AN INTEGRATED OPTIMIZATION MODEL FOR PRODUCTION SCHEDULING MAINTENANCE AND QUALITY

BY

AHMED OSMAN ALI EL-KHALIFA

A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS
DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

INDUSTRIAL AND SYSTEMS ENGINEERING

OCTOBER 2015

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by **AHMED OSMAN ALI EL-KHALIFA** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN INDUSTRIAL AND SYSTEMS ENGINEERING.**

Dr. Salih O. Duffuaa (Advisor)

Dr. Umar M. Al-Turki
(Member)

Dr. Mohammad M. AlDurgam
(Member)

Dr. Hesham K. Al-Fares
Department Chairman

Dr. Salam A. Zummo
Dean of Graduate Studies

27/4/16

Date

Dedicated To My family with love

This thesis is dedicated to my Idol and Mentor, my beloved Father,
Osman Ali EL-Khalifa

To my beautiful Mother, She is My Everything

To my awesome Brothers and Sisters

Thank you

ACKNOWLEDGMENTS

Praise be to Allah for this blessing. The completion of this thesis is a major milestone in my life and a dream come through. I am happy and grateful that I have finally reached this stage. It took enormous self motivation, discipline and encouragement from my advisor, family and friends to overcome the frustrations and barriers to reach this phase.

There are a number of people without whom this thesis might not have been written, and to whom I am greatly indebted.

My deepest appreciation and gratitude goes to my parents who were, after Allah the source of success in my life, thank you. Also, I would like to extend my gratitude to my brothers and sisters for their love, support and patience to complete this study. This thesis is dedicated to all of them.

I would like to express special thanks to my academic and thesis advisor, Prof. Salih Duffuaa, for his advice and help. I acknowledge his guidance, encouragement, support, efforts, patience and valuable time. I am deeply indebted to him.

I extend my gratitude to my thesis committee members, Dr. Umar Al-Turki and Dr. Mohammad AlDurgam. Their cooperation, advice and insightful feedback are truly appreciated. Acknowledgment and special thanks goes to Prof. Shokri Selim for his valuable effort and motivation.

Thanks are due to all my friends and mates for their good wishes, moral support and the memorable days shared together.

Finally, acknowledgment is due to king fahd university of petroleum and minerals for giving me this chance to accomplish this achievement. I appreciate the stimulating and pleasant environment in the university. Special thanks and appreciation to the systems engineering department.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

THESIS ABSTRACT

NAME: AHMED OSMAN ALI EL-KHALIFA

TITLE OF STUDY: AN INTEGRATED OPTIMIZATION MODEL FOR PRODUCTION SCHEDULING MAINTENANCE AND QUALITY

MAJOR FIELD: INDUSTRIAL AND SYSTEMS ENGINEERING

DATE OF DEGREE: October 2015

In today's competitive environment, the importance of continuous production, quality improvement and perfect maintenance planning has forced production and delivery processes to become extremely reliable. Keeping equipment in good condition through maintenance activities can ensure a more reliable system. However, maintenance leads to temporary reduction in the availability and capacity of machines that could otherwise be utilized for production. Therefore, the coordination of maintenance, production and quality is important to guarantee a good system performance. The central purpose of this study is integrating maintenance, production scheduling and quality decisions to minimize the total cost by ensuring high quality production and effective maintenance interval. Two models are developed in this thesis. The first model integrates maintenance and production scheduling. The second model develops a method that integrates production scheduling, maintenance planning and quality. The models are tested using examples from the literature and compared with some benchmarks situation. The results indicate that the total integration proposed model is better than all other different joint scenarios.

ملخص الرسالة

الاسم الكامل: أحمد عثمان علي الخليفة

عنوان الرسالة: النموذج التكاملي الأمثل لجدولة الإنتاج والصيانة والجودة

التخصص: هندسة النظم الصناعية

تاريخ الدرجة العلمية: محرم ١٤٣٧هـ

أصبحت عمليات الإنتاج ، وتحسين الجودة المستمر ، والتخطيط السليم لعمليات الصيانة في غاية الأهمية في ظل البيئة التنافسية التي نشهدها هذه الأيام وذلك لتجعل من عمليات الإنتاج والجدولة عملية موثوقًا بها للغاية. إن الحفاظ على الآلات والمعدات في حالة جيدة من خلال عمليات الصيانة الدورية يضمن توفر نظام أكثر موثوقية ، غير أن عملية الصيانة تؤدي في المقابل إلى انخفاض مؤقت في توافر الماكينات والطاقات الإنتاجية التي كان من الممكن أن تستخدم في عملية الإنتاج لولا أنه تم تعطيلها مؤقتاً لإجراء الصيانة. لذا ، فقد أصبح التكامل بين عمليات الصيانة ، والإنتاج ، وضبط الجودة مهمًا جدًا لضمان توفر نظام جيد الأداء.

إن الهدف الرئيسي من هذا البحث هو تطوير نماذج رياضيه تدمج عمليات الصيانة ، والإنتاج ، وضبط الجودة في عملية تكاملية لتقليل التكلفة الكلية من خلال ضمان إنتاج عالي الجودة وتحديد فترات زمنية لصيانة فعالة.

تم تطوير نموذجين في هذه الأطروحة: النموذج الأول يدمج بين جدولة عمليتي الإنتاج والصيانة. والنموذج الثاني طوّر أسلوبًا يدمج بين عمليات جدولة الإنتاج ، والتخطيط للصيانة ، وضمان الجودة. وتم إختبار النماذج وقورنت النتائج لعدة حالات. وقد دلت النتائج أن النموذج المقترح لدمج وتكامل جميع العمليات أفضل من مختلف السيناريوهات المشتركة الأخرى. ومن ثم اقترحت الرساله عدة مجالات لتطوير الأبحاث في هذا المجال.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Maintenance planning and quality control along with production string are three interrelated functions in any production environment and are the most important and influential aspects in any manufacturing and industrial system. In a production system the normal case is having the process running in a controlled state but due to the deteriorating behavior of the system with respect to time or a sudden shut down the operation may move out of control that is usually observed by a technique of quality control known as SPC. At the in control state the system produces an outcome of high and near perfect quality products. Preventive maintenance is usually employed to keep the manufacturing system from deteriorating and the production processes within control. When moving out of control the system will result in more insufficient elements that will be scraped or reworked with the chance that the rework process can be imperfect.

Corrective maintenance and preventive maintenance which might be imperfect are performed to repair the failure and maintain the machine. They are assumed to recover the system to it's preceding new status. Thus, SPC and maintenance activities are the basic mechanism for planning and controlling a production schedule. It seems clear that in order to have a production system that performs efficiently and effectively these three activities production scheduling, maintenance and quality have to be managed jointly.

Traditionally in the literature the above three activities of the production systems have been investigated separately and a tremendous amount of research has been accomplished over the years. However, recently the investigation and development of joint and integrated models considering a different combination of these three concepts with different objectives has brought many investigators and researchers interest in the past couple of decades.

The aim of this chapter is to highlight the goal of this thesis and provide an overview of production, maintenance and quality systems. Section 1.2 focuses on production scheduling followed by maintenance in section 1.3. Section 1.4 presents quality in production systems and Section 1.5 states the thesis objectives. Section 1.6 outlines the thesis organization.

1.2 Production

A production system basically deals with two problems:

- Production Scheduling:

Address the allocating problem of the feasible production quantity and assigning start times to production jobs. **(Pinedo 2002)**

- Production Planning:

  Determines the optimal production quantities, also known as lot-sizing, and evaluates the required production capacity. **(Nahmias 2005)**

1.3 Maintenance

Defined as the collection of actions performed on a system to retain it's functionality and good performance. These systems are in most cases production systems that yield either products or services and in some situations both. Maintenance is performed at a scheduled production stops after working hours and during holidays also is implemented while production is active. However, a total shutdown of the production process need to be don for the maintenance to take place. This will probably cause a pressure between the departments of production and maintenance in a company. The production department requires a well maintained equipments but in the down side this will result in a production loss due to the operations being shut down. Therefore, it is clear that both can benefit from the assistance of mathematical models decisions.

The challenges for coordination of maintenance and production depend on the type of maintenance strategy. The general maintenance strategy of a production system can be one of the following:

1.3.1 Corrective Maintenance

Where there is no control over machine conditions and corrective action is conducted after machine collapse. This strategy is appropriate if the machine failure behavior is independent of its state, for example, its age, or if precautionary maintenance is not beneficial due to economic considerations.

1.3.2 Preventive Maintenance

Machine conditions can be partially controlled by performing maintenance both before and at failures to decrease the number of breakdowns. This maintenance strategy is applicable if the frequency of machine failure changes depending on its state or there is a measurable condition which can signal incipient failures.

1.4 Quality Control

Defined by **Taguchi (1986)** as "the loss a product causes society once it has been shipped, apart from any losses caused by its actual functions". According to ISO 8402 (International Organization for Standardization, 1986), "quality is the totality of features and characteristics of a product or service that have a bearing on its ability to satisfy stated or implied needs".

One of the most implemented approaches of quality control is the SPC, where the variation of the process is controlled and monitored by statistical techniques in order to guarantee a fully operational effort with a minimum of waste (rework or Scrap). A fundamental tool of the SPC is control charts.

1.4.1 Quality Control Charts

In **1924 Shewhart** invented the control chart for industrial statistical quality control. They are graphics that describe if the products and processes being sampled are satisfying the required design specifications and if they don't the level by which they differ from these specifications. Evaluating the style of variation obtained from the charts will help in determining whether errors are happening systematically or at random. These quality charts can also show whether a process or product vary from one (univariate) or more than one (multivariate) desired outcome. Different types of quality control charts can be used with different types of data analysis, some of the most know are the X-bar, Np and S charts.

Integration of the three above activities is expected to bring benefits and that attracted the interest of many researchers. Next we briefly review the literature on this subject.

1.5 Thesis Objectives

The central objective of this study is the development of two integration models. The first model investigates production and maintenance integration. The second model investigates production, quality and maintenance integration. This will be done by solving the decision variables of the three problems simultaneously through the following sub-objectives:

- Review of past research in the field of integrated models.

- Develop a model for production and maintenance scheduling parametrically.

- Develop a model for quality, maintenance and production scheduling by integrating the logic of the first step in a maintenance and quality control model.

- Present examples from the literature to clarify the utility of the suggested models.

- Conduct analysis for the computed results.

1.6 Thesis Organization

The remaining of the thesis is organized as follows: chapter 2 presents a detailed literature review. Chapter 3 contains the development of the joint model of production scheduling and maintenance planning with the objective of optimizing the total penalty cost of tardiness. Chapter 4 discusses the development of the integrated model of quality, production scheduling and maintenance planning. Finally, Chapter 5 summarizes the work don in this thesis, and briefly recommend some possible future work.

CHAPTER 2

LITERATURE REVIEW AND OBJECTIVES

2.1 Introduction

The purpose of this chapter is to show a detailed literature review on integrated approaches for production, maintenance and quality models.

