research gaps. A systematic literature review was conducted in order to identify the gaps in maintenance systems simulation literature. The methodology applied identified peer-reviewed papers which were analysed for content and research direction. Simulation has been applied to model different maintenance sub-systems (asset utilisation, asset failure, scheduling, staffing, inventory, etc.) but these are typically addressed in isolation and overall maintenance system behaviour is poorly addressed, especially outside of the manufacturing systems discipline.

Keywords: Simulation, Maintenance, Discrete Event Simulation, Engineering Services.

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1. Introduction

The area of asset maintenance is becoming increasingly important as greater asset availability is demanded. This is evident in increasingly automated and tightly integrated production systems as well as in service contracts where the provider is contracted to provide high levels of availability.

Maintenance is defined by Geraerds (1985) as: “All activities aimed at keeping an item in or restoring it to, the physical state considered necessary for the fulfilment of its production function”. In a highly competitive industrial environment, operations and maintenance are key areas where more proficient techniques can be developed.

As most production expenditure can be predetermined, one of the major issues for cost and performance enhancement is maintenance (Al-Najjar and Alsyouf, 2003) which can account for a significant amount of the total production expenditure (Percy and Kobbacy, 2000; Kothamasu and Huang, 2007). Savings in maintenance cost will consequently lead to the reduction of product costs. Therefore, it is an important area for research focus.

Maintenance activities can be classified into a self-maintenance category where the maintenance team belongs to the organisation and performs different maintenance tasks within the organisation (e.g. manufacturing systems). The other category, field maintenance, is where maintenance is carried out at a remote location (e.g. customer site). The area of Product Service Systems (PSS) (Baines, et al, 2007) deserves a mention here, as it is increasingly being used as a mechanism to provide a service through a product. The product in turn will require maintenance as part of the service provision. Lean manufacturing eliminates waste from manufacturing processes and builds quality which can include maintenance. All business processes in manufacturing must have common goals in lean transformation. It means timely billing just as much as it means skilled, accurate machining and reliable production equipment (Smith and Hawkins, 2004). This applies to service systems as well as manufacturing systems. Thus, the importance of maintenance function has increased due to its role in keeping and improving the availability, product quality, safety requirements, and asset cost-effectiveness levels.

The maintenance function may incorporate different policies including reactive, preventative, predictive, and proactive maintenance (Lee and Wang, 2008). For the proactive policy, condition monitoring is one of the technologies implemented to warn about future failure of equipment. This technology is being used directly by the owning company or provided through contracts, such as MAN Truck & Bus UK and Alstom (Lightfoot et al., 2011), that in turn forms a PSS.

In order to implement PSS effectively, high asset availability is required. Given the complexity of PSS, this may require different maintenance policies. There is a need to understand the whole system performance and the interaction of different aspects (including demand, asset performance, asset location, inventory, maintenance staff and overhaul operations) as constraints may appear in different areas at different times. There is a challenge to implementing PSS as tools are needed to support the assessment need to be developed (Mont, 2002).

A wide variety of tools exist to support the analysis of complex systems such as those involving maintenance from simple static spreadsheet based tools to those incorporating more sophisticated simulation techniques.

Various analytical and statistical modelling approaches have been widely utilised in maintenance research. Queuing theory has been employed as an analytical instrument for various of applications, e.g. telephone traffic, aircraft landing, repair of machinery, and taxi stands (Gross and Harris, 1985). When humans are part of the system, queuing theory considers them to act in a predefined way to satisfy the controlled queue assumptions (Warwick, 2009). In addition, it always assumes that the arrival and service times have particular distributions (Robinson, 2004). Hence, when attempting to model complex systems with bespoke queuing logic, it is difficult to capture and represent complexity using analytical queuing theory. Further, if the probability distribution varies with time, then it may be impossible to generate analytical solutions and for such problems. Simulation would appear a more appropriate tool for such situations (Gross and Harris, 1985). Simulation has been widely used for manufacturing systems as well as defence operations, healthcare services and public services (Jahangirian et al, 2010). It is defined as "experimentation with a simplified imitation of an operations system as it progresses through time, for the purpose of better understanding and/or improving that system" (Robinson, 2004). Simulation techniques have the capability to analyse the performance of any operating system without affecting the real system.

Simulation has two main approaches, namely continuous and discrete, both of which depend on the time varying dynamic behaviour. In the continuous approach, the values gradually change throughout the simulation run (Pidd, 1998). The continuous approach is usually used in maintenance of a single machine and only at the high level maintenance operation in an abstract form. For the discrete approach using Discrete Event Simulation (DES) is based on the assumption that time only exists at determined points, and that events will only take place at these points hence more appropriate for detailed operations systems where each item needs to be traced within the organisation dynamics (Robinson, 2004). This is particularly relevant to maintenance operation systems.

Simulation has been the second most widely used technique in operations management after modelling (Pannirselvam, 1999) and has the potential to represent the complexity of maintenance systems. However, when seen in the context of wider manufacturing analysis, maintenance modelling is poorly covered within the literature. Additionally, very little work has been done to review the applications of simulation in maintenance systems.

This paper focuses on simulation application in maintenance. A literature search was conducted in order to identify the gaps in the literature of simulation in maintenance systems. The method applied identified peer-reviewed papers and analysed them for content and research direction. Eight major categories of the application of simulation to maintenance were uncovered. Despite the significant amount of work in simulation it is apparent there is little documented use in maintenance systems, especially for areas such as field maintenance and maintaining assets under emerging business models such as PSS. This suggests there is potential for research in the deployment of simulation in maintenance systems to better understand and improve the effectiveness of overall operations.

2. Research programme

2.1 Aim, scope, and research questions

The aim of the research presented in this article is to assess the potential contribution that simulation can make to better understand the performance of maintenance operations. The scope of this study is the application of simulation to maintenance systems within a wide range of industrial sectors presented in literature. Only papers that are in the domain of simulation *and* maintenance will be included for further investigations, excluding those pure simulation and pure maintenance.

