UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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SYSTEM PERFORMANCE EVALUATION THROUGH PREVENTIVE MAINTENANCE SCENARIOS USING SIMULATION TECHNIQUE

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SYSTEM PERFORMANCE EVALUATION THROUGH PREVENTIVE MAINTENANCE SCENARIOS USING SIMULATION TECHNIQUE

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DECLARATION

I declare that this thesis entitle "System Performance Evaluation Through Preventive Maintenance Scenarios Using Simulation Technique" is the results of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ……………………………………………………….

Name : ……………………………………………………….

Date : ……………………………………………………….

APPROVAL

I hereby declare that I have read this dissertation/report and in my opinion this dissertation/report is sufficient in terms of scope and quality as a partial fulfilment of Master of Manufacturing Engineering (Manufacturing Management).

Signature : ………………………………………………….

Supervisor Name : ………………………………………………….

Date : ………………………………………………….

DEDICATION

To my beloved father, mother, and siblings.

Non scholae, sed vitae discimus.

(We do not learn for the school, but for life)

- Lucius Annaeus Seneca

CHAPTER 1

INTRODUCTION

1.1 Introduction

Equipment is one of the major contributors to the performance and profitability of manufacturing systems and its importance is rather increasing in the growing advanced manufacturing technology application stages (Kutucuoglu *et al*., 2001). The equipment is subject to deteriorations and failures as the consequence of usage, aging, fatigue, environmental conditions or other extreme events. Such system deterioration may lead to higher production cost, lower product quality and increase probability of breakdown (Mobley, 2002).

Unexpected breakdowns not only increase the operating cost of the productive machines but in fact, the cost of lost production is inevitable for operation interruptions. Scheduled downtime is to control when the system will be down in favour of production. According to Ali *et al*. (2008), downtime will be more predictable if preventive maintenance is employed. The area of asset maintenance is becoming increasingly important as greater asset availability is demanded. Effective maintenance management is essential and critical as a way to reduce the adverse effect of equipment failures and to maximize equipment availability (Muhammad *et al.*, 2010). The ultimate goal of maintenance is to provide optimal reliability and availability of production equipment, and maintain its operability to meet the business needs of the company.

From strategic or philosophical points of view, most of the relevant maintenance practices can be classified into two general categories, preventive maintenance (PM) and corrective maintenance (CM), also known as unplanned maintenance. Brown (2004) emphasized that unplanned maintenance arises when equipment is repaired as it fails, usually on an emergency basis and the downtime incurred by the operation usually occurs at an inopportune moment and can also cost money because of lost business. On the other hand, PM is defined as the maintenance carried out according to a predetermined time schedule or a prescribed criterion with a goal to reduce the probability of failure or the performance degradation of the system (Smith and Hinchcliffe, 2003).

Through the last decade, an increasing number of organizations switched from conventional approach of fixing the equipment after failure into preventive action. PM is important to ensure efficient operation. Nevertheless, if PM is applied too frequently, down-time due to maintenance interruptions will increase while down-time to sudden breakdown will decrease. On the other hand, if PM is applied on rarely, down-time due to maintenance interruption will decrease while down-time due to sudden breakdown will increase (Bahrami-G *et al.,* 2000).

The most important problem is to determine when and how to maintain preventively units before failure. However, it is not wise to maintain units with unnecessary frequency. Taking equipment down unnecessarily to perform maintenance that is not yet required is very expensive due to production lost and cost incurred for unnecessary maintenance. Reported survey of maintenance management effectiveness indicate that one-third—33 cents out of every dollar—of all maintenance costs is wasted as the result of unnecessary or improperly carried out maintenance (Robertson and Jones, 2004, cited in Jardine and Tsang, 2006). Hence, finding the ideal preventive maintenance intervals timing is crucial to eliminate the unnecessary maintenance.