Research in those three main areas was for many years a source of inspiration for a great number of researchers and professionals. This was due to the growing markets and industries rivalry. As a result, approaches and methods was became more and more mature in these areas. The independent examination of these models was considered as the reason of having a suboptimal results by a lot of researchers. Thus, an increasing number of the integrated models has gained place in the literature recently. Available literature can be classified as in Figure 2.1.

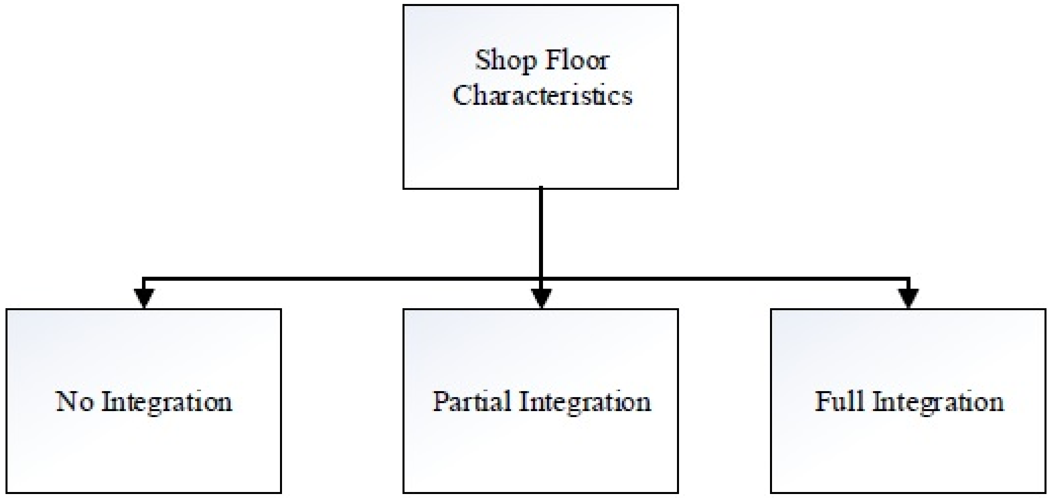

Figure 2.1: literature classification

2.2 Production and Maintenance Scheduling Integrated Models

2.2.1 Single Machine Scheduling

Adiri et al. (1989) considered the question of running a set of jobs on a single machine so that the sum of the finishing times of all the jobs is minimized. The machine might breakdown during jobs processing. The cases of a single breakdown and multiple breakdowns are considered and solved with a shortest processing time (SPT) proposed algorithm. SPT is a standout amongst the most commended algorithms and has been demonstrated to perform amazingly well in numerous cases of planning criteria. **Lee and Liman (1992)** investigated **Adiri et al.** problem for the deterministic model. They provided a shorter NP-integrity demonstration of the deterministic single-machine problem. For the SPT sequence it shows that the worst situation error bound has 2/7 to the error bound shown in **Adiri et al.** that is 1/4.

X. Qi et al. (1999) the problem was studied with preventive maintenance (PM). The completion time of all jobs was the optimization target. The model was found to be strongly NP-hard and a branch and bound algorithm along side a three heuristics where examined. **Asano and Ohta (1999a)** considered the problem with shutdown constraints and the setup times between jobs where sequence dependent. They developed two optimization algorithms to find the lowest of the highest tardiness. One will employ the shutdown starting time named as the post processing algorithm and the other one is a branch-and-bound (B&B). In **(1999b)** they considered the shutdown constraints along side (due time and time zero). They developed a heuristic algorithm that focuses one finding the minimum sum of reduction amount in shutdown times and the holding number for earliness. Computational test for the developed method is presented since it's strongly NP hard. **O'Donovan et al. (1999)** presented an approach of scheduling that absorb the impacts of breakdowns by adding more idle time into the schedule. They applied it to the problem considering stochastic machine failures keeping in mind optimizing the maximum delay. Furthermore a rescheduling heuristics is proposed considering the case where machine breakdowns are affected by the processing times of job.

Schmidt (2000) analyzed in his review the single and multi-machine problems complexity with the due dates and completion times being considered. The review focused on approximation algorithms, polynomial optimization and intractability results. Enumerative heuristics and algorithms were being covered.

Yang et al. (2002) provided a computational experiments heuristic algorithm for the problem with a flexible maintenance. They considered that within the scheduling interval the tool must be stopped to reset or to maintain for a given period.

Liao and Chen (2003) solved the problem for the case of periodic maintenance (maintenance composed of different maintenance intervals) under maximum delay optimization. They proposed a B&B along with a analysis considering large-sized problems to find the near-optimal result. **Wu and Lee (2003)** studied availability constraints and tumbling jobs to obtain the optimal makespan. Since the starting time is the structure for the function of processing time it might be dealt with through a binary integer programming method given its proportional. **Cassady and Kutanoglu (2003)** optimized the overall tardiness (TWT) of jobs and determined the decisions corresponding to PM planning and the production schedule simultaneously by developing an integrated production and maintenance paradigm. The solution obtained from the joint problems was compared with the solutions gathered from solving each of the problems independently.

Cai et al. (2004) considered the problem with respect to random breakdowns and tardiness to derive optimal policies for maximizing the jobs completion discounted reward earned and minimizing the weighted tardiness. They also utilized the Laplace transform to extend the work to a more general cost function.

Sadfi et al. (2005) studied the problem subjected to periodic maintenance for minimizing the total makespan. An algorithm was suggested for the problem having worst case error bound. **Cassady and Kutanoglu (2005)** optimized the overall completion time expected weight (TWC) of procedures and determined the decisions corresponding the joint complications simultaneously. The solution obtained from the joint problems was compared with the solutions gathered from solving the issues individually. Total enumeration technique and a heuristic approach were considered for solving smaller and larger sized issues correspondingly. **Sortrakul et al. (2005)** considered solving the previews **Cassady(2003 and 2005)** integrated optimization models by developing a genetic algorithms based heuristics.

Chen J.S. (2006) examined the problem subject to periodic maintenance having the jobs mean flow time as the objective to be minimized. For a constant time w the machine will periodically be stopped for reset or maintenance during the scheduling interval. To solve the problem, he proposed four models of mixed binary integer programming. A large-sized problems heuristic is also suggested. **Chen W.J. (2006)** dealt with the same issue and proposed a B&B for solving it.

Raza et al. (2007) reviewed and investigated the cooperative complication for the case of optimizing the total earliness and delay of operations. Simulated annealing and hybridized tabu search algorithms were proposed as a solution approaches. **Cassady and Sortrakul (2007)** developed heuristics for solving **Cassady and Kutanoglu (2003)** integrated minimization model (TWT) under the genetic algorithms. **Kuo and Chang (2007)** investigated the optimality of the integrated issue under a cumulative damage process for minimizing the total tardiness.

Yulan et al. (2008) considered the integrated models of **Cassady and Kutanoglu (2003,2005)** which have a single objectives and developed a multi objective model that includes reducing the overall time, TWC, TWT and the maintenance value in addition to machine availability maximization. They solved the problem using a Multi-objective genetic algorithm (MOGA).

Chen (2009) developed an effective heuristic based on Moore's algorithm in order to obtain the sequence that lowers the overdue tasks for the issue having a periodic correction in which later to a periodic time period each maintenance period is to be scheduled.

Low et al. (2010) focused on the issue of scheduling considering a deterministic environment under machine availability bonds due to its periodic maintenance behavior and flexible maintenance considerations for the goal of makespan optimization. The machine will be stopped when processing a given number of tasks for tools changing or after a periodic time period. It's NP-hard. A first fit decreasing (DFF) algorithm that based on the computational results obtained was suggested. **Pan et al. (2010)** went for the reduction of the maximum weighted delay for the integrated model under variable maintenance time and machine degradation.

Yang et al. (2011) handled the case for multiple jobs in order to minimize the overall completion time. Given the resumable situation the SPT algorithm is shown to be optimal also the events where the SPT is excellent for the nonresumable case were studied. **Benmansour et al. (2011)** considered a failure-prone machine for the integrated production and maintenance problem and suggested a simulation approach for studying it. Two decision variables where investigated S and T which represent the sequence of jobs in order to reduce the amount linked to production and maintenance and the time for performing actions of preventive maintenance. **Hadidi et al. (2011)** derived a solution for the issue considering perfect PM planning model with the objective of finding the array of processes and the decisions of PM that minimizes the total expected costs.

Mokhtari et al. (2012) considered it with multiple PM actions and suggested a joint production scheduling model. For solving the issue a nonlinear mixed integer technique of programming that uses a neighborhood search algorithm (PVNS) was developed and solved. **Hadidi et al. (2012)** conducted a method for scheduling and maintenance planning model with a goal of finding the order of jobs and the decisions of preventive maintenance that minimize the TWCT. A mixed integer programing modeling was suggested for solving the model. **Suliman and Jawad (2012)** proposed a model for the problem with the objective of optimizing the PM age and size. The following costs were considered in the model including the inventory holding, the shortage, the non-conforming items and the maintenance average total values.

Wang et al. (2013) considered the integrated status and suggested a B&B solution for it given that the time a process will require to fail follows a Weibull probability function. **Hsu et al. (2013)** proposed and tested a lower bound heuristic considering non sequel event and simple linear declining impact for the problem with deteriorating jobs and multi-maintenance activities. **Wang et al. (2013)** considered the integrated matter having setup times being attached in order to optimize both the maximum expected times of machine failure and the total expected jobs completion time. In other work, he investigated the integrated problem with imperfect preventive maintenance and lots of products to be produced. An integer linear programming was formulated and solved through several multi-product lot-sizing problems comparisons.

Benmansour et al. (2014) investigated the objective of optimizing costs of summing the maximum earliness and maximum weighted tardiness when scheduling against a common and restrictive due date. Two assumptions were considered, one considering the machine without availability constraints and the other assumes it undergoes a periodic preventive maintenance. Models were presented for both cases. **Wei-WeiCui et al. (2014)** studied a joint model in a one machine system having stochastic failure behavior to integrate the policy containing PM and CM reactions in order to enhance the solution along with biobjective of quality robustness concurrently.

2.2.2 Parallel Machines Scheduling

Schmidt (1988) examined a given m semi-identical processors in a parallel machine for constructing a preemptive schedule that is feasible. All processes are running in different time periods of availability with identical speeds. A time O(nm log n) algorithm was shown to develop the schedule. As a result he examined the relationship between the total number of deadlines and processing intervals on one hand and the number of induced preemptions was on the other.

Lee (1991) considered the issue with the goal of optimizing the overall finishing time and makespan for m parallel identical instruments with n independent tasks to be scheduled on. He assumed that at the beginning of the schedule all jobs are ready unlike machines which some of may not be. It's a general consideration for the well-known multiprocessor scheduling problem in which all machines are ready at the beginning of the schedule (time zero). the (LPT) and another modified (MLPT) algorithms were provided and compared the obtained makespan.

Lee and Liman (1993) focused on the objective of optimizing the total fulfillment space. They relaxed the assumption of continuous machine availability so only one of the machines is available for processing at some period. They named it the capacitated sum of job completion times problem (CSCT). Without this constraint the SPT algorism will solve it. A pseudo-polynomial dynamic programming algorithm was suggested as a solution.