The authors considered the following questions to guide the search whilst being mindful that the literature obtained may not be sufficient to fully answer them:

1- *What are the applications of simulation in maintenance systems?*
2- *How was simulation applied to different maintenance systems research?*
3- *What are the potential opportunities for research in DES in maintenance systems under emerging business models?*

2.2 Search Strategy

An organised procedure for literature review was adopted to manage the number of papers published in this research area. The conventional method of narrative literature reviews could be affected by preconceived ideas or prejudices by the researcher (Mulrow, 1994; Denyer and Neely, 2004). The organised review theory developed from medical research techniques is attracting interest and understanding in the area of management research (Tranfield et al, 2003; Denyer and Neely, 2004). Systematic reviews “bring together as many studies as possible that are relevant to the research being undertaken, irrespective of their published location, or even disciplinary background” (Thorpe et al, 2005). This has to be carried out in a manner that can create transparency in the decisions made during review, thereby giving the readers opportunity to assess the appropriateness of the studies included as well as the strength of the conclusion (Denyer and Neely, 2004).

The search strategy was developed by first defining the relevant data sources, and keywords. Initially, a wide selection of databases was identified. These databases included ProQuest, EBSCO (E-journals), and Scopus using the following keywords: (simulate* and maint*) or (simulate* and engineering service) or (simulate* and (PSS or Product* Service* System*)).

2.3 Result and Analysis

The search resulted in 74,195 papers and as would be expected from such a generalised keyword search, many papers found were not relevant. Exclusion criteria were applied to provide focus on the interrelationship between simulation and maintenance for engineering services.

This research focuses on the engineering services area and so healthcare operations was outside scope (as they focus on maintaining performance rather than maintenance operations). Those papers were excluded, which reduced the remaining papers to 6,753. Upon reviewing their titles and abstracts, the papers related to the subject area fell to 148 after applying the inclusion and exclusion criteria as shown in Table 1 and Table 2 respectively. The papers were then grouped against their year of publication to assess year-on-year changes of simulation in maintenance publishing. Figure 1 shows an overall growth to date after ignoring most recent years due to timing of literature review (May 2011) and lag in papers being abstracted by databases.

Table 1Domain specific exclusion criteria

Criteria	Reasons for exclusion
Health care	Significant number of the papers appear on the search were related to health care simulation problems (such as emergency department simulation, nursing assignment, etc.) those have to be removed as they did not relate to engineering and would not inform engineering maintenance research.
Pure maintenance papers	This research examines the use of simulation of maintenance systems.
Pure simulation papers	This research examines the use of simulation of maintenance systems.
Maintenance organisation selection	Commercial selection of service providers did not inform how maintenance operations can be modelled for performance and improvement.
All conference papers	Peer review is considered important for research rigour.
All production research papers that takes maintenance into	Such work focuses on production. Maintenance receives an acknowledgement but not detailed assessment.

account in minor way	

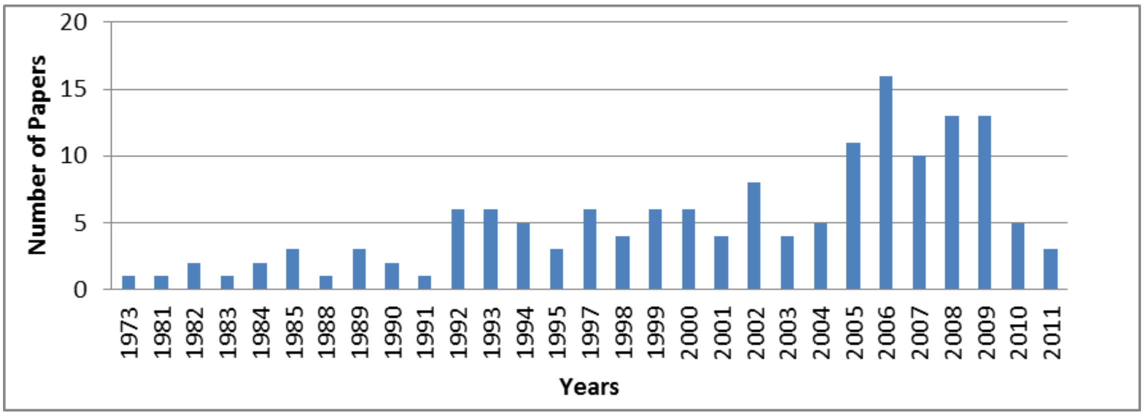

Figure 1 Number of publications over time

According to Andijani & Duffuaa (2002) the purpose of simulation studies in maintenance systems has been classified, evaluated and categorised into: (1) Organisation and Staffing, (2) Evaluation of maintenance policies, (3) Maintenance Planning and Scheduling, (4) Spare parts and material management, (5) Shutdown policies. These five categories are extended by this review. Given in their review category (5) only has one reference and this review retrieved more papers due to the passage of time and key words used, a revised categorisation was developed incorporating (1) to (4) and adding four others. The original categories were used as baseline and the new categories developed reflect a wider review and diversity of the research those new categories were established according to the keywords repeated across the reviewed papers as well as the objectives that those paper trying to achieve. The keywords were used to establish clusters and these were iteratively revised to ensure they were exclusive to one another and could capture all the areas of maintenance in a small number of categories. Classifications of the type of the maintenance research that involve simulation are shown in Figure 2. The instances of papers relating to each category were tallied. Each paper could appear in more than one category; hence the sum of all the categories is higher than the number of papers reviewed. The definitions of each category are given next.

Appendices A and B show the full range of papers examined in this review. Furthermore, each paper was assessed on which maintenance category it belonged to and the type of simulation application.

3. Highlights of simulation applications in maintenance systems

This section will highlight most relevant applications of simulation in maintenance system for each category. There are two main types in applying simulation in maintenance systems:

- The first application is the use of simulation without optimisation for comparison, evaluation, and validation purposes.