Determination of optimal timing of the PM action can be estimated analytically for a simple system. To date, researchers seek for various methods including mathematical models, heuristic techniques and metaheuristic approach's to find the optimal solutions for this problem. On the contrary, for a more complex system, simulation allows the determination of these timings (Garg and Deshmukh, 2006). One of the simulation is discrete event simulation model, constructed of real-life system allow us to observe the changing behaviour of the system over time about the required performance measure. In addition, simulation is appropriate to perform experiments on the simulation model that would be too expensive, too dangerous, or too time consuming to perform on real system (Ben-Daya and Alghamdi, 2000). In this research, the simulation approach in finding the ideal timing for PM is explored.

1.2 Problem Statement

The research is based on the case study at Push Pickling Line (PPL), CSC Steel Holding Berhad, Ayer Keroh, Melaka. The product range includes hot-rolled pickled and oiled steels, automotive wheels, strapping, tubing, racks and automotive inner stamping parts. According to the PPL production records, the total production capacity is approximately 30,000 units annually and the demands are notably increasing every year. The basic problem of the current manufacturing system is that the production capacity does not meet the future business environment, so the current system has to be improved significantly.

Since the significant raise of the product demand in the past 3 years, PPL is facing the problem in improving their production capacity in order to meet the demand. One is by improving their machine reliability and availability through PM. The sound and healthy machines are the key factor for the PPL to produce higher production.

Present, PM intervals are partially established by experience. Depending on the inspection results over a period of several intervals, the technician may decide to keep the same interval, increase the interval, or decrease the interval. There is no statistical analysis to determine when the ideal timing for each machine is and which component to undergo PM.

PPL is a complex system consists of a structure of 36 machines with 19 components, which performs a particular function. All the machines are arranged in series layout with a standby redundancy on one of the component. CM and PM operations on serial lines can cause significant production losses, particularly if the production stages are rigidly linked. The reliability and availability of such system are very much affected by the machine failures. This is because whenever a machine in the system is broken down, then the whole production line is stopped.

In determining the best PM model for the machine, experimentation on the real system would be inappropriate because of the risk and time factor. To solve the problem mathematically would be time consuming, and might be complicated to be solved. A method in assessing the current system's failure and repair performance is crucial and the experimentation without interrupting production is an advantage.

1.3 Research Objectives

The aims of this research are to:

1. Develop a simulation model of the existing PPL manufacturing system to represent the base maintenance system.
2. Perform "what-if" alternative experimentation of preventive maintenance in the validated model, and to evaluate the system performance of alternative preventive maintenance models.

3. Assess and compare the performance criteria of proposed alternatives. The performance measures in this research are including frequency of preventive maintenance and corrective maintenance, system downtime, availability and throughput.

1.4 Scope of the Research

A discrete event simulation (DES) model will be developed using commercial simulation software, WITNESS PwE® to replicate the real manufacturing system and to observe the behaviour of the machines' failure over time. This research is taken at a steel manufacturing company. Specifically the case study is carried out at PPL production.

The research is only concentrate on the maintenance aspect of this factory, in this case preventive maintenance of PPL. The study will focus on the savings aspect in terms of production time, specifically the down time, and systems availability, however the cost aspect of preventive maintenance is not considered.

The research assumes that any spare parts needed for maintenance are available. Any delayed during repairs are not considered in the study. It is assumed that the crews are always available in terms of their skill and number whenever maintenance actions are needed.

1.5 Significant of Research

This research will perform experimentation for a case study of a real manufacturing system using DES method. The focus is on developing the PM model on the system that is able to improve the performance of the system. Experimentations will be developed based on 'what-if" scenarios and the performance measures will be created to evaluate each of the scenarios. In general, the result of the study will contribute to the body of knowledge featuring the redundancy design, grouping maintenance policy, and reliability theory in developing PM model. Referring to the reviewed literatures, there has not been any published research combining these options in the studies for performances improvement.

In particular, the result of the research will contribute the organization under studies a valuable input and consideration for supporting their decision making process in improving the PM management and the performance of the system. Developed models can be used to study the failure behaviour of the systems and predict the breakdown of the machines in the future. The result PM simulation may be used by the organization reduce their down time, which in turns will increase productivity.