Mosheiov (1994) studied the same problem, assuming a machine-dependent time intervals. He proposed a straightforward minimize constrained on the excellent amount heuristic as a solution method.

Chakravarty and Balakrishnan (1995) studied the problem considering a deteriorating limited capacity machine. Machine failures, preventive maintenance and the limited capacity will cause machine total down-time which in terms increases the makespan. A three problem scenarios are developed with only the third scenario considering preventive maintenance scheduling and solved with branch-and-bound algorithms. **Ho and Wong (1995)** considered minimizing the makespan on parallel m machines with a duo instrument minimization algorithm (TMO).

Lee (1996) studied the problem under various machine environments and various performance measures. The stochastic breakdown and deterministic preventive maintenance actions will affect the availability of the machine. A pseudo-polynomial dynamic programming models and a polynomial optimal algorithm were proposed. **Suresh and Chaudhuri (1996)** developed two algorithms to the problem given unrelated parallel machines when machine vacations (The duration for which the machine is not available) are specified. Machine vacations may or may not be known prior to scheduling. **Brandolese et al. (1996)** considered a one-stage production of machines operating in parallel with multi-objectives. First, minimizing the total times, that is the combination of setup, processing, maintenance and machine idle times. Then, minimizing the total cost that is the combination of the setup, maintenance and production costs.

Kellerer (1998) examined the problem with the objectives of optimizing the minimum completion and the makespan. Algorithms are presented to solve both problems.

Lee and Chen (2000) considered the problem with m parallel machines where maintenance is performed once on every instrument. The goal was to locate the schedule that decreases TWC. They considered two scenarios in where one machine is to be maintained at some time and the other is maintaining more than one together. A column generation (B&B) was proposed. **Rabinowitz et al. (2000)** went through the issue with two machines and different types and deterministic maintenance. The objective is to maximize the portion of time with an operational machine. Considering small-sized problems they proposed and tested heuristic methods and cyclic solutions.

Leung and Pinedo (2004) studied the problem assuming machines are not available all the time and allowing preemptions. Analysis is don for the highest delay, the total finishing time and the makespan taking into consideration precedence constraints and the deadlines that jobs have to meet.

Liao et al. (2005) studied the problem with availability constraint considering both resumable and nonresumable. For solving they divided it to four small-problems to minimize the makespan. **Chen and Liao (2005)** considered the issue having the target as optimizing the amount of delayed tasks in a manufacturing company that has different situations of maintenance.

Chen (2006) addressed the problem and proposed eight mixed binary integer programming models with the total tardiness as the objective function taking both nonresumable and resumable scenarios under consideration. **Chan et al. (2006)** reviewed scheduling adjustable manufacturing structure (FMS) for the objective of maximizing the system efficiency. To do so, an optimal planning using genetic algorithm with dominant genes (GADG) approach among various processes must be found.

Liao et al. (2007) investigated two diverse scheduling boundaries, the short-time and long-term for the problem with feasibility conditions. For the infeasible duration interval short-terms are the time before it and the long-term are the time after it. A B&B based optimization algorithms was suggested for the minimization of the makespan. **Chen (2007)** derived a method for the textile company studied in **(2006)**. The objective was to minimize the maximum tardiness. A B&B and heuristic algorithms were proposed.

Lee and Wu (2008) assumed that job processing times follow simple linear deteriorations and each machine has a maintenance duration noted in prior. For that they inspected the issue given a group of machines with no availability and an objective of minimizing the makespan. Heuristic algorithms are derived for each case. **Xu et al. (2008)** handled the case with periodic maintenance activities for minimizing the last finished maintenance completion time. They suggested a polynomial time similarity solution 2 T' / T. **Chen and Tsou (2008)** considered the problem under periodic maintenance for finding the minimum total flow time. A B&B algorithm was proposed. **Sbihi and Varnier (2008)** investigated the problem with several maintenances periods. Periodically fixed intervals and not steady intervals in which the running time is decided. The goal is to optimize the overall delay. **Chen (2008)** considered the same problem, he studied in **(2006)** but for a different objective of minimizing the makespan. For solving it, he proposed a near-optimal productive heuristics for big issues and BIPM. **Gurel and Akturk (2008)** with the target of finding the lowest total finishing time. They provided a new search algorithm and proposed optimality properties for the problem.

Mellouli et al. (2009) came up with a new approach for optimizing the makespan of the problem having identical parallel machines and planned maintenance periods on each machine. They proposed three methods to solve the problem at hand. Several heuristics were also proposed. **Berrichi et al. (2009)** considered a new method with reliability models for the joint issue. The target is to optimize the makespan considering manufacturing and the availability lack considering maintenance all together. A comparison of two genetic algorithms was suggested to find the solution.

Sun and Li (2010) two scheduling models were considered to handle the problem having two identical parallel machines so that the machine breakdown probability is minimized. The primary model objective is to lower the makespan considering periodic maintenance activities. The second model handles the minimization of jobs total completion time. Two algorithms were applied respectively, the O (n2) time algorithm named MHFFD that they introduced and classical SPT algorithm. **Berrichi et al. (2010)** developed a Multi-Objective Ant Colony optimization algorithm (MOACO) as a solution method for the problem they proposed in **(2009)**. The PM intervals and the best assignment of jobs were the targets to be determined.

Rebai et al. (2012) suggested an evolutionary algorithm for the problem with m maintenance tasks in order to decrease the overall WCT.

Berrichi and Yalaoui (2013) proposed a bi objective ant colony optimization method for the integrated problem. They considered the unavailability of the production system and the total tardiness as performance criteria. **Bandyopadhyay and Bhattacharya (2013)** proposed three objectives to modify the Multi-Objective Evolutionary Algorithm NSGA-II. The objectives were minimization of the total cost due tardiness, the makespan and the deterioration cost. The problem was solved with the modified version of NSGA-II.

Mirabedini and Iranmanesh (2014) considered a multi-objective multi-parallel machines functions made up of difference delays, makespan, PM value, and variety cost with multiple jobs. An original approach of PM scheduling in two conditions where items are fixed or replaced was presented. A dynamic genetic algorithm (GA) was used as a solution method.

2.2.3 Flow Shop Scheduling

Lee (1997) studied the flowshop scheduling problem having two-machine that are not available all the time. He assumed that the time where machines are not available is known in advance. He proposed a pair of $O(n\ log\ n)$ duration heuristics, one considers imposing availability constraints on machine 1 and the other imposes it on machine 2.

Espinouse et al. (1999) treated the issue for the target of minimizing the maximum finishing time. For arbitrary unavailability periods numbers it's complicated NP-Hard. An error bounding heuristic design analysis were provided.

Blazewicz et al. (2001) considered the same problem with two machines and proposed a local and constructive search based heuristic algorithms. The algorithms were examined considering 10 unavailability constrained intervals and up to 100 jobs. **Espinouse et al. (2001)** proved that even when considering the availability constraint on only one machine the problem is still NP- hard.

They provided an error bounding based heuristic with analysis as solution method.

Kubiak et al. (2002) studied the problem where machines are subject to PM and preschedules. The objective was to minimize the makespan. A B&B algorithm was proposed based on an important characteristic they developed of some optimal schedules.

Allaoui and Artiba (2004) considered the issue under correction conditions with the target of optimizing the due date and flow time. They illustrated by an experimental work that the breakdown times affect the efficiency of the applied heuristics. Also focused on integrating simulation and optimization to handle this NP-hard practical problem. Under particular conditions, these proposed heuristics shown to be better than NEH heuristics. **Aggoune (2004)** handled the problem of scheduling with vacant conditions (FSPAC) given two non-preemptive variations so that the makespan is minimized. The first case, assumes a fixed maintenance starting time for each job where the second case has a given maintenance time windows the for jobs. He proposed genetic method along with a tabu search as a solution method.

Kubzin and Strusevich (2005) studied the minimization of the completion time of all jobs for the problem having two machines on of which must be maintained and under an approximate polynomial time design.

Allaoui and Artiba (2006) considered the hybrid flow two-stage problem in which one machine is scheduled on one stage and m machines on the other. The makespan is to be minimized. A B&B, LPT, LIST algorithms and H-heuristic worst case performance were calculated.

Allaoui et al. (2008) considered the problem with one of the machines is under maintenance once during the first T periods. They studied only the non-resumable case. Properties of the optimal solution where presented. **Yang et al. (2008)** examined the problem subject to a separated preservation restraints. Subsequently to finishing a specific figure of tasks a constant time is needed to maintain the machine. The objective was to minimize the makespan by finding the optimal job schedule and combinations. A heuristic algorithm and some polynomial solvable cases were proposed.

Liao and Tsai (2009) proposed a combination of Johnson's algorithm along with H and HI heuristics naming the developed algorithm H&J for the problem. Moreover, they proposed a time complexities O(n2) constructive heuristic. **Gholami et al. (2009)** considered the problem subject to stochastic breakdown and sequence dependent setup times (SDST) under the target of lowering the overall expected time. They described and implemented how simulation can be incorporated using a genetic algorithm method. **Naderi et al.**

(2009b) investigated the problem considering different preventive maintenance policies and SDST times. They studied how to avoid the drawbacks of models and suggested improving some existing metaheuristics with high performing and a novel variable neighborhood search (VNS).

Sitayeb et al. (2011) studied the JPMSP problem, assuming that there are no machine breakdowns, preemption or setup times. Two meta-heuristics and a constructive heuristic were suggested.

Wang and Liu (2014) studied a two phase hybrid issue in which one tool scheduled on one phase and m parallel exact tools scheduled on the other. A bi-objective integrated optimization approach was proposed considering a non-resumable tasks. Tabu multi objectives search (MOTS) mechanism was adjusted.

2.2.4 Job Shop Scheduling

Burton et al. (1989) proposed and studied a job shop problem under machine failures and preventive maintenance policy. The efficiency of some maintenance techniques of scheduling was taken into consideration.

Banerjee and Burton (1990) considered a set of emulation tests to research the effectiveness of a dynamic problem, under machine failures.

Holthaus (1999) studied the problem subject to interruptions and with respect to due date and flowtime objectives.

Gao et al. (2007) suggested a combination GA on the issue having unfixed availability constraints due to maintenances.

Naderi et al. (2009a) investigated the goal of lowering the overall run time for the issue with PM actions and SDST. Simulated annealing along with GA based metaheuristics where proposed as a solution with two more metaheuristics modified from the literature.

Ben Ali et al. (2011) examined the problem having concurrent operations and tasks of production and PM scheduling for the sake of lowering both the overall amount of maintenance and the makespan. A multi targets elitist genetic algorithm was proposed to gather the best set of Pareto solutions. **Moradi et al. (2011)** studied a multi-objective integration in a flexible job shop (FJSP) so as to gain the PM activities and the suitable allocation of n jobs on m machines at the same time so that the system unavailability and the makespan are minimized.

Golmakani and Namazi (2012) proposed a heuristic method as a solution for the multiple-route problem with age-dependent and fixed periodic PM jobs.