- The second application combines simulation models with optimisation techniques to optimise a given problem.

Figure 2 shows the maintenance categories and classifies the number of papers that falls in each application for each category.

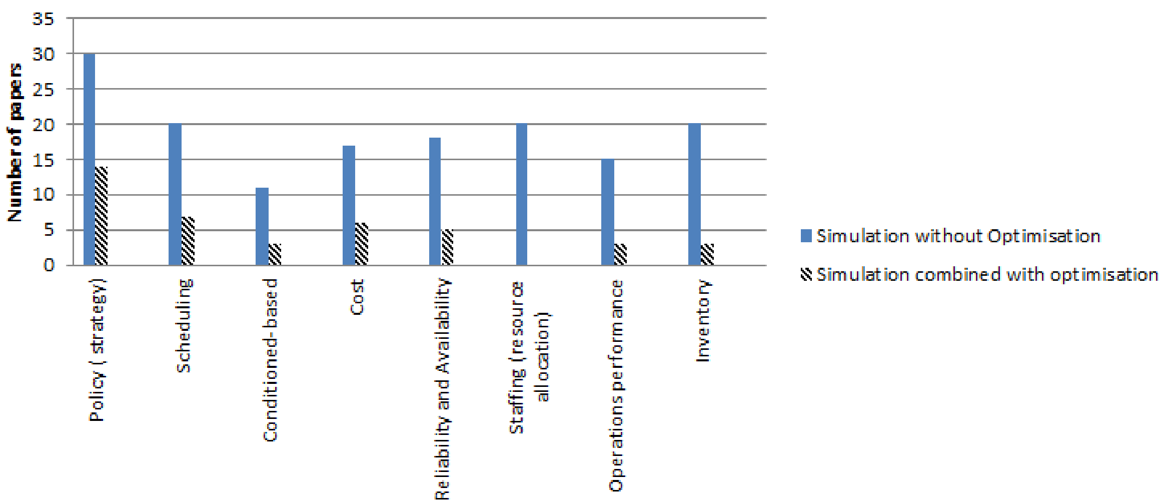

Figure 2 Analysis of number of publications against maintenance categories

3.1 Maintenance policies

Maintenance policies are defined as the components of the framework for maintenance, e.g. proactive, reactive, etc. Maintenance policies are the main research focus identified. Two policies that are commonly considered by simulation are reactive/corrective maintenance and preventive maintenance (Wang, 2002).

The review shows a dominant focus on evaluating traditional maintenance policies, such as preventative and corrective maintenance, within the manufacturing boundaries. One such example is the development of a DES model to evaluate several performance measures to determine optimum operating policies given resource failure (Albino et al, 1992). Here different maintenance policies were assessed in order to better understand their impact on overall system performance for multi-stage manufacturing line. This work and that of Finger and Meherez (1985), Banerjee and Burton (1990), Dekker and Smeitink (1991), Kaegi and Kröger (2009) and Boschian et al, (2009) focused on the preventative and corrective maintenance policies.

One of few examples that have tackled non-traditional maintenance policies is Gong and Tang (1997) who evaluated on-line monitoring of a machine in manufacturing plant for random deteriorations. This and other papers lacked insight into the implications of such policies on maintenance operations in a wider context.

Apart from manufacturing systems, few papers compared maintenance policies in different settings. Chasey et al (2002) developed a simulation framework to understand and quantify the impact of deferred maintenance on highway systems. While Crocker and Sheng (2008) developed a DES model to compare different maintenance policies applied to high value, repairable assets. As with other literature on maintenance, their comparison was mainly on preventative and corrective policies.

One of the few cases of combining simulation with other techniques was Hennequin et al (2009) who proposed a method based upon fuzzy logic and simulation-based optimisation to optimise defective preventive maintenance and remedial steps carried out at single equipment level.

It is evident from the reviewed papers that the main focus of the research conducted on maintenance policies using simulation are within the manufacturing systems boundaries. All of the policies were compared and evaluated in terms of their impact to resource allocations, performance, and cost. The emphasis of the policy evaluation was on traditional maintenance. No papers investigated the use of prognostics technology to warn of next expected asset breakdown and the organisational response to once the asset actual breakdown happens. In light of some businesses moving from selling products to services, there is a lack of understanding on how to evaluate different maintenance policies for products such as after sales services, or maintenance contracts. The main focus is on the production side and whilst this is important, evaluating maintenance policies for products in service that significantly influence performance are neglected. Maintenance is important to assure the production flows smoothly to avoid unexpected stoppage but, evaluating maintenance policies for the products sold is essential as this will influence the reputation of the manufacturer/supplier.

Finding 1: Simulation of maintenance policies outside of manufacturing system boundaries (i.e. field maintenance) receives little attention. Researchers are encouraged to pursue further investigations to evaluate their policies for product maintenance contracts outside the manufacturing plants where more complexity is involved.

Finding 2: Literature shows the application of DES to evaluate traditional maintenance policies is well addressed. However, it is deficient in the assessment of non-traditional policies such as proactive maintenance despite the inherent potential of DES to evaluate the wider system of maintenance.

Finding 3: Maintenance policy selection methods to compare different policies (traditional vs. non-traditional) by DES is absent within manufacturing systems as well as service systems.

3.2 Maintenance scheduling

Maintenance scheduling describes the timing of when activities will take place. It is not restricted to preventative maintenance, as it covers scheduling reactive maintenance and associated maintenance resources. Scheduling maintenance activities is an important area where organisations could save time and money. A number of authors have looked into maintenance scheduling using simulation for validation or comparing purposes such as Percy and Kobbacy, 2000; Baek, 2007; Aissani et al, 2009; Celik et al, 2010. Those papers range from looking into preventative maintenance scheduling to reactive scheduling and at times combination of the two. The focus is generally on preventative maintenance scheduling.