1.6 Outline Structure

The structure of the thesis is as follows. Chapter 2 provides the detail definition of the maintenance, PM, CM, and reliability terminologies. The current developments on the subject of PM models are discussed. The gap of knowledge in solving PM and reliability problems are identified. Chapter 3 maps out the research steps and methodology. The conceptual model and data analysis are presented in Chapter 4. The conceptual model comprises the case situation and the formulation of the failure and maintenance actions. The input data analysis emphasises on the data testing and distribution analysis of the simulation input data. In Chapter 5, the development of the simulation model and the experimental models are explained. The results and analysis of the simulation output are presented in Chapter 6. Finally, Chapter 7 gives the concluding remarks on the research and the directions for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The first section in this chapter defines the term maintenance, preventive maintenance, corrective maintenance and reliability and total productive maintenance. Section 2.3 presents the review on various techniques and models related to preventive maintenance issues. In section 2.4, the key works that utilize Monte Carlo and discrete event simulation model are reviewed. Section 2.5 emphasizes on the emerging issues and the gap of knowledge.

2.2 Background on Maintenance and Reliability

Today as more and more factories employ new technology, the need for highly effective maintenance management becomes crucial. This is due to the fact that the failure of even a single component will not only idle the machine and facility but also the failure can quickly idle the entire production system. The failure may come from lack of maintenance, improper or intensive operation, unstable operating environment, and so on (Sharma *et al*., 2011). According to Wireman (2004), maintenance is a unique business process. It requires an approach that is different from other business processes if it is to be successfully managed. Levitt (1997) described maintenance as war. The enemies are breakdown, deterioration, and the consequence of all types of unplanned event.

Levitt (1997) briefly defined maintenance as acting in the act of holding or keeping in a preserved state of the asset to avoid the failure. In detail definition, according to the European Standard of Maintenance Terminology, EN13306, (2001, cited in Manzini *et al.*, 2009) , maintenance is the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function. Maintenance is distinguished into two main types as preventive maintenance (PM) and corrective maintenance (CM), as shown in Figure2.1.