2.3 Production and Maintenance Planning Integrated Models

Finch and Gilbert (1986) established a conceptual paradigm for the integration having production planning capacity and priority activities and the maintenance planning aspects of CM and PM (maintenance craft labor).

Lou et al. (1992) gone into the issue with random repair and breakdown times in a multi-product manufacturing system having N unlimited buffers for it. A total work-in-process (WIP) inequality with respect to time was derived.

Dedopoulos and Shah (1995) considered the problem under multipurpose manufactories. A two-step solution procedure is discussed, it begins with deciding the rate relationship performance-failure then considering this relationship for utilizing the optimization of the maintenance plan. **Sanmarti et al. (1995)** studied the problem with batch multi-purpose plants that are subject to failure. A study is given to show the incorporation of reliability and preventive repair methodologies into the overall planning framework.

Rishel and Christy (1996) evaluated the material requirements planning system (MRP) that consist of production planning, inventory control and scheduling with the influence of considering forecasted emergency activities or different scheduled policies of maintenance. They showed that an appropriate maintenance policy is hard to be defined by utilizing the characteristics and evaluating failure of the machines separately.

Duffuaa and Al-Sultan (1997) proposed an expansion of **Finch and Gilbert** maintenance management information system to have a well monitored maintenance scheduling problem through using the mathematical programming techniques. In other work **(1999)**, they considered a stochastic structure and developed a stochastic program of the **Robert and Escudero** model for scheduling with alternatives. The result obtained by an illustrative example indicates that the stochastic solution showed improvement over the deterministic formulation. **Weinstein and Chung (1999)** looked into triplet step paradigm to analyze a maintenance planning approach. It begins with generating a linear programming formulated production plan. Next, the objectives of weighted variations considered in the formulated production plan were minimized by developing a master production schedule. Throughout the production planning range failures were investigated and demonstrated as a final step. Tests for investigating the efficiency of different key factors of the maintenance policy were presented. **Vaurio (1999)** constructed cost rate model with unavailability constraint and random failure. Inspections and periodic testing were considered to test fire occurrences. The costs of the model include costs of finite maintenance, testing, lost production and finite repair. For the solution method different approached were proposed for finding the optimal cost as well as the optimal maintenance and test periods.

Abboud et al. (2000) considered his work in **Abboud and Salameh (1987)** and extends it by allowing shortages and having a randomized time in which machine might not be ready at the specific time when producing starts the next batch. They obtained the minimum cost of summing the inventory carrying, shortage and procuring costs per unit of time.

Cassady C.R. et al. (2001) established a computational structure to support deciding and determining the best group of maintenance activities to carry out preceding the start of the following operation. This technique of selective maintenance is a wide research field for having a further intelligent and creative maintenance.

Sudiarso A. and Labib A.W. (2002) gave a design for converting maintenance stats as shop floor report. A fuzzy logic formula is applied to define the best control actions for the production environment and optimal batch size. **Coudert et al. (2002)** studied scheduling using the multi-agent paradigm and fuzzy logic.

Sloan (2004) came up with a Markovian choice making pattern for the issue where demand is irregular. The goal is to select concurrently the volume to produce along with the equipment servicing to conduct the minimum total production, backorder and holding expected expenses. Identification is don between his strategy and the common policy. **Cheung et al. (2004)** proposed a MILP and site paradigm as an attempt of optimizing the short term site wide repair duration.

Guo et al. (2007) developed an arrangement to check out the reflection of CM and PM tactics on the execution of scheduling given an unavailability scheme having the target as to lower the rapier interval.

Budai G., et al. (2008) provided an outline of mathematical templates which acknowledge the connections among maintenance and production.

Nourelfath et al. (2010) combined PM with tactical manufacturing designing within a different cases environment for the issue. The goal was to lower the combined total of CM and PM, setup, holding, backorder and production expenses although keeping the demand fulfilled.

Najid et al. (2011) production and maintenance planning integration model was proposed to minimize manufacturing, supply, starting times, demand lack and CM/PM expenses. A time windows planned PM actions model is developed.

Portioli-Staudacher and Tantardini (2012) proposed a different decision confirming operation for the issue to administer the rescheduling involvements of PM. **Fitouhi and Nourelfath (2012)** considered combining non periodical PM and well-planned production on one process. The target is to lower the total of PM/CM, installation, equity, backorder and manufacturing expenses. **Alaoui-Selsoulia et al. (2012)** provided a way to clarify the issue of correlation. The proposed heuristic is based on lagrangian form of relaxation to handle the integer formulate dilemma.

Wang (2013) extended a model that integrates EPQ and PM aiming to blend potentiality of essential adjustment and modifications. The proposed idea simultaneously locate the amount of inspections, search periods, EPQ and PM steps needed.

Zhao et al. (2014) proposed a joint method that better integrates the problem at the tactical level via repeatedly deciding a flow of MILP occurrences combined with adjustment of several specifications preceding every repetition.

Previous studies considerations were of either not realistic enough cases or incomplete. An iterative solution algorithm was proposed. **Xiang et al. (2014)** studied the joining structure in a recurrent inspection conditions follows a problematic requirement and unplanned output. The issue was expressed as a Markov procedure. The target was to lower the costs concord from formulation, holding and repair.

2.3.1 Economic Manufacturing Quantity Models

The classical EMQ is perhaps the first inventory management model, **Groenevelt et al. (1992)** provided an exact optimal and closed form approximate lot sizing formulas to study the response of sudden shut down and CM onto the issue. They proposed a couple of production regulation actions to treat the conflict of randomness. One suppose no continuity of operation after a failure and the other suppose the operation is instantly continued after a failure. Various structural properties for these policies are presented.

Sarper (1993) studied a sample problem with the target of lowering the missed vending cost along with guaranteeing no undone tasks. He derived a mathematical way to bundle the capacity of correction having small order big units.

Anily et al. (1998) considered finding the optimal schedule for activities with respective kinds given the constraint of one action being connected to one duration at most. They assumed having the value related to the class of action has an increasing linear relationship with the number of periods. A greedy algorithm and a heuristic based on regular cycles were proposed.

Vassiliadis and Pistikopoulos (2001) designed framework of a MINLP with the goal of analyzing the needed amount of repair plans on a predefined period for the sake of improving the system capability. **Cavory et al. (2001)** considered the appointing of corrective duties for a particular line of manufacture. A Taguchi method approach is used to discover the leading collection of sets for every variable and statistically test their outcomes.

Ben-Daya (2002) investigated the combined issue of EPQ and PM level for a defective operation with rising error rate following a general degradation probability function. He used an arithmetical illustration to exhibit the effect of loss in cost when moving away from control on PM.

Chung (2003) provided a superior resemblance to the issue than EMQ knowing that it is a good analogy for the perfect lot size (**Groenevelt et al. (1992)**). He studied the convexity (concavity) of the total annual cost function. Numerical examples were shown.

Lee (2005) came up with a cost/benefit paradigm in a faulty production environment with defective output condition and equipped capacity to support investment strategies about inventory and PM.

Lin and Gong (2006) focused on the influence of casual process breaks on the classical EPQ design having an expanding failure and within a non continuous stock control plan. The objective was to find the best way for lowering the overall setup, CM, stock carrying, degradation and missed sales expected expenses.

Kenne et al. (2007) developed a way to handle the issue having to connect the PM plans to an inventory age attached. Numerical examples and sensitivity analyses were included.

Lodree and Geiger (2010) studied line up obstacles based on rate altered actions (RMAs) and dependent running procedural times. They considered makespan problem of a independent range and dependent status stage.

Lu et al. (2013) proposed a joint model formulated as a mixed-integer linear program for combining run based PM into a capacitate lot sorting situation (CLSP). **Kazaz and Sloan (2013)** considered the case on a system that break down ongoing production actions and get better with repairs.

The objective was to identify the best choices at all levels as an attempt to improve the average expected run reward. A number of contributions were proposed.

Fitouhi and Nourelfath (2014) integrated noncyclic PM with tactical production planning in a different cases organization. The target was to come up with a joint formation that will lower the overall expenses of every model cost through out the running period.

2.3.2 Inventory Control Models

Srinivasan and Lee (1996) obtained an approach of control so that the industry cost frame composed of a group of expenses.

Pistikopoulos et al. (2000) came up with a setting formulated as a MILP model for system effectiveness optimization to clarify properties for maintaining operations at the planning step. Numerical example is used.

Okamura et al. (2001) generalized **Srinivasan and Lee (1996)** paradigm by thinking of a continuously repeated production/demand time running scheme. Sudden shut down happens in a Poisson process behavior.

Goel et al. (2003) considered the accuracy distribution during the run-up level and extended it to a simultaneous optimization framework of combined formulation of the issue in multipurpose procedure manufactures. Case was formulated as a MILP model. **Dieulle et al. (2003)** concentrated in developing a different artistic procedure built on the half correlated property of the growth activity of a continuously deteriorating system for the goal of computing the expected value of long time run.

Ben-Daya and Noman (2006) came up with a joining paradigm which supplies choices on stuck grades, manufacturing running extent and intervals of PM all together within a breaking up system.

Aghezzaf et al. (2007) defined a collection unit composed strategy for an integrated lot-allocation and PM structure that fulfill all units requirement throughout the line and lower the overall costs. Illustrative example is provided.

El-Ferik (2008) introduced a joint paradigm to decide on the best amount of output rounds (EPQ) and the interval of PM plans with the target of lowering the long time median estimate assuming that correction is incomplete and failure is at random.

Berthaut et al. (2011) resolved the joining issue of PM and production/inventory control strategy to lower the total price associated with CM/PM and storage carrying. They considered production cell with probabilistic maintenance lag in an unreliable mono machine/product space.

Nourelfath and Chtelet (2012) continue his work in **Nourelfath et al. (2010)** for a manufacturer includes a group of equivalent elements taking into account the attendance of errors and industrial dependence (CCF). **Dhouib et al. (2012)** proposed an integrated way for the issue at hand in a cell environment having faulty process. The target was to decide on a joining perfect plan to reduce the total value of production.

Yan-Chun Chen et al. (2013) drove an integrated solution over imperfect production/rework process while considering PM errors when determining EPQ. It's assumed a given percent of nonconforming units is possible to reworked where the remaining are regarded as wast. **Horenbeek et al. (2013)** purposed and classified a literature review a bout the issue and recommend some missing ideas. The work they presented was based on holding policies, maintenance features, lateness, single against multi components systems and optimization mechanisms. **Liao (2013)** considered backorder along with loss in stock owed to small manufacturing rate in an EPQ system, and forther more expanded to the case where process is failing and risk rate is growing. **Horenbeek et al. (2013)** thought of a imitation mechanism to look into the influence of fleet range on the joint issue where the quality of extra accessories can range. **Prakash et al. (2013)** developed the mathematical model for a manufacturing inventory system under CM and PM repair time, failure and sudden stops. The perfect run time which lowers the overall run cost is extracted.