Condition Monitoring (CBM) and its implications to scheduling maintenance activities has been neglected except for the research conducted by Baek (2007) that examined how CBM could influence the reduction of unnecessary preventive maintenance activities to reduce time and cost. CBM assesses the asset condition through real-time monitoring and could have a significant impact on scheduling maintenance activities for reactive as well as preventative policies. Their study shows that intelligent maintenance scheduling approach proposed does not necessarily guarantee an optimal scheduling policy, but from mathematical point of view. But it is verified through a simulation-based experiment that the intelligent maintenance scheduler is capable of providing a good scheduling policy that can be used in practice.

Cavory et al. (2001) optimised a preventative maintenance schedule for single line production using simulation. This shows one of a few examples where simulation is combined with an optimisation techniques. Away from the manufacturing boundaries, few papers have tackled this aspect. Cheung et al (2007) incorporated Genetic Algorithms (GA) to look into aircraft service scheduling by using simulation as a technique to verify their proposed method. Cheu et al (2004) proposed a method to optimise scheduling of highway maintenance to reduce the travel time of vehicles as they involve in lane closures. Their objectives was to minimise the travel time incur by these closures using GA for maintenance scheduling combined with a traffic simulation.

Scheduling is an essential activity as it influences the cost and time through reducing unnecessary preventative maintenance. The literature shows significant research on applying simulation to maintenance scheduling within manufacturing systems and how would that impact the stoppage of production lines while the scheduling of maintenance activities beyond the production side has been very low. Manufacturers/suppliers are now focusing on enhancing their products' performance at customer locations through effective maintenance. CBM has the capability to influence the scheduling activities as it predicts future failure of an asset through diagnostics and prognostics technologies. There is an absence of literature on CBM influence on reactive/correction maintenance scheduling using simulation beyond reducing the preventative activities within manufacturing systems. Scheduling has an important role to reduce the cost and enhance the product performance through the maintenance response time.

Finding 4: It is evident that simulation has been applied in scheduling preventative activities within manufacturing systems but reactive maintenance has received little focus.

Finding 5: Applying simulation on scheduling maintenance activities beyond the manufacturing systems where the focus is the product rather than the production systems is very poor despite the ability of DES to capture the complex dynamic behaviour.

Finding 6: Asset monitoring technologies as in CBM has an impact on the scheduling activities. However, their impact on reactive maintenance has not been investigated through simulation applications within the manufacturing systems context or beyond.

3.3 Condition-Based Maintenance

In recent years, new technologies have been utilised in the area of maintenance. Condition-Based Maintenance (CBM) monitors the condition of a system based upon constant supervision or checking so as to ascertain necessary maintenance before any forecasted breakdown (Grall et al, 2002). Most papers published in this category simulated machine deteriorations, where the emphasis were on machine reliability using continuous simulation (Barata et al, 2002; Marseguerra et al., 2002; Coolen-Schrijner et al, 2006; Caesarendra et al, 2010). The core of literature took a manufacturing systems perspective and there was no wider discussion of CBM strategies to monitor products in use or enhancement beyond reactive strategies. Only Vardar et al. (2007) designed a queuing-location model to assess the adequacy of after sales service providers through information from remote diagnosis tools. While assuming the consequences of congestion, the model optimises the place, capability and the service centre category by means of a simulation optimisation based on genetic algorithms

One of few research papers in the literature has looked into combining CBM as a maintenance policy and the spare part levels (de Smidt-Destombes et al, 2006). They stated that a maintenance policy, spare part levels, and repair capacity can control the system availability. They presented two analytical approaches to evaluate system availability. Their DES model showed the trade-off between inventory, repair capacity, and maintenance policies for the proposed approaches. This work is one of the few to discuss different operational settings together instead of the common practice in the research where each setting is modelled in isolation. Nevertheless, they have not covered all the operational settings, e.g. labour availability. As the complexity of the operational system increases the application of analytical models will be harder (de Smidt-Destombes et al, 2006).

There is potential to apply DES techniques to evaluate different maintenance strategies incorporating all the maintenance operational settings such as asset location, spare part levels, labour availability, travel time to asset, etc. rather than using hard analytical models. The

DES approach will enable organisations to choose the appropriate maintenance policy (reactive, proactive: where CBM is introduced) suitable for their use from operational point of view rather than a machine reliability view. DES technique will enable them to have an understanding of the overall dynamic operation.

Research papers in this category commonly used analytical models. Simulation, where used, was mainly applied as a comparison technique between different models. There are cases where a CBM simulation technique was utilised and the way prognostics technologies are employed in forecasting equipment breakdowns in recent times. This appears to be apt as simulation is an operation performance assessment technique. There are gaps in identifying the performance of maintenance control systems in the move to CBM from reactive maintenance. Papers in this category investigated CBM from an equipment point of view and technicalities. CBM enhancement in context of maintenance operations using simulation, and in particular DES, is lacking.

Finding 7: It is evident that CBM is already implemented in manufacturing systems, however, no discussion is apparent on failure prediction and maintenance of products that are sold to customers located in distributed area and the subsequent organisational response.

Finding 8: Investigating whether implementing diagnostics/prognostics technologies will improve the maintenance operation performance against different performance metrics such as machine down time, maintenance personnel utilisation, availability of spare parts, and maintenance cost using simulation is not well covered in the literature.

There is potential to use DES as the tool to analyse the performance before and after implementing diagnostic and prognostics technologies. DES could evaluate the level of improvement that diagnostics/prognostics technologies can offer over reactive maintenance. This applies to manufacturing systems as well as instances where maintenance is carried out at customer site.

3.4 Maintenance cost

Whilst papers across most maintenance categories used in this research are developed to reduce or optimise the maintenance cost in one way or another, papers falling under this category were those that focused primarily on cost or the assessment of cost.