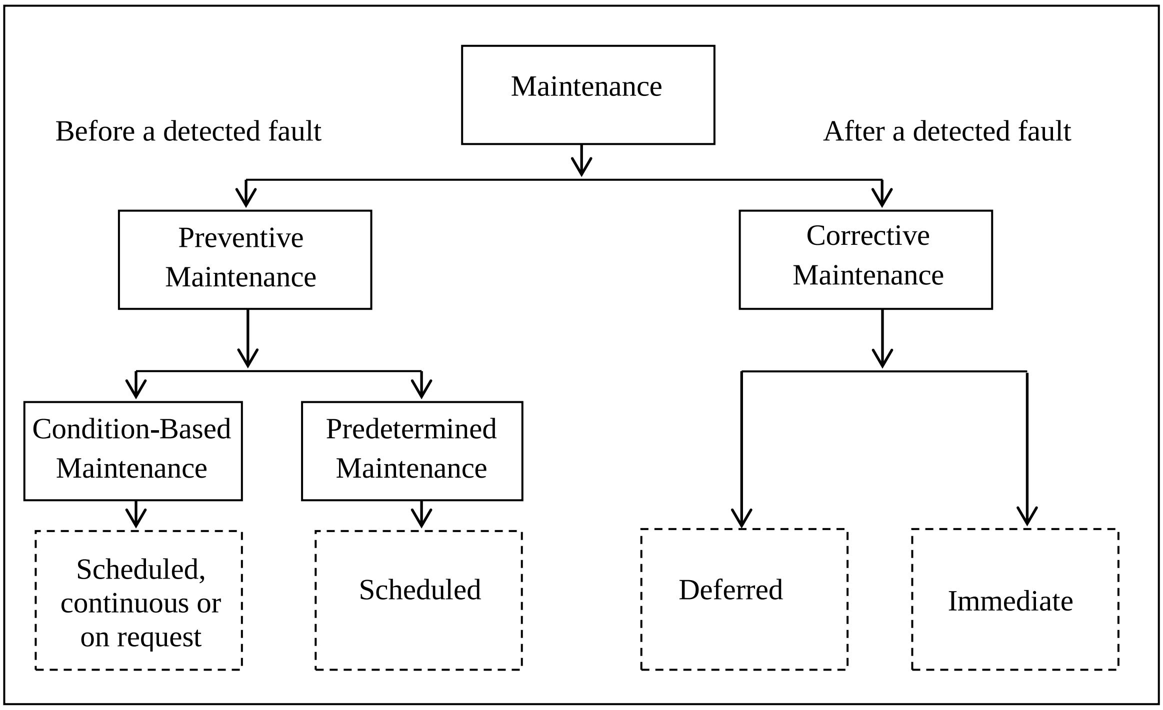

Figure 2.1: Maintenance strategies (EN 13306, 2001 cited in Manzini *et al.*, 2009)

When a unit is repaired after failure, CM is done and it may require much time and high cost. In particular, the downtime of such systems as computers, plants, and radar should be made as short as possible by decreasing the number of system failures. In this case, to maintain a unit to prevent failures, PM is needed, but not to do it too often from the viewpoints of reliability and cost (Nakagawa, 2005).

2.2.1 Corrective Maintenance

Corrective maintenance (CM) is initiated after fault recognition and intended to put an item into a state in which it can perform a required function (EN 13306:2001 Maintenance Terminology, cited in Manzini *et al.*, 2009). Vineyard *et al.* (2000) highlighted that CM is performed only when machine is failed. This policy usually requires operating in an emergency mode with an aim of getting the equipment back in service as quickly as possible and virtually new condition.

The purpose of CM is improving equipment reliability, maintainability and safety; design weakness (material, shape); existing equipment undergoes structural reform; to reduce deterioration and failures, and to aim at maintenance-free equipment (Ahuja and Khamba, 2008.

According to Blischke and Murthy (2003), in the case of a repairable product, the classification of CM referred to the behaviour of an item after a repair depends on the type of repair carried out. Various types of repair action can be defined:

1. Good-as-new repair: Here, the failure time distribution of repaired items is identical to that of a new item, and we model successive failures using an ordinary renewal process.
2. Minimal repair: A failed item is returned to operation with the same effective age as it possessed immediately prior to failure. Failures then occur according to a nonhomogeneous Poisson process with an intensity function having the same form as the hazard rate of the distribution of the time to first failure. This type of

rectification model is appropriate when item failure is caused by one of many components failing and the failed component is replaced by a new one.

3. Different-from-new repair (1): Sometimes when an item fails, not only are the failed components replaced, but also others that have deteriorated sufficiently. The mean time to failure of a repaired item is assumed to be smaller than that of a new item. In this case, successive failures are modeled by a modified renewal process.
4. Different-from-new repair (2): In some instances, the failure distribution of a repaired item depends on the number of times the item has been repaired.

2.2.2 Preventive Maintenance

Preventive maintenance (PM) is considered as an activity that improves a system's reliability as well as its service life. A sound PM is essential to improve the performance for a manufacturing environment. The cardinality of PM is realized by both researchers and practitioners (Raza and Al-Turki, 2007). Bevilacqua *et al.* (2005) stated that a good PM program may be discriminated by observing the number of unscheduled downtime and breakdowns occurring, which clearly indicated that the whole system is not running as it should.

The first class of PM is the so-called statistically and reliability based PM, which mainly refers to the analysis of the equipment historical records. PM is any planned maintenance performed to counteract potential failures. It can be implemented based on use or equipment condition. Time- or use- based PM is performed on an hours-run or calendar basis. It needs a high level of planning. The specific routines to be carried out are known as well as their frequencies. In determining the frequency, knowledge about failure distribution or equipment reliability is usually needed (Duffuaa *et al.*, 1999).

The timing of the time- or use- based PM action is scheduled before failure on usage (hours, miles, and output), calendar time, or some combination of these. The cost effectiveness of this maintenance will depend (among other things) on the predictability of time-to-failure of the item concerned, such as on the dispersion, or spread, of the distribution of observed time to failure (Kelly, 1997).