Zhang et al. (2014) proposed an effective technique for dealing with the issue having a growing error rate. It differs from the case where failure is addressed independently under the static realization. **Chakraborty and Giri (2014)** studied the cooperative influence of imperfect rework of malfunctioning units, shift, inspections and imperfect PM on the perfect decisions for a deteriorating production system. The formulation was done for the general situation and resolved under a very famous inspection strategies, known as the cyclic and the fixed cumulative hazard. **Tsao (2014)** considered a paradigm for a manufacturing system having limited warehouse space, business trust and maintenance. The target was to define the best assembly work time to minimize the overall expenses.

2.4 Production and Quality Integrated Models

2.4.1 Imperfect Economic Production Quantity Models

The EPQ paradigm supposes that components are developed in a perfectly stable manufacturing action having a constant install value. **Porteus (1986)** introduced a straightforward formula that clarifies the considerable relation of lot amount and quality. Cases of decreasing setup costs, chance of moving out of state and simultaneously do both of the options were under quality investigation. **Rosenblatt and Lee (1986)** studied the effect of linear, exponential, multi-state deteriorating processes and an insufficient operation to the perfect production rotation. In other work **(1986)**, they provided a proportional examination in crumbling systems for the persistent and cyclic inspection behaviors where the cost involves layout, check up, stock holding, imperfect and repair values. They considered tradeoffs between both behaviors.

Keller and Noori (1988) extended **Porteus (1986)** effort adding the likelihood occurrence of requests through the start time. Using a logarithmic cost function, clear resolution were acquired in a particular demand circulations.

Chand (1989) recognized a small lot sizes knowing that the traditional EOQ approach leads to a large lots. The entire value is to be decreased interpreted to an upgraded operation quality and lower starting costs. **Cheng (1989)** proposed a paradigm having an adjustable and incomplete manufacture action. Then defined and resolved the inventory choice issue as a (GP).

Cheng (1991) recommended EOQ paradigm with conditional requirement element value and deficient procedure. The backlog arrangement issue is then formulated and solved as a GP. **Mehrez et al. (1991)** studied quality from the technology effect over the perfect manufacturing amount size. They formulated duo phases problematic program. An algorithm and numerical example to find the optimal solution were presented.

Hong (1995) examined the influence of the assembly lead times (MLT) and PQ on the optimal lot amount also on the corresponding overall relevant value (TRC). Both of these fundamental principles, shortened MLT and high PQ are in demand to fulfill the just-in-time (JIT) production.

Hariga and Ben-Daya (1998) thought of the EPL issue with imperfect production processes. They considered general time of variation out of position distributions and provided based/free allocation limit on the perfect value rather than using the exponentially one for the period.

Kim and Hong (1999) derived using EMQ a perfect minimum average cost and manufacture run distance having linear, steady and exponential error growing operations. **Voros (1999)** developed a technique that considers PQ enhancement, structure cost decreasing and bounded structure time assuming restricted rate and an almost zero cost of completion.

Salameh and Jaber (2000) developed a mathematical mechanism for a construction/inventory position in which the input and output units are out of standard. The model is an extension of classical EPQ/EOQ. **Ben Daya**

and Hariga (2000) expanded the economic LSP with a numerical formation considering the impact of incomplete characteristic and operations restoration.

Chiu et al. (2007) derived an advanced guideline for a manufacturer perfect sizing issue under the bonds of reshape and unsystematic scrap to lower the total estimated expenses along with meeting standards of service.

Oke et al. (2008a) considered an up to date technique to evaluate the sensibility of TPM scheduling evaluation test. Furthermore in **(2008b)**, they studied a facility maintenance scheduling model for a shipping firm which incorporates opportunity and inflationary costs. The objective is minimizing the costs of maintenance (MC), maintenance-Inflation (MIC), maintenance-opportunity (MOC) and combined maintenance opportunity-Inflation (MOIC).

Chen et al. (2010) advanced a combining idea for the EPQ problem thinking about the conditions of having damaged operations, correction and deficiency. Numerical analyses were proposed. **Faria et al. (2010)** proposed an analytical model and a procedure for the layout and investigations of industrial manufacturing operations with respect to the joint assessment of the cost and quality of service. The industrial production system is a sequence of accomplishment operations corresponding to the cost-effectiveness and the time delivery of a specified quantity. **Sana and Chaudhuri (2010)** determined the best average, lot portion, working period and safety interest of production through developing a scheme of tactics. Numerical example was investigated.

Ghosh et al. (2011) considered the issue for a failing element under time conditional demand/fractional backlogging. Model was determined empirically to acquire the best results. **Abid and Tadj (2011)** studied the issue having elements and basic components are under potential failure. They considered the case of unlimited shifts and relaxed the assumptions of consistent degradation and steady system rates to act as a common time functions. **Madhavi et al. (2011)** conducted a technique of EOQ for failing elements with seconds sale.

Wang and Tsai (2012) developed an excellent approach for the issue having a various common shift allocation. Inspection guideline for supplies and units was proposed. **Yoo et al. (2012)** proposed a perfect paradigm for the issue having search quality placement combining the values available. The target is locating the best Type I/II examination error ratios, modification frequency and defective proportion that increases overall earnings and decreases overall quality cost. **Jeang (2012)** work out a joining technique that allow specifying production lot size, procedure specifications and rotation periods all at once at the beginning phase of designing and managing for production.

Tsao et al. (2013) considered both PM and CM to increase the system reliability. Within process degradation and business traffic the goal was to define the perfect manufacture interval and correction regularity at the same time lowering the whole cost. **Bouslah et al. (2013)** looked at the joint determination for a best proportion volume with manufacture jurisdiction actions having an imperfect and unreliable environment giving that acceptance sampling outline was implemented for monitoring the lots production activity.

2.4.2 Production Planing and Quality Models

Lee and Rosenblatt (1987) developed a simple relationship of combined observation of manufacture cycles and preserving by inspection for the economic manufacturing paradigm to determine simultaneously the effectiveness of this type of maintenance. The issue was settle through applying an estimation for the cost operation.

Peters et al. (1988) proposed an integrated cost pattern for incorporating the control systems of Bayesian quality and steady order volume in an approval sampling share condition. A formulation was established to discover the operating parameters for the combined systems.

Lee and Rosenblatt (1989) considered perfecting the regularly utilized identical interval repair schedule and developed sufficient conditions for it. They considered in the explanation step the concurrent limitation of the number of maintenance inspections, length of the manufacture run, EMQ and maximum level of backorders. An algebraic case was used to clarify the procedure optimal rate achieved compared to cost obtained by using the classical EMQ model.

Ohta and Ogawa (1991) studied the jointly determination of perfect economic production and analysis consistency for an individual unit with inspection error.

Goyal et al. (1993) developed a strategic scope for a functional layout for manufacturing. Accepts of examination, output lot categorizing and modification were integrated.

Rahim (1994) proposed a joint determination model for an EPQ, control chart design and check up schedule in a defective output procedure problem. Objective was to define the best variables of chart layout and manufacture batch for the sake of getting the cooperative cost of quality and inventory minimized. Examples of Weibull shock models were provided. **Liou et al. (1994)** combined Type I/II investigation faults within economic manufacturing paradigm having an insufficient environment where the shift has a common behavior and the analysis period is random. The target was to minimize overall expenses while locating the perfect manufacture cycle distance and perfect inspection number. Sensitivity analysis is provided.

Tseng (1996) integrated a PM theory to the failing issue at hand and attained a perfect plan for it. He considered a group of distributions IFR , Weibull and intense value to clarify the suggested model.

Ben-Daya and Makhdoum (1998) considered the collective optimization between economic production/design of monitoring graph and studied the influence of several PM arrangements on it. All three accepts of production were determined through this model for each policy. Growing risk rate Weibull shock case was utilized to clarify the effects.

Wang and Sheu (2003) jointly determined the rotation, examination intervening periods and correction standard by developing a arithmetical paradigm employing the Markov chain. There optimality were specified through lowering the expected mean value.

Manna et al. (2009) considered a delayed declining units having the demand average as a conditional on time issue and developed an EOQ model for it. Deficiency and backlogged are recognized to a limited degree. Numerical examples where used to illustrate the results.

Abid and Tadj (2011) combined an inventory model having raw equipments and units with conditional deflection. They developed an accurate formulation to the listing overall value.

Jain and Naresh (2012) investigated a group of stages break down environment associating the notions of inspection and CM/PM. **Yoo et al. (2012)** considered a settled manufacture/supply procedure and studied both inner and outer consequence of out of order production and receipt due to the deficient at the examination processes. With regard to sampling and whole lot checking inspections they developed revenue raise insufficient standard inventory paradigms. **Hajji et al. (2012)** considered an unreliable multiple-product manufacturing system and proposed a combined control/characteristics framing agreement making technique. Due to randomness and correction, the target was to maximize the long term average gain of a mutual steps of quality and quantity conditional trading income while minimizing stock and stack expenses. **Pan et al. (2012)** considered unifying EPQ, SPC and correction concepts. The target been reducing costs related to the implementation of every objective through collecting the best decision variables.

Shih and Wang (2013) extended a previous production and inspection (PI) model considering an imperfect process that has a general hazard rate instead of a constant failure rate. They developed a algorithm to define the perfect PI policy that lowers the expected overall value, which includes the cost of inspection, shortage and production.

2.4.3 Other Integration Models

Rahim and Banerjee (1988) suggested an investigation algorithm and a diagrammatic procedure to handle the issue of finding the perfect manufacture run in an operation subject to unsystematic linear movement.

Schneider et al. (1990) addressed the issue of deciding the opening standard of the job average and the scale where it must be regulated back to that opening state. They developed optimal and simple approximate solutions rather than the mostly utilized linear straightforward strategy to this issue.

Lee and Zipkin (1992) considered a simple production system that is contained employ a various kanban methodology with a possible malfunctioning element at every phase.

Gunasekaran et al. (1995) came up with a statistical pattern for capacity and quality control various parameters problem. They employed the concepts of smaller lot-size production and dynamic process quality control to eliminate defective items.

Yeh et al. (2000) described the issue for a breaking application through the implementation of double stages extended term Markovian chain in which the outcomes will be offered and guaranteed a free of charge minimum fix.

Rahim and Fareeduddin (2011) advanced a formation of an arithmetical paradigm for the issue having a deficiency for units offered for sale under assurance of a very little restoration cycle. The objective was to minimize the entire cost.

Singh et al. (2012) they considered both cases where production is within control resulting in an outcome of hight quality units also the case when it's running beyond the boundaries resulting in a low quality outcomes.

Valliathal and Uthayakumar (2013) studied a manufacture paradigm through a limitless time perspective for a delayed Weibull failing units having complete backlogging and also extended to the finite time horizon. **Huang et al. (2013)** A Weibull capability law technique was implemented to outline the deficiency and a passive binomial examining was taking in to acquire skill in the functioning cases. **Darwish et al. (2013)** developed an incorporated targeting method for the issue where demand is considered to be an unplanned parameter. The objective was to simultaneously discover in (Q-R) persistent analysis paradigm the perfect average, portion size and exchange point.

2.5 Maintenance and Quality Integrated Models

Quality control in terms of charts along with the plans of PM are an important experimentation areas that lately have been given a major deal of observation in the reliability literature. Systems are observed through quality charts to keep them away from expensive breakdowns. The sample size,interval and control limits are the main elements under observation in the chart.