Boussabaine and Kirkham (2004) presented an innovative simulation based technique utilising a maintenance cost model for a sport centre and argued that the building maintenance expenditure can account for a considerable proportion of the entire life span expenditure. Similarly, Dessouky and Bayer (2002) introduced a simulation with design of experiments modelling approach to shrink buildings maintenance cost. One of the few examples on warranty service was created by Rao (2011) who developed a Decision Support System (DSS) for the repair/replace decisions using the criterion of expected cost of servicing the remaining warranty. Then he used simulation to verify the effectiveness of the proposed DSS. Others have looked into maintenance cost in terms of equipment reliability in manufacturing systems (e.g. Heidergott 1999; Iwamoto and Dohi 2008).

Maintenance costs were investigated throughout different maintenance categories. For example, Chang et al, (2007) have applied simulation to investigate the trade-off between maintenance personnel levels and production line throughput while da Silva et al, (2008) developed a simulation tool to calculate the cost associated with maintenance in a food plant.

As with other maintenance categories, the main focus of the literature is manufacturing systems. Nevertheless, Lanza and Raül (2009) developed a method to enables manufacturers to support their products through service. Their method enables manufacturers to calculate the costs of service contracts during the offer phase. Cost will be determined by Monte Carlo simulation in order to estimate the uncertain forecast. Their research is one of the few in the literature that has incorporated simulation to calculate maintenance contracting.

Cost is a major objective in maintenance research and most of maintenance research aims to reduce the cost by either reducing direct maintenance cost, or through improving machine performance to increase productivity as in da Silva et al (2008). Interestingly, with the introduction of CBM technologies where remote monitoring is possible, there are no apparent discussions on the cost of introduction such sensing technologies for products in use. A question must be raised on the cost efficiency on introducing such technologies for the service contracted product such as the case in PSS.

Maintenance cost optimisation is being investigated through other tools such as linear and non-linear programming (Tam et al, 2006; Adeyefa and Luhandjula, 2011) as it is perceived to be more suitable when dealing directly with cost there appears to be little simulation based assessment. However, simulation techniques have the ability to model system complexity and the key variables that form the cost drivers to in turn evaluate the overall system performance over time. Therefore, simulation is able to capture the complexity and dynamics to investigate the detail of the drivers of the cost performance rather than provide cost only as an output.

Finding 9: Maintenance cost is a major research area with significant work on cost reduction by the introduction of efficient maintenance policies, scheduling, staffing, etc.

Finding 10: DES has the potential to calculate maintenance operation cost, especially to address the cost efficiency of introducing product monitoring (sensing) technologies for product located within customer locations as the case in PSS.

3.5 Maintenance reliability and availability

According to Blank (2004) “the reliability of a process, product, or system is the probability that it will perform as specified, under specified conditions, for specified period of time”. Also, he defined availability as “the per cent of time a product or process is ready for use without expenditure of additional effort or unplanned waiting”. Simulation covers evaluation and optimisation of reliability, with most work on evaluation of the reliability and availability of an operating system. Several authors used simulation to assess reliability (for example Greasley, 2000; Ciarallo et al, 2005; El Hayek et al, 2005; Ke and Lin, 2005; Basile et al, 2007; Chew et al, 2008).

Boulet et al (2009) suggested a multi-objective representation which employs a corrective and preventive model to reduce maintenance expenditure whilst capitalising the availability of the system. Most papers have applied simulation as enabler of their proposed methodologies. Manufacturing system reliability dominates published papers in this category except for one published by Greasley (2000) on assessing the reliability of a train depot maintenance facility to enable service provider bidders greater understanding.

Simulation modelling has an enabler role to proposed methodologies or analytical models of system reliability. There is potential for more research to be conducted on the application of simulation to be combined with optimisation techniques on reliability.

Finding 11: Simulation techniques were employed as an enabler for system reliability research as to verify methodologies and analytical models. As simulation tends to capture the operational side of the system where as analytical models are appropriate for reliability of a machinery systems.

Finding 12: reliability research using simulation has been conducted in manufacturing but little research has addressed systems involving product reliability.

3.6 Maintenance staffing (Resource levels and allocation)

Deciding the number of staff required to conduct maintenance activities efficiently plays an important role. Differing skills between workers and the number of workers will impact on the maintenance cost and asset availability.

Researchers have focused on evaluating staffing configuration in isolation. Al-Zubaidi and Christer (1997) created a simulation model for a specific hospital complex to investigate the potential gain to be realised using different manpower management and operational procedures. They argued that simulation modelling is a suitable tool to analysing complex manpower problems in the area of building maintenance. Mjema (2002) has developed a simulation model to analyse the influences of the exchangeability of personnel (i.e. location flexibility) in decentralised maintenance centres and the flexibility regard the qualification type, and number of personnel on throughput time of the equipment downtime and on capacity utilisation of the personnel. He argues that the location flexibility of personnel is the main factor affecting the capacity utilisation of the personnel, throughput of the work order and downtime of the equipment. A lot of papers published focus away from production systems where the staffing will be critical due to the complexity involved in travel time and skills (e.g. Agnihothri and Karmarkar, 1992; Duffuaa and Andijani, 1999; Antoniol et al, 2004; Agbulos et al, 2006).

Most of the authors did not consider the effect of spare part availability on manpower requirement or utilisation, as in most cases if the spares are not available nothing can be achieved to repair the machine even if the personnel are available. One of the few authors who discussed staffing requirement and spares planning was Danish and Bhadury (1993). They looked into the effectiveness of manpower resources and spares requirement planning through an application for a subsystem of a thermal power unit using simulation. Literature is weak on manpower requirements for more complex maintenance operations when the maintenance centre is dealing with different customers in different locations. One of the few examples on studying the staff resources in very complex maintenance operations beyond the manufacturing systems is Ribeiro et al (2011). They presented a simple robust simulating annealing algorithm to solve a scheduling problem for the workover rigs for onshore oil wells. Finally, Duffuaa and Andijani (1999) present a model to integrate all sub-systems in the maintenance operations for an airline company. Although their integration is complex but was created conceptually.