Another class of PM is condition-based PM, carried out on the basis of the continuous monitoring and knowledge of operating condition and performance of the equipment. The condition of the equipment is determined by monitoring key equipment parameters whose values are affected by the condition of the equipment. This strategy is also known as predictive maintenance (Dufuaa *et al.*, 1999).

PM actions generally require shutdown of an operational system and are intended to increase the length of its lifetime and/or its reliability. Actions range from relatively minor servicing requiring a short downtime, such as lubrication, testing, planned replacement of parts or components, and so forth, to major overhauls requiring a significant amount of downtime (Blischke and Murthy, 2003).

The development of an effective PM program keeps the equipment at a high level of overall effectiveness (Ben-Daya, 2000). A good PM program provides interval or timed servicing of the equipment so the components can be replaced as they wear. Cleaning, lubricating, adjusting, inspecting, repairing, replacing, and testing can decrease deterioration (Besterfield *et al.*, 2003).

Even though they make the production system unavailable for certain periods, PM operations are absolutely necessary to reduce the number of failures whose human and economic consequence may be very important in an industrial context (Boschian *et al.*, 2009)

2.2.3 Reliability

Reliability is a characteristic of an item, expressed by the probability that the item will perform its required function under given condition for a stated time interval. From a qualitative point of view, reliability can be defined as the ability of an item remains functional. Quantitatively, reliability specifies the probability that no operational interruptions will occur during a stated time interval (Birolini, 2004).

Manzini *et al.* (2009) highlighted that the aim of reliability theory is to study the failure behaviour of components, such as part of a production system, and the failure behaviour of complex systems in order to guarantee that they function correctly during a period when they are in operation. The applications of theory of reliability in improving PM systems are including the interval reliability and a two-unit standby system (Nakagawa, 2005)

The importance of measuring reliability is closely related to risk determination and control the generic risk event is related to the quantification of a probability, i.e., the reliability, and simultaneously the magnitude of the consequences. The importance of reliability also finds justification in the continuous quality control and improvement of the products/services, process, and production systems, and safety requirements and expectations: the more complex the product is, the larger the number of laws and regulations the product must comply with (Nakagawa, 2005).

2.2.4 Total Productive Maintenance

Total productive maintenance (TPM) is universally defined as a productive maintenance technique that is made up of a set of activities to be performed by every operator in order to get zero defects (Manzini *et al*., 2009). TPM is a maintenance system set-up to eliminate barriers to and losses in production. TPM identifies production losses and uses production operator teams to solve the problems causing the waste (Levitt, 2005).

TPM is a manufacturing program designed primarily to maximize the effectiveness of equipment throughout its entire life by the participation and motivation of the entire workforce (Nakajima, 1988 as cited in Manzini *et al.*, 2009). This approach provides a synergistic relationship among all the company's functions, but particularly between production and maintenance, for continuous improvement of product quality, operational efficiency, capacity assurance, and safety.

TPM is an evolution of the "preventive maintenance approach." In the early 1960s in some Japanese companies (e. g., the famous Nippondenso) maintenance became a problem as soon as the demand for personnel dedicated to maintenance increased. The management decided to assign the routine maintenance of equipment directly to the operators, thus creating one of the pillars of TPM, the concept of autonomous maintenance. The maintenance personnel took up only important or difficult maintenance interventions, and at the same time suggested some solutions to improve reliability (Willmott and McCarthy, 2001).

2.3 Techniques used in Preventive Maintenance Problem

Throughout the years, the importance of the PM functions and therefore of maintenance management has grown. A lot of literature is available from various resources and fields of PM. The existing literature on the applied methods in solving PM issues can be grouped into mathematical model, heuristics, metaheuristics and artificial intelligence (AI) techniques.

2.3.1 Mathematical Model

The mathematical model of a business problem is the system of equations and related mathematical expressions that describe the essence of the problem (Hillier and Lieberman, 2010). Banks (1998) denoted that this method is based on mathematical structure on the relations between the problem components, mathematical programming can more specifically be referred to as linear programming (i.e., all relations can be expressed as a set of linear relations) or integer programming (some of the variables restricted to binary or whole numbers). The objective function and the constraints are defined as mathematical functions.