2.5.1 Maintenance and Economic Design of Control Charts

Banerjee and Rahim (1988) proposed a unit price paradigm that utilizes changing sampling periods under Weibull shock models instead of the fixed distance ones used by the classical **Duncan (1956)** technique of Markov impact paradigm.

Moskowitz et al. (1994) studied the consequence of the option of procedure failure structure on the design of SPC model and $\overline{X}$ chart framework employing a persistent time approach.

Chiu and Huang (1995) gave a couple of $\overline{X}$ and R along with $\overline{X}$ and s^2 graphs combined with the effect of PM. They also studied the systematic and unsystematic testing period arrangements having no PM. **Ben Daya and Duffuaa (1995)** planned a pair of techniques for connecting maintenance with quality and designing their combined optimization. First plan was established considering that correction actions changes the failing paradigm. Second plan was established considering Taguchi's method of quality in which PM is carried out if the quantity of variance regulating standard extended a specified edge.

Chiu and Huang (1996) using the similarity designs determined by **Duncan (1956)** approach. They modeled steady and unsteady operations while looking for assignable reason under the assumption that the correcting and the insufficient outcome values are setback functions. Several numerical examples comparisons were illustrated.

Ben Daya and Rahim (2000) solved the issue of optimally connecting correction actions to the monitoring $\overline{X}$ graph considering a deteriorating process that falls into a growing failure average feasibility allocation. The effect of the correctness level on quality control costs is illustrated using a Weibull impact. **Cassady et al. (2000)** introduced a mutual planning of $\overline{X}$ chart and PM age-replacement policy having a declining operation that goes beyond standard limits as a result of industrialization tools errors. A simulation development technique was implemented to reveal the performance.

Linderman et al. (2005) revealed the usefulness of coordinating SPC and repair management through simultaneously optimizing them for the goal of lowering their overall costs.

Zhou and Zhu (2008) developed a paradigm that incorporate CC and MM. Cost reduction under investigation was analyzed to detect the best variables through a grid seeking algorithm. **Yeung et al. (2008)** a disconnected period Markovian conclusion mechanism was developed for the issue with the intention of finding the perfect strategy that lowers the costs of correcting and inspecting. **Wu and Makis (2008)** thought about both economical and economic analytical design of a condition-based maintenance (CBM) χ^2 where failure behave as a three steps constant time Markovian string. Objective was to lower running medium repair cost through perfecting the chart parameters.

Panagiotidou and Nenes (2009) considered monitoring the issue by a Shewhart control chart. The developed pattern grant the assurance of parameters that reduces the anticipated unit price of quality and maintenance.

Charongrattanasakul and Pongpullponsak (2011) considered the issue according to an EWMA control diagram. The objectives were to advance the connectivity between SPC and PM. This was done in **(Zhou & Zhu, 2008)** model using four control plans. In this model they increased the plans from four to six considering $(n,\ h,\ w,\ k,\ \eta,\ r)$. **Mehrafrooz and Noorossana (2011)** developed and integrated model which considers complete failure using the concept of SPC and planned maintenance simultaneously. Six different scenarios were proposed. **Yin and Makis (2011)** developed an optimization mechanisms for a three cases CBM design based on a multivariate Bayesian graph. Control borders and failure event were outlined. Results show that the multivariate Bayesian is preferable over the CBM χ^2 graph. **Chen et al. (2011)** incorporated Taguchi quality function for the economical plan with PM.

Pandey et al. (2012) developed minimal CM and imperfect PM integrated with Taguchi loss model. The objective was to decide which values are perfect for the model variables. **Wang (2012)** considered Bayesian monitoring with real time CBM to optimize the anticipate average running cost of complex systems. **Panagiotidou and Tagaras (2012)** developed an integrated SPC and PM paradigm for a procedure with three situations, two practical and one impractical failure.

Liu et al. (2013) thought of the issue for two corresponding element chain frameworks with CBM. A five level steady period Markovian string described the equipment. **Morales (2013)** studied ESD for both flow charts $\overline{X}$ and S in a cost example that unite PM with public error allocation. **Xiang (2013)** suggested a unified paradigm for the common optimization of SPC and imperfect PM. The production operation failing behavior was sampled as a distinct time Markovian series.

2.5.2 Other Integrated Model

Pate-Cornell et al. (1987) considered four correction strategies for monitoring crumbling systems and used a Markovian technique to differentiate the failing activity.

Tagaras (1988) presented an economical pattern that simultaneously optimizes actions monitoring and maintenance procedures design parameters. Numerical examples of a Markovian downturn hypothesis were considered.

Collani (1999) investigated an economic approach including wear-out phenomena compensated by means of continuous maintenance with a decision function reacting simultaneously on movements in the operation medium and instability.

Panagiotidou and Tagaras (2007) optimized PM in a two quality cases, within limits and out of limits. First they derived structure of the devices age. Then they provided amounts for the two analytical maintenance periods, shift and failure.

Panagiotidou and Tagaras (2008) considered two types of maintenance in the development of the issue having two quality situations, MM where age remains the same after rapiers and perfect PM where age is restored to the beginning.

Mehdi et al. (2010) develop a combined QC and PM scheme in s system with convenient and inconvenient elements. The target was to decide simultaneously the optimal rejection rates and buffer size.

Berrade et al. (2012) studied false alarms and wrong rejections in a framework having inspection and renewal theories.

2.6 Production Maintenance and Quality Models

Tseng et al. (1998) investigated evenly spaced and evenly cumulative risk imperfect maintenance action plan in failing systems to realize the EMQ. **Rahim and Ben Daya (1998)** proposed a popularized paradigm in a permanent manufacture environment for concurrent resolution of it's amount, analysis timetable and control flow chart.

Huang and Chiu (1995) developed a two monitoring approaches towards a better planning of production, scheming inspection and PM. The goal was to calculate the perfect manufacture cycle duration while lowering the cost for the two approaches (PM put to use and not put to use). **Makis and Fung (1995)** gave an EMQ paradigm to study the influence of the protective restoration on the perfect lot amount and check up duration. Numerical examples using Weibull distribution was presented.

Ben Daya (1999) considering a common chance distribution for running within limits having a rising failure percentage. He developed a paradigm that simultaneously represent perfecting the EPQ, $\overline{X}$ flow chart and the correction duration.

Rahim and Ben-Daya (2001) considered that the failing elements follows an arbitrary proportion with an ordinarily distinctive quality allocation for studying the issue. In another work **(2001)**, they reviewed the literature for the work which combines the three notions giving ideas and suggestions for following research.

Chelbi et al. (2008) proposed a link among EMQ, age related PM and quality for an uncertain manufacturing systems making convenient and inconvenient outcomes.

Pandey et al. (2010) reviewed the literature for all attempts on coordinating the three main aspects of all manufacturing environments.

Rahim and Shakil (2011) went through EPQ, $\overline{X}$ non constant $(n,\ k\ and\ h)$

and PM levels. A tabu seach algorithm was used to discover the perfect values. **Pandey et al. (2011)** attained two separate models for joint optimization of the three manufacturing system aspects. They first developed a model to join the correction actions to the quality monitoring. Then they integrated the optimal PM interval obtained among the series of batches that will be scheduled. **Hadidi et al. (2011)** reviewed the previous studies on the complete joining issue in the literature dividing them as interrelated and integrated presented formulations.

Colledani and Tolio (2012) showed a general hypothesis to evaluate the incorporated techniques in a different phase nonparallel manufacture organizations.

Haoues et al. (2013) considered a single output random break down and improvable machine with the approach of integrating all three. A mathematical model was proposed and a based optimization genetic design was used to deal with the proposed model.

Fakher et al. (2014) integrated production and sales planning with PM scheduling taking into account quality aspects of the production system.

Although interest in integrating these areas production, quality and maintenance exist for some time and many papers appeared in the literature still many aspects of the integration can be improved.

Gabs in the literature includes having most of the maintenance optimization models contemplates a steady amount of the cost of CM. Nonetheless, the breakdown of the machine additionally comprises performance declination in the form of bad quality generating rejection of outcome assembled by the instruments. In such a way the set back of CM consist of down time damages, adjustment/restoration costs and the rejection cost. Also the integrated models unconditionally neglect the probability of tools deficiency in the sense of instant discontinuation of system or incorrect operating of the gear that consequence a bad output quality and suggest a correction activity.

The purpose of this thesis is to enhance the level of integration by providing an alternative approach for integrating the three functions.

CHAPTER 3

AN INTEGRATING MODEL FOR PRODUCTION SCHEDULING AND PREVENTIVE MAINTENANCE PLANNING

3.1 Introduction

The ambition of this chapter is to develop a mathematical method that integrates production scheduling and PM planning for a single machine. The target is to define the optimal production schedule and PM simultaneously to reduce the cost. The motivation behind the integration is to be able to plan maintenance and jobs order for production. The completion time values for the batches are stochastic considering that the production unit might fail while operating on a batch and the chance of having a machine failure is affected by PM decisions. Two models from the literature are presented. One for PM and the other for jobs scheduling. Then they are integrated in a single model for determining the optimal preventive maintenance and jobs scheduling to reduce the anticipated cost of tardiness. Section 3.2 contains the statement of the problem followed by the integrated model in section 3.3. Section 3.4 describes the outcomes and presents sensitivity analysis. The chapter is concluded in section 3.5.

3.2 Statement of The Problem

Consider a manufacturing system with one machine that is needed to process a set of n jobs as a batch of size $N_{[i]}$. The machine in use to operate the tasks is subject to breakdown and the duration to failure is administered by a two-parameter Weibull probability allocation having the shape value exceeding 1. The failure of a machine tool is described as any incident that either leads the tool down or leads to the machine still running but producing a bigger rejections. Two types of maintenance actions are studied, minimal CM and perfect PM. When the machine break down, we suppose it's minimally repaired in t_{CM} time units, i.e. the tool is renewed to an operating position, however it's age will remain the same as before failure. This suggests that, after the occurrence of failure, the machine worker carries out just enough maintenance to continue machine function.

Because the shape is more than 1, probably it's functional to perform PM on the machine in order to lower the growing hazard of tool failure. The PM restores the machine in t_{PM} time units to it's original new condition, in which the machine age turn into zero. It is assumed that an age based PM strategy is practiced, i.e. PM is implemented on the machine after certain time units of working. It is also assumed that jobs disrupted by a failure can be continued after adjustment with an added time penalty ($PN_{[i]}$), and tasks are not blocked for PM.

Since the machine may or mayn't fail, it will cause a stochastic behavior affecting the expected completion time of each batch. The number of fails, throughout jobs processing is highly influenced by the tool age. When a lot of jobs is postponed beyond its due date owning to failures a penalty cost is incurred and is formulated through

$$Penalty\ Cost\ =\ (PN_{[i]})\ (Completion\ time -\ Due\ date)$$

The problem that being addressed here is to develop a combined production scheduling and PM designing model that provides the optimal PM interval, batch sequence and PM plan. Our goal is to minimize the overall penalty cost of tardiness (TPC) and maximize machine availability.