As can be seen from the literature staffing requirements have been investigated. In light of the modern technologies of monitoring levels, this will have an impact on the staffing requirements but the literature is weak from this perspective.

Finding 13: Evaluation of maintenance staffing is well established in the simulation literature for manufacturing systems as well as outside the manufacturing systems, but it is considered in isolation of other system constraints such as spare part availability.

Finding 14: Despite the introduction of equipment monitoring technologies as in CBM, there is little evaluation of the impact of such technologies on the maintenance personnel levels through simulation modelling.

3.7 Maintenance operations performance

Evaluating and analysing the maintenance performance using simulation has focused mostly on up-time and down-time of machines. Simulation has the ability to model such complex operations and evaluate their performance. This category and unlike other categories of maintenance has the focus outside manufacturing systems.

Perutt and Lau (19820 stated that DES is a right tool to understand and evaluate performance measures in complex systems as highway maintenance operations. They incorporated different dynamic interactions in the system such as (labour and trucks required) while, they neglected inventory impact on such operation. Louit & Knight (2001) developed a simulation model to improve mine maintenance. The fundamentals of an integrated simulation model for SAUDIA airlines were illustrated by Duffuaa & Andijani (1999). In their study, they described planning and scheduling, organisation, supply, quality control and performance measurement modules that made up the integrated model. Along a similar vein, Bengu & Ortiz (1994) proposed a new integrated maintenance operation of a telecommunications system and compared this against the existing maintenance operation using simulation. However, the comparison was limited to manpower requirement and service level.

Agnihothri & Karmarkar (1992) developed a model to evaluate the performance of field maintenance and tested their proposal by employing simulation. From this review it was noticed that little research was conducted in field maintenance. The objective of the maintenance provider may differ commercially from that of the asset operator. This could mean that different elements of the maintenance operation would be measured and optimised independently.

All of these examples are tackling the evaluation of maintenance operation performance. Some has the focus on the staffing requirements (Pruett and Lau 1982; Bengu & Ortiz 1994), scheduling (Hani et al., 2008), or understanding the system behaviour (Mattila et al, 2008).

Monitoring technologies as their implications on maintenance performance using simulation was generally ignored. Of the few papers published, Simeu-Abazi and Bouredji (2006) modelled predictive maintenance of equipment in a manufacturing environment. While, Proactive approach which depends on the actual feedback from the equipment via wireless as in diagnostics/prognostics applications have not been addressed by them.

Finding 15: Papers in this category focus on field maintenance. There is a lack of research of the value that DES can provide to understand the behaviour of complex field maintenance operation with multiple combine components (such as asset location, asset utilisation, staff availability, and stock) and discern the influence on performance of maintenance operations (especially in field maintenance) on scheduling, delays, location of parts, travel time, etc.

3.8 Maintenance inventory

Analysis of inventory of spares for maintenance is the focus of many papers as inventory is sensitive area with regards to cost.

Authors used simulation to assess spare parts management. Dhakar et al (1994). They presented a stock level policy for high value-low demand parts and used simulation to determine the parameters of replenishment policy. Additionally, Lau et al (2006) studied multi-echelon repairable item inventory system under the phenomenon of passivation (where serviceable items are “switched off”) upon system failure. They proposed an efficient approximation model to compute time-varying availability that is validated by Monte Carlo simulation. Other authors have looked into maintenance inventory with simulation and optimisation combination (e.g. Petrović et al, 1982; Kumar et al, 1994; Lin and Chien, 1995; Rezg et al, 2005; Wang et al, 2009) but the instances of this application area were very low. In general the controls systems modelled were simplistic and confined to simple reorder point types.

Chua et al (1993) have formulated a mathematical model for batching policies for repairable (overhauling) spare parts and then examined these policies by simulation. In most cases the inventory system was open-loop except for Chua et al (1993), where the spares inventory was consumed and left the model on failure. Discussion of closed-loop inventory systems where the failed part is repaired and returned to storage as would be the case in Maintenance, Repair and Overhaul (MRO) systems, typical in aerospace and defence sectors, is lacking. Particularly, the interaction of such policies with other system interactions such as labour, and the introduction of CBM is not covered. Whilst there may be examples of modelling the MRO operation in isolation there is a lack of understanding of stock modelling for maintenance of assets where the spares stock is re-lifed using MRO functions.

Finding 16: Closed-loop maintenance inventory modelling (such as MRO systems) is absent in terms of the interactions with other system elements as labour and equipment location.

Finding 17: The impact of CBM technologies on inventory ordering has not been explored.

4. Discussion

This review shows high usage of simulation techniques for the purpose of evaluation, comparison, and validation in maintenance research and this has been increasing steadily over the years. Secondly, there was evidence of some use of simulation combined with optimisation in general. Applications highlighted have included manufacturing systems as the main research focus, with areas such as airline hubs, and highways given lesser attention. Simulation has been applied to different maintenance systems research ranging from policy to inventory analysis. From the analysis potential opportunities for further research have been highlighted and are discussed below.

Simulating traditional maintenance policies (e.g. preventative, reactive) is well addressed in the literature as simulation shows its ability to compare and evaluate different policies within manufacturing systems. However, non-traditional policies of diagnostics/prognostics technologies have not been modelled operationally and compared to traditional policies. Despite that, DES has the potential to assess such policies. Furthermore, different maintenance policies of field maintenance were not assessed.

Little use of simulation in scheduling maintenance activities was found especially in the area of reactive maintenance. Scheduling modelling has been invariably done in isolation of other factors (such as asset location or stock levels). This is particularly so in the areas beyond manufacturing systems where the assets need to be maintained at different customers' sites. Very little work on combining simulation and optimisation techniques for maintenance scheduling is apparent.