Mathematical method is widely explored to find the optimal solutions of the problems. The accuracy of the algorithm depends, however, on good estimates for work in progress levels within the planning horizon. However, this technique also suffers from the fact that the solution time of an integer program may be very long even for moderately sized problems. Therefore, the use of mathematical programming for solving industrial problems is limited (Banks, 2010).

Mellouli *et al.* (2009) emphasized on three exact methods; mixed integer linear programming method, dynamic programming based method, and a branch-and-bound method to solve identical parallel machine problem with planned maintenance period on each machine. Several constructive heuristics were proposed. The new adapted shortest processing time algorithm was proved. Two branching schemes were presented and compared.

Haghani and Shafahi (2002) applied integer programming in tackling bus maintenance problem. The study was aimed to maximize the weighted total vehicle maintenance hours and to minimize the weighted total number of maintenance hours. Results showed significant reduction in the amount of time the busses to be pulled out of their scheduled services for PM. The study concluded that the proposed method could reduce negative impact of overdue maintenance as well as increase the reliability of the system significantly.

A mathematical model was developed by Tsai *et al.* (2004) in order to study PM by simultaneously considering 3 actions- mechanical service, repair and replacement for a multi component system. The main improvement involves both maintainability of component itself and the maintenance support. Results showed that the PM interval is affected obviously by the maintenance times. The bigger the ratio of the CM to the PM times, the shorter the PM interval would be. Meanwhile, the smaller system effectiveness would be incurred following the ratio increased.

Das *et al*. (2007) proposed integer programming technique for reliability-based PM plan in a cellular manufacturing environment. This paper discussed a cost-based, a reliability-based and a combined, multi-objective model for maintenance. The objectives function of the problem was minimizing the total maintenance cost and the overall probability of machine failures. The reliability-based model determines a common PM interval subject to an acceptable level of machine failure probability. The combined, multi-objective model determines the PM interval by taking into account both the costs and the machine reliability; however, as the acceptable level of machine failure probability decreases, the model's behavior was similar to that of the reliability based model. To overcome the limitations of the three approaches, a group PM plan centered on an 'effective maintenance interval' for the cellular manufacturing system machines was developed by modifying the reliability based model.

For a single machine and nonresumable job of flexible maintenance activities problem, Chen (2008) applied binary integer programming method. The objective was to minimize the makespan. The study managed to optimally solve up to 100 job instance.

Based on computational model, the proposed model and heuristic achieved quite satisfactory performance.

2.3.2 Heuristics Model

The basic approach is to develop feasible solution in order to satisfy the constraints (Banks, 1998). The constraint-based technique includes heuristics and metaheuristic. A heuristic method is a procedure that is likely to discover a very good feasible solution but not necessarily an optimal solution, for the specific problem being considered. Heuristic methods commonly used to find a good feasible solution that is at least reasonably close to being optimal for some problems that are so complicated, may not be solved for an optimal solution (Hillier and Lieberman, 2010).

According to Eiselt and Sandblom (2010), exact algorithms have the obvious advantage of providing the best possible solution there is, given the user-defined constraints, whereas heuristic does not. Some heuristics do have error bounds, some actually proven, while others are empirical, i.e. certain heuristic typically on average finds solutions that have a certain quality. Heuristic algorithms typically have two phases. The first phase is the construction phase, in which a solution is established. This phase starts with nothing, and by the end of the phase, we have a solution. Phase 1 should be followed by Phase 2, which is an improvement phase, in which the method uses simple modifications of the present solution that improve the quality of the solution.

Xhafa and Abraham (2008) emphasized that the limitations of heuristic method is that possible combinations can be seldom be achieved in practical problem. In addition, the 'local improvement' can short-circuit the best solution because heuristic lacks a global perspective, and independencies of parts of a system were ignored by the heuristic, have a profound influence on solution problem in the total system.

Guo *et al.* (2007) studied on the worst case bound of heuristic technique for single- and multiple-machine corrective and PM. The findings showed that neither corrective nor PM scheme was clearly superior. But that the applicability of each depends on several system parameters as well as scheduling environment itself.