3.3 Model Development

In this part we explain in details the development of the joining function that integrates the costs associated with performing maintenance ordering, quality and production organizing on the system.

The integrated model of production organizing and maintenance positioning is presented. The target of the model is to discover the optimal PM term associated with the optimal batch sequence. The notations used in this model are presented in the following table.

$\mathbf{n}$	number of jobs to be scheduled
$\mathbf{N}_{[\mathbf{i}]}$	batch size
$\mathbf{x}_{\mathbf{i}j}$	job sequencing decision variable
$\mathbf{p}_{[\mathbf{i}]}$	processing time of i^{th} task in the series
$\mathbf{d}_{[\mathbf{i}]}$	due date of the i^{th} task in the series
$\mathbf{P}N_{[\mathbf{i}]}$	penalty of the i^{th} task in the series
$\mathbf{C}_{[\mathbf{i}]}$	completion time of the i^{th} task in the series
$\theta_{[\mathbf{i}]}$	lateness of the i^{th} task in the series
η	Weibull distribution scale parameter of $\mathbf{T}$
β	Weibull distribution shape parameter of $\mathbf{T}$
$\mathbf{t}_{\mathbf{C}M}$	time required to carry out corrective maintenance
$\mathbf{t}_{\mathbf{P}M}$	time required to carry out preventive maintenance
τ	ideal PM interval

τ^*	optimal value of τ
$\mathbf{N}(\tau)$	number of machine failures in τ time units
$\mathbf{A}\,(\tau)$	stable state machine availability
$\mathbf{T}$	time to machine failure
$\mathbf{z}(\mathbf{t})$	risk function of $\mathbf{T}$
$\mathbf{y}_{[\mathbf{i}]}$	PM batch decision variable
$\mathbf{a}_{[\mathbf{0}]}$	age of the machine before job scheduling and PM planning
$\bar{\mathbf{a}}_{[\mathbf{i-1}]}$	age of the machine immediately before the i^{th} job in the schedule
$\mathbf{a}_{[\mathbf{i}]}$	age of the machine after the i^{th} job in the schedule
$\mathbf{F}\,(\mathbf{t})$	probability of having a machine failure
$\overline{\mathbf{F}}\,(\mathbf{t})$	probability that the machine does not fail

Table 3.1: The joint model of scheduling and maintenance symbols

3.3.1 The Preventive Maintenance Planning Model

The process and correction of the machine can be formed as a renewal action since that PM is supposed to bring back a machine into a "good as new" status with the end of each PM batch as a renewal point. This renewal process can indicate the event of failures throughout any of it cycle applying a non-homogeneous Poisson process since failures are maintained through minimal repair.

Let $N(\tau)$ be the amount of machine failures throughout each cycle and $z(t)$ be the hazard function for Weibull probability distribution. Then, the anticipate number of repairs is

$$E\left[N\left(\tau\right)\right]=\int_{0}^{\tau}z\left(t\right)\;dt\;=\int_{0}^{\tau}\frac{\beta}{\eta^{\beta}}\;t^{\beta-1}\;dt\;=\left(\frac{\tau}{\eta}\right)^{\beta} \tag{3.1}$$

The availability of the machine is largely based on what types of downtimes considered in the analysis. The downtime period during each cycle consists of the expected number of repairs of range t_{CM} and the PM action of range t_{PM}. Therefore, the stable case availability $A\left(t\right)$ of the machine as a function of the ideal PM interval is

$$A\left(\tau\right)=\frac{\tau}{\tau+t_{PM}+E\left[N\left(\tau\right)\right]*t_{CM}}=\frac{\tau}{\tau+t_{PM}+\left(\frac{\tau}{\eta}\right)^{\beta}*t_{CM}} \tag{3.2}$$

Thus, the optimal ideal PM interval is

$$\frac{\partial A\left(\tau\right)}{\partial\tau}=0$$

$$\frac{1}{\tau+t_{PM}+\left(\frac{\tau}{\eta}\right)^{\beta}*t_{CM}}-\frac{\tau\left(1+\frac{\left(\frac{\tau}{\eta}\right)^{\beta}\beta*t_{CM}}{\tau}\right)}{\left(\tau+t_{PM}+\left(\frac{\tau}{\eta}\right)^{\beta}*t_{CM}\right)^{2}}=\frac{t_{PM}-\left(\frac{\tau}{\eta}\right)^{\beta}t_{CM}\left(\beta-1\right)}{\left(\tau+t_{PM}+\left(\frac{\tau}{\eta}\right)^{\beta}*t_{CM}\right)^{2}}$$

$$\frac{t_{PM}-\left(\frac{\tau}{\eta}\right)^{\beta}t_{CM}\left(\beta-1\right)}{\left(\tau+t_{PM}+\left(\frac{\tau}{\eta}\right)^{\beta}*t_{CM}\right)^{2}}=0$$

Then

$$\tau^* = \eta \left[\frac{t_{PM}}{t_{CM}\left(\beta - 1\right)} \right]^{\frac{1}{\beta}} \tag{3.3}$$

Therefore, the optimal PM plan should be considered after τ^* units of time.

3.3.2 Job Scheduling Model

The goal of production scheduling is to select an optimal series for the tasks. Suppose the single machine considered for jobs processing ignores the possibility of failure, so maintenance is not required. Preempting one job for another is not allowed. Assuming that the objective is to minimize the total penalty of jobs tardiness, let

$$x_{ij} = \begin{cases} 1 & if\ the\ ith\ job\ performed\ is\ job\ j. \\ & i = 1,\ 2,\ \ldots n, \\ & j = 1,\ 2,\ \ldots n, \\ 0 & otherwise. \end{cases}$$

$$PN_{[i]} = \sum_{j=1}^{n} PN_j\ x_{ij} \qquad i = 1, 2, \ldots, n$$

$$p_{[i]} = \sum_{j=1}^{n} p_j\ x_{ij} \qquad i = 1, 2, \ldots, n$$

$$d_{[i]} = \sum_{j=1}^{n} d_j\ x_{ij} \qquad i = 1, 2, \ldots, n$$

$$C_{[i]}=\sum_{k=1}^{i} p_{[k]} \qquad i = 1, 2, \ .. ., n$$

$$\theta_{[i]} = \max\left(0, C_{[i]} - d_{[i]}\right) \tag{3.4}$$

This production scheduling issue is solved applying complete enumeration with $n!$ potential job sequences in which every location in the schedule gets a single job and every job is allocated to a single location in the sequence. The resulting mathematical programming formulation to compute the objective function value for each sequence is

$$\text{Minimize} \qquad \sum_{\mathrm{i=1}}^{\mathrm{n}} \left(\mathrm{PN_{[i]}}\right)\times\theta_{[\mathrm{i}]} \tag{3.5}$$

Subject to

$$\sum_{j=1}^{n} p_j \ x_{ij} = 1 \qquad i = 1, 2, \ .. ., n$$

$$\sum_{i=1}^{n} p_j \ x_{ij} = 1 \qquad j = 1, 2, \ .. ., n$$

3.3.3 The Integrated Model

In order to obtain the optimal time after which the preventive maintenance should be performed on the machine, i.e. PM interval on the tool (PM_I), we consider the time to perform PM as a batch to be inserted in the production sequence with its processing time as the expected time of performing PM (t_{PM}) and its due date as the optimal ideal PM interval time (τ^*).

Since the machine may or mayn't fail while processing a task, the completion time of a batch is strongly affected by the probability of a machine failure. Respectively, this probability is influenced by the machine age and PM actions.

The following assumptions are made:

1. The batch manufacturing time is the aggregate of the processing times of its tasks and the setup time.

2. A job cannot be permitted by another job.

3. The machine can't be interrupted for PM till all the tasks in a batch are finished. So, the industrialist can pick a PM operation only prior to the beginning of serving a job sequence.

Let the age of the machine before the starting the schedule and performing PM decisions be $a_{[0]}$, the age of the machine instantly before carrying out the ith batch in the sequence (after PM batch, if any) be $\overline{a}_{[i-1]}$ and the age of the machine instantly after the ith batch in the sequence be $a_{[i]}$.

Let $y_{[i]}$ be the variable that restores the machine age after the PM actions (decision) defined as

$$y_{[i]} = \begin{cases} 1 & when\ the\ PM\ batch\ is\ shceduled\ befor\ the\ i^{th}\ batch \\ & i\ =\ 1,\ 2,\ \ldots\ n \\ 0 & otherwise \end{cases}$$

Then, machine age is defined as

$$\overline{a}_{[i-1]} = a_{[i-1]} \left[1 - \left(y_{[i]}\right)\right] \tag{3.6}$$

$$a_{[i]} = \overline{a}_{[i-1]} + p_{[i]}$$

The probability of having a machine failure acts accordingly to a Weibull distribution with T as the time until failure for a new machine and F (t) as the cumulative distribution function of T. Then,

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \tag{3.7}$$

$$\overline{F}(t) = 1 - F(t)$$

Therefore, the probability that the machine fails while processing the *ith* batch $\left[\overline{a}_{[i-1]} < T < a_{[i]}\right]$ is determined as follows

$$F\left(a_{[i]} = p_{[i]} + \overline{a}_{[i-1]} \;\middle|\; \overline{a}_{[i-1]}\right) = \Pr\left\{T \leq p_{[i]} + \overline{a}_{[i-1]} \;\middle|\; T > \overline{a}_{[i-1]}\right\}$$

$$= 1 - \exp\left[-\left(\frac{p_{[i]} + \overline{a}_{[i-1]}}{\eta}\right)^{\beta} + \left(\frac{\overline{a}_{[i-1]}}{\eta}\right)^{\beta}\right]$$

$$= 1 - \exp\left[-\left(\frac{a_{[i]}}{\eta}\right)^{\beta} + \left(\frac{\overline{a}_{[i-1]}}{\eta}\right)^{\beta}\right] \tag{3.8}$$

Define $\Phi_{[i]}$ as

$$\Phi_{[i]} = F\left(a_{[i]} \;\middle|\; \overline{a}_{[i-1]}\right) \qquad i = 1, 2, \ldots, n, \tag{3.9}$$

$$\overline{\Phi}_{[i]} = 1 - F\left(a_{[i]} \mid \overline{a}_{[i-1]}\right) \qquad i = 1, 2, \ldots, n,$$

While performing PM i.e. processing the PM batch, the probability of having machine failure during PM is

$$\Phi_{[i]} = 0 \qquad i = PM\ batch \tag{3.10}$$

$$\overline{\Phi}_{[i]} = 1$$

Now, due to the maintenance actions the completion time of batch $C_{[i]}$ is a discrete random variable that rely on the coming elements:

1. The age of the tool instantly before manufacturing the batch ($\overline{a}_{[i-1]}$).
2. The processing time of the batch and the completion time of previous batches.
3. Probability of having a machine breakdown while processing a batch and the corresponding repair time.