PSS concepts place emphasis on the sale of use rather than the sale of the product (Baines et al, 2007) behave as complex systems and their behaviour needs to be understood as different constraints are involved: asset utilisation, asset location, spare parts availability, staffing levels, etc.

This review shows how that most research focused on simulating maintenance operations within the manufacturing systems boundary. Little attention has been given to the maintenance operations in the field, in particular at customers' sites for Product Service Systems (PSS) where through the paradigm of product offering the maintenance ownership is shifted to the separately located manufacturer/supplier. This supports the importance of investigating such service offering beyond manufacturing systems.

It is evident that CBM has been implemented in manufacturing systems. Whilst, CBM has an impact over reactive maintenance scheduling has not been addressed., The literature has not addressed the implementation of such technologies for products in use. There is a need to know how would CBM affect the maintenance operation overall and comparing different levels of asset health monitoring. It appears there has been no work on failure prediction and maintenance of products at customer sites. This is especially so with the rise of emerging business models, e.g. PSS.

This paper finds out that the maintenance cost is a major area of research. Most papers addressing cost reduction by introducing efficient maintenance policies, schedule, staffing, etc. DES is a potiential tool to capture the maintenance operation cost based on dynamic behaviour of the system. DES has potential to address whether it is cost efficient to introduce product monitoring (sensing technologies) for product located within customer locations as the case in PSS.

Simulation techniques were used as an enabler for reliability study to verify a proposed methodologies and analytical models. As simulation tends to capture the the operational side of the system where as analytical models are appropriate for reliability studies in machinery systems. Simulation was used to evaluate reliability research within manufacturing systems, but a few papers used simulation to evaluate the reliability of products.

Mont (2002) stated that tools are required to be developed to face the challenges of PSS implementation. DES is the most employed technique in operations management (Pannirselvam et al. 1999). It would be appropriate to investigate what value DES can provide to understand the behaviour of complex field maintenance that would arise under PSS implementations. Here the manufacturer/supplier is dealing with different customers at different locations to maintain availability of the product in use. It was noted that there is little simulation work in the area of PSS, especially in asset maintenance operations.

Emerging technologies such as diagnostics and prognostics where the asset is able to diagnose the failure cause or to predict the next failure respectively are not well covered by simulation literature. DES could be used to compare different maintenance strategies and to assess the limit of performance improvement that diagnostic and prognostic strategies can offer over a reactive maintenance policy. Simulation metrics that encompass asset availability, maintenance personnel utilisation, availability of spare parts, and maintenance cost are absent from the literature. This applies to both operational efficiency as well as overall business model justification.

Staffing is an important part in any maintenance operation both within manufacturing and beyound. Literature shows weak link to other factors that can affect it indirectly, i.e. location of assets or spare parts availability. Simulation models are mostly created to examine those factors independently and do not evaluate system integrated way, e.g. impact of monitoring technologies on staffing.

Simulating stock levels have been discussed in isolation of other factors in maintenance systems despite some efforts to integrate stock levels with staff levels. Closed-loop modelling (such as MRO) which is applied in high value assets (such as in the aviation sector) and how it would affect the stock ordering have been absent from the literature.

5. Conclusion

This work set out to understand what research has been reported on the application of simulation to support maintenance system design and operation. Simulation is inherently capable of providing significant insight to maintenance systems in the same way it has been proven for the value adding processes in manufacturing systems.

The approach used was to examine peer reviewed literature in a structured and disciplined way to establish the connection between simulation and maintenance. The approach used exclusion criteria to reduce the large number of sources to only those relevant to the area of simulation and maintenance together which resulted in a relatively small sample. This sample of papers was reviewed and categorised for analysis.

The analysis showed that although simulation is being applied in maintenance the dominant applications where elsewhere in the valuing adding processes of manufacturing systems, service systems and their associated support activities. This review shows that simulation has well established link in maintenance research, and the use of simulation in maintenance has been increasing. Simulation has a broad spread of application in maintenance and mostly used as a tool of evaluation with a small number of instances of combining simulation with optimisation approaches such as GA, or analytical models.

A number of key gaps that could warrant further investigation were identified. How to assess the value that can DES provide to analyse such complex maintenance offering beyond the manufacturing systems, including for products under Product Service System (PSS) concept or after sale services needs further work. The use of optimisation with simulation is generally low, particularly in the areas of operations and staffing. The modelling of inventory used for maintenance operations receives little attention even though it has the potential to impact asset repair time. This will be more pronounced where maintenance is part of a service contract for products in the field. Additionally, there is little work on understanding the impacts of using condition based maintenance, especially when moving from a reactive maintenance approach by introducing the technology. Finally, the general area of field maintenance is given little attention and there is little work on response times and contract performance.

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Appendix A: Systematic literature review summary

Table A.1 and table A.2 provides legendary to be used in Table A.3. Table A.3 provide the full list of 148 papers that were examined. Each paper was classified into which maintenance category it belongs to and what application type of simulation was applied.

Table A.1 Legend of maintenance categories

A	General	**B**	Maintenance policy
C	Maintenance scheduling	**D**	Condition-based
E	Maintenance cost	**F**	Maintenance reliability
G	Maintenance Staffing (resource allocation)	**H**	Maintenance operations performance
I	Maintenance inventory		

Table A.2 Legend of the applications type of simulation in maintenance research

1	evaluation, comparison, or validation	**2**	combination of simulation with optimisation techniques

Table A.3 List of papers and their application areas

Authors	A		B		C		D		E		F		G		H		I	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Percy and Kobbacy (2000)					X													
Pruett and Lau (1982)															X			
Seal (1995)															X			
Adamides et al, (2004)															X			
Agbulos et al, (2006)													X					
Agnihothri and Karmarkar (1992)													X		X			
Aissani et al, (2009)					X													
Albino et al, (1992)			X															
Al-Zubaidi and Christer (1997)													X					
Andijani & Duffuaa (2002)	X																	
Antoniol et al, (2004)													X					
Baek (2007)					X		X		X									
Balakrishnan et al, (2006)			X															
Banerjee and Burton (1990)			X										X					
Barata et al, (2002)							X											
Barnett and Blundell (1981)													X					
Basile et al, (2007)											X							
Bengu and Ortiz (1994)															X			