Sriram and Haghani (2003) proposed random search and depth first search heuristic algorithm to minimize maintenance cost of an aircraft. The study showed that the closeness of the solution produced by proposed heuristic to the global optimal solution largely depends on how many different combinations of orders of aircraft and orders of nodes were explored. Heuristic consistently produces good solution with objective values within 5%. It was concluded that heuristic solves the problem in a very reasonable amount of time.

Liao and Chen (2003) compared heuristic techniques and branch and bound algorithm to minimize the tardiness of single machine and non-resumable job problem for PM scheduling. The results verified that both heuristic and branch and bound algorithm perform satisfactorily. Direct application of the results of this study to those companies where maintenance is performed periodically is easy and worthwhile.

Sbihi and Varnier (2008) presented branch and bound technique, focused on maintenance on a single machine with *n* non-resumable jobs, and integrated with production schedule to minimize tardiness. In the paper, two situations were investigated. In the first one, the maintenance period were periodically fixed, and the second one, the maintenance was not fixed but maximum continuous working time of the machine was allowed was determined. Computational experiments have been done to evaluate the effectiveness of the algorithms, and the result demonstrated that the proposed heuristic shows the superiority of the former.

Sun and Zhang (2010) developed an approach to predict the reliability of repairable system with interactive failure, when the failure of some components will affect failures of other components. The aim was to minimize the number of PM action. Low *et al.* (2009) also employed heuristic algorithm for single machine maintenance problems. The aim of the research was minimizing makespan.

2.3.3 Metaheuristic and Artificial Intelligence Methods

A structured metaheuristic is a general solution method that provides both a general and strategy guidelines for developing a specific heuristic method to fit a particular kind of problems. Metaheuristics have become one of the most important techniques in the toolkit of operational research practitioners (Hillier and Lieberman, 2010). Metaheuristic methods have an advantage over simpler heuristic in terms of solution robustness; however they need special information about the problem to be solved to obtain good results (Xhafa and Abraham, 2008).

Examples of metaheuristics include simulated annealing (SA), tabu search (TS), iterated local search (ILS), evolutionary algorithm (EA), evolutionary programs (EP), genetic algorithms (GA), and scatter search (SS). In addition, there are many hybrid approaches combining features of several of these techniques simultaneously (Ravindran, 2009). In preventive maintenance field, the published literatures in metaheuristics studies are numerous.

The application of GA method to maintenance and reliability problem was illustrated by Bris *et al.* (2003). The GA optimization techniques was used and briefly described to create the Matlab's algorithm to solve the problem of finding the best maintenance policy with the given restriction. Adjacent problem, which was called reliability assurance, was also theoretically solved, concerning the increase of the cost when asymptotic available values conforms to a given availability constraints. The study was focused on series and parallel system based on time dependence. The objective function was to minimize the maintenance cost of the system.

Zhao and Liu (2003) provided a unified modeling idea for both parallel and standby redundancy optimization problems. A spectrum of redundancy stochastic programming models was constructed to maximize the mean system-lifetime, α-system lifetime, or system reliability. This paper considers both parallel redundant systems and standby redundant systems whose components were connected with each other in a logical configuration with a known system structure function. Three types of system performance-expected system lifetime, α-system lifetime and system reliability-are introduced. A stochastic simulation was designed to estimate these system performances. In order to model general redundant systems, a spectrum of redundancy stochastic programming models is established. Stochastic simulation, NN and GA are integrated to produce a hybrid intelligent algorithm for solving the proposed models. Finally, the effectiveness of the hybrid intelligent algorithm is illustrated by some numerical examples.

Lapa *et al.* (2006) considered GA as an appropriate optimization technique for policy evaluation based upon a cost-reliability model. The authors developed a model that includes preventive and corrective maintenance actions and the associated cost with them, outage times, reliability of the system, and probability of imperfect maintenance. The results showed that by applying the proposed cost-reliability model, it was possible to find preventive maintenance policies which provide a high level of reliability with low costs. If