Authors	A		B		C		D		E		F		G		H		I	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Boschian et al, (2009)			X															
Boulet et al, (2009)										X		X						
Boussabaine and Kirkham (2004)									X									
Bris et al, (2008)										X		X						
Burton et al, (1989)					X													
Caesarendra et al, (2010)							X											
CASSADY et al, (2000)				X														
Cavory et al, (2001)						X												
Celik et al, (2010)					X													
Chang et al, (2007)									X				X					
Chasey et al, (2002)			X						X									
Chen and Tseng (2003)										X						X		
Cheu et al, (2004)						X												
Cheung et al, (2005)					X													
Chew et al, (2008)											X							
Chootinan et al, (2006)						X												
Chua et al, (1993)					X												X	
Ciarallo et al, (2005)											X							
Coolen-Schrijne et al, (2006)							X											
Crocker and Sheng (2008)			X															
da Silva et al, (2008)			X						X									
de Smidt-Destombes et al, (2006)							X				X						X	
de Smidt-Destombes et al, (2007)											X						X	
Dekker and Smeitink (1991)			X															
Deris et al, (1999)					X													
Dessouky and Bayer (2002)									X									
Dhakar et al, (1994)																	X	
Duffuaa and Raouf (1992)													X					
Duffuaa et al, (2001)	X																	
El Hayek et al, (2005)											X							
Finger and Mehrez (1985)			X															
Gertman (1992)													X					
Gharbi and Kenne (2005)				X						X								
Gong and Tang (1997)			X				X		X									
Greasley (2000)											X				X			
Guarnieri et al, (2006)					X								X					
Gupta and Lawsirirat (2006)						X												
Taha et al, (1989)											X							
Hani et al, (2008)						X										X		
Heidergott (1999)									X									
Hennequin et al, (2009)				X														

Authors	A		B		C		D		E		F		G		H		I	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Humphrey et al, (1998)																	X	
Iwamoto and Dohi (2008)									X									
javadpour and knapp (2003)							X											
Joo et al, (1997)			X															
Kaegi et al, (2009)			X								X							
Ke and Lin (2005)											X							
Kenne and Gharbi (1999)				X														
Kilpi et al, (2009)			X														X	
Kim et al, (1994)						X												
Kuei and Madu (1994)												X						
Kumara et al, (1994)																		X
Kurien et al, (1993)											X							
Langer et al, (2010)			X															
Lanza and Ruhl (2009)									X									
Lau et al, (2006)																	X	
Lavy and Shohet (2007)									X				X					
Lei et al, (2010)			X															
Li & Ni (2009)			X															
Liao et al, (2009)			X				X											
Lin and Chien (1995)				X														X
Logendran and Talkington (1997)			X															
Louit and Knights (2001)															X		X	
Madu and Georgantaz (1988)			X															
Madu and Kuei (1992)			X															
Madu and Kuei (1993)												X						
Madu (1999)			X										X					
Madu et al, (1990)															X			
Marquez and Lung (2007)											X							
Marquez et al, (2005)			X															
Marquez et al, (2006)					X													
Marseguerra and Zio (2000)				X														
Marseguerra et al, (2002)								X										
Mathew and Rajendran (1993)					X													
Mattila et al, (2008)			X								X		X		X			
Michaelides et al, (2003)																	X	
Mjema (2002)													X					
Mohanty (1989)					X													
Mosley et al, (1998)					X													
Newman (1985)																	X	
Ng et al, (2008)							X											
Ntuen and Park (1999)													X					

Authors	A		B		C		D		E		F		G		H		I	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Oke and Charles-Owaba (2006)					X													
Oke (2005)									X									
Okogbee and Huang (1992)			X															
Oyarbide-Zubillaga et al, (2008)				X														
Padalkar et al, (1995)							X											
Petrovic et al, (1982)												X						X
Pulcini (2001)											X							
Quintana et al, (2009)					X				X		X				X			
Radhoui et al, (2009)				X														
Rao et al, (2007)											X							
Rees et al, (1984)									X									
Rezg et al, (2005)				X														X
Rishel et al, (2006)			X						X									
Roux et al, (2008)				X											X			
Sarker and Haque (2000)			X														X	
Savsar (1997)			X										X					
Savsar (2005)				X														
Savsar (2006)				X														
Scudder (1984)					X												X	
Semra (1993)			X												X			
Dinesh and Bhadury (1993)													X				X	
Sheu and Lin (2006)					X													
Simeu-Abazi and Bouredji (2006)															X			
Sleptchenko et al, (2002)																	X	
Sloan and Shanthikumar (2002)			X															
Smith (1973)					X													
Sohn and Oh (2004)															X			
Spanjers et al, (2005)																	X	
Sun et al, (2007)											X							
Szczerbicki and White (1998)							X											
Tersine (1983)			X															
Vardar et al, (2007)								X		X								
Verrijdt et al, (1998)																	X	
Vineyard et al, (2000)			X															
Wang and Mao (2008)							X										X	
Wang et al, (2009)				X				X										X
Yang et al, (2005)					X				X									
Yang et al, (2008)					X													
Yun et al, (2008)											X		X				X	
Zhou et al, (2006)			X															
Zhou et al, (2007)				X						X								

Authors	A		B		C		D		E		F		G		H		I	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Zhou et al, (2009)						X												
Zijm et al, (2003)																	X	
Duffuaa and Andijani (1999)															X			
Berthaut et al, (2011)			X						X								X	
Ribeiro et al, (2011)													X					
Rao (2011)									X									
Fallah-Fini et al, (2010)																X		

Appendix B: References for the systematic literature review

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