Therefore,

$$C_{[i]} = \left(\sum_{i=1}^{i} p_{[i]}\right) + V_{[i]} \qquad i = 1, 2, 3, \ldots n \tag{3.11}$$

Where, $V_{[i]}$ is a discrete random variable defined for considering the machine failures and the time to correct them, it can take two possible values zero or t_{CM}. Let $N_i = \{1, 2, \ldots i\}$ and $N_{i,k}$ denote a subset of N_i containing k elements.

Then, $V_{[i]}$ has the coming probability mass function:

$$\pi_{[i,k]} = \Pr\left\{V_{[i]} = k \cdot t_{CM}\right\} = \sum_{N_{i,k}} \prod_{l \in N_{i,k}} \Phi_{[i]} \prod_{l \notin N_{i,k}} \overline{\Phi}_{[i]} \quad , \tag{3.12}$$

$$k = 0, 1, 2, \ .. \ i \quad ,$$

Where,

$$\Phi_{[i\ =PM\ \ Batch]} = 0 \qquad \overline{\Phi}_{[i\ =PM\ \ Batch]} = 1$$

Thus, the batch completion time will be

$$C_{[i,k]} = \left(\sum_{i=1}^{i} p_{[i]}\right) + k \cdot t_{CM} \quad , \qquad k = 0, 1, 2, \ .. \ i \quad , \quad i \ = \ 1, \ 2, \ . \ . \ ., \ n \tag{3.13}$$

Then, the expected completion time of batch i in the schedule is given by

$$E\left(C_{[i]}\right) = \sum_{k=0}^{i} C_{[i,k]} \ \pi_{[i,k]} \tag{3.14}$$

The PM interval for the machine will be the time completed prior to start processing the PM batch and is given as

$$PM_I = a_{[0]} + E\left(C_{[i-1]}\right) \qquad i \ = PM \ batch \tag{3.15}$$

The number of PM intervals to be inserted in the sequence is an integer defined as

$$N_{PM} = \frac{\sum_{i=1}^{n} p_i}{\tau^*} \qquad N_{PM} \geq 0 \tag{3.16}$$

The penalty cost will occur when a batch is delivered after its due date and when the PM batch is delivered before or after its due date (ideal PM interval).

Let $\Theta_{[i]}$ be the tardiness of batch i. Note that $\Theta_{[i]}$ has $(i+1)$ possible values such as

$$\theta_{[i,k]} = \max\left(0, C_{[i,k]} - d_{[i]}\right) \qquad k = 0, 1, 2, \ .. \ , i \tag{3.17}$$

For the PM batch the earliness and tardiness are given by

$$\theta_{[i=PM\ \ Batch, \quad k]} = \left|C_{[i=PM\ \ Batch, \quad k]} - \tau^*\right| \qquad k = 0, 1, 2, \ .. \ , i \tag{3.18}$$

Thus, the expected lateness of the *ith* batch in the sequence is given by

$$E\left(\Theta_{[i]}\right) = \sum_{k=0}^{i} \theta_{[i,k]}\ \pi_{[i,k]} \tag{3.19}$$

Therefore, the overall penalty cost as a result of batch and maintenance delays can be calculated as

$$\mathrm{TPC}_{\mathrm{scheduling\ \&\ maintenance}} = \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{PN}_{[\mathrm{i}]}\ \mathrm{E}\left(\Theta_{[\mathrm{i}]}\right) \tag{3.20}$$

The developed mathematical programming method of the integrated issue is presented by

$$\text{Minimize } \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{PN}_{[\mathrm{i}]}\ \mathrm{E}\left(\Theta_{[\mathrm{i}]}\right) \tag{3.21}$$

Subject to

$$\sum_{i=1}^{n} x_{ij} = 1 \qquad j = 1, 2, 3, ..n$$

$$\sum_{j=1}^{n} x_{ij} = 1 \qquad i = 1, 2, 3, ..n$$

$$p_{[i]} = \sum_{j=1}^{n} p_j \ x_{ij} \qquad i = 1, 2, \ .. ., n$$

$$x_{ij} \quad binary \qquad i = 1, 2, 3, ..n$$

$$y_{[i]} \quad binary \qquad i = 1, 2, 3, ..n$$

3.4 Numerical Example and Results

In this part, a descriptive illustration for the model developed earlier is shown utilizing the data in the literature (**Richard Cassady, 2003**). For the numerical analysis, a program is developed to solve any n number of batches using Maple 18 software.

Consider a single machine production system that is subject to failures. The machine has the following failure, PM and repair characteristics: a two parameter Weibull distribution with $\beta = 2$ and $\eta = 100$ as the shape and scale parameter, time to carryout preventive maintenance $t_{PM} = 5$ and time to carryout corrective maintenance $t_{CM} = 15$. Assume the age of the tool before making the job arranging and PM determining is $a_{[0]} = 68$. The machine will be processing a set of 3 batches having the following parameters

Batch	Processing time	Due Date	Penalty
1	23	67	10
2	28	114	2
3	43	65	5

Table 3.2: Parameters for processing a set of three batches

The first procedure in our current explanation is to determine the optimal idle preventive maintenance intervals i.e. the due dates of the PM batches and the number of PM batches to be introduced to the sequence.

$$\tau^* = \eta \left[\frac{t_{PM}}{t_{CM}\left(\beta - 1\right)} \right]^{\frac{1}{\beta}} = 100 \left[\frac{5}{15\left(2-1\right)} \right]^{\frac{1}{2}} = 57.7$$

$$N_{PM} = \frac{\sum_{i=1}^{n} p_i}{\tau^*} = \frac{94}{57.7} = 1.629 \approx 1$$

Therefore, only one PM action has to be carried out on the machine as another batch added to the schedule, with the following parameters

Batch	Processing time	Due Date	Penalty
1	23	67	10
2	28	114	2
3	43	65	5
PM	5	57.7	0

Table 3.3: PM batch production parameters

The integrated problem is solved using enumeration technique. The feasible sequences for this example are $n!$ enumerated as follows

Batch sequence	**P**$M_{\mathbf{I}}$	**Objective function value**
$B_1 - B_2 - B_3 - PM$	222.9	253.9
$B_1 - B_2 - PM - B_3$	133.3	238.9
$B_1 - B_3 - B_2 - PM$	222.9	87.6
$B_1 - B_3 - PM - B_2$	154	81.8
$B_1 - PM - B_2 - B_3$	96.4	224.6
$B_1 - PM - B_3 - B_2$	96.4	70.6
$B_2 - B_1 - B_3 - PM$	229.3	274.5
$B_2 - B_1 - PM - B_3$	133.3	259.6
$B_2 - B_3 - B_1 - PM$	229.3	600.8
$B_2 - B_3 - PM - B_1$	161	583.6
$B_2 - PM - B_1 - B_3$	102.8	244.2
$B_2 - PM - B_3 - B_1$	102.8	529.1
$B_3 - B_1 - B_2 - PM$	249	152
$B_3 - B_1 - PM - B_2$	154	146.3
$B_3 - B_2 - B_1 - PM$	249	500.9
$B_3 - B_2 - PM - B_1$	161	483.7
$B_3 - PM - B_1 - B_2$	122.5	132.2
$B_3 - PM - B_2 - B_1$	122.5	436.8
$PM - B_1 - B_2 - B_3$	68	222.6

PM–B$_1$–B$_3$–B$_2$	**68**	**62.0**
$PM - B_2 - B_1 - B_3$	68	233.9
$PM - B_2 - B_3 - B_1$	68	517.3
$PM - B_3 - B_1 - B_2$	68	103.5
$PM - B_3 - B_2 - B_1$	68	433.6

Table 3.4: Results obtained from the joint model

Once this search has been executed among all sequences of jobs, the tasks sequence having the most lowest objective function value is determined as the global optimal solution. Outcomes for this model are explained in Table 3.4. It's clear that the perfect solution is to carry out the batch sequence $B_1 - B_3 - B_2$ having PM implemented before batch 1 and the optimal time after which PM should be carried out on the machine is 68.

3.5 Sensitivity Analysis

In this part, we design a collection of numerical examinations to investigate the advantages of implementing the integrated model. We consider two standards to analyze the differences of the integrated solutions and its correlative objective function values; and the PM decisions and job sequences obtained as follows

Benchmark 1: Detect the job sequence through solving the weighted lateness issue considering no PM batches. Then, calculate the objective function value (expected total weighted tardiness). This solution ignores having any PM batch while the objective function calculation does include the probability of machine failures.

Benchmark 2: Determine the job sequence though solving the weighted lateness issue considering no PM batches. After that, determine the PM interval. Next, calculate the objective function value. keep in mind that in this criteria the job order and PM interval are driven separately.

Therefore, we study the next questions:

1. Compare the joint objective function value to the value obtained solving Benchmark 2?

2. Compare the optimal (joint) job schedule and PM determination to the independently acquired job schedule and PM period in (Benchmark 2)?

3. Compare the joint objective function value to the value obtained solving Benchmark 1?

4. Compare the optimal (joint) job schedule to the one acquired from solving just the scheduling issue in (Benchmark 1)?

We studied these interrogations for the numerical example explained in Section 3.4. Then, we outline the answers to these comparisons for more analytical illustrations.

The objective function value under the first benchmark is 152.02 with the jobs scheduled as $[B_3 - B_1 - B_2]$. Therefore, the lowest objective function value gathered from the integrated solution 62.03 represents a saving of 59.3% over the scheduling only benchmark 1 model.

For the second benchmark the resulting minimum objective function value is 103.5 with the jobs scheduled as $[PM - B_3 - B_1 - B_2]$. Therefore, the lowest objective function value gathered from the integrated solution 62.03 represents a saving of 40.5% over the independent integrated benchmark 2 model. Table 3.5 represent the results.

Benchmark	**TPC**	**Savings of the proposed Integration**
Scheduling Only no PM	152.02	59.3%
Scheduling + PM	103.5	40.5%

Table 3.5: Comparison between the joint model and the independent considerations

CHAPTER 4

AN INTEGRATED PRODUCTION MAINTENANCE AND QUALITY COST MODEL

4.1 Introduction

4.1.1 Relationship Between The Main Components of The Production System

The triple production, quality and maintenance interact and impact customer satisfaction, profitability and business survival. In the following the impact of each one on the other is discussed.

Maintenance specially planned maintenance increase the capacity for production and if the equipments are maintained in good condition they produce products with minimum variability and high quality. Hence maintenance at the right level impact production and quality in a positive sense, however if equipments are not maintained that my reduce capacity and delay production and result in not meeting customer demand and that expected to lead to customer dissatisfaction. In practice production may have priority over maintenance and this may lead to delays in planned maintenance and if maintenance is delayed this will result to having machines in less than adequate condition and hence breakdown. Machines that are not well maintained produce more defective items and upon failure reduce production capacity.

Quality is an important component in every production system, the purpose of quality control is to ensure the lowest defect rates and to achieve the highest level of customer satisfaction at the lowest possible cost. The process is considered in control; i.e., producing units that satisfy product design specifications, if the variation measured in standard deviations is less than one-third the difference between the control limits and the process mean. Eliminating non-conforming, rework and wasted resources will reduce the need to overly maintain the processes and producing more units. The use of variation analysis will increase the production system ability to find defects and other installation faults after the maintenance level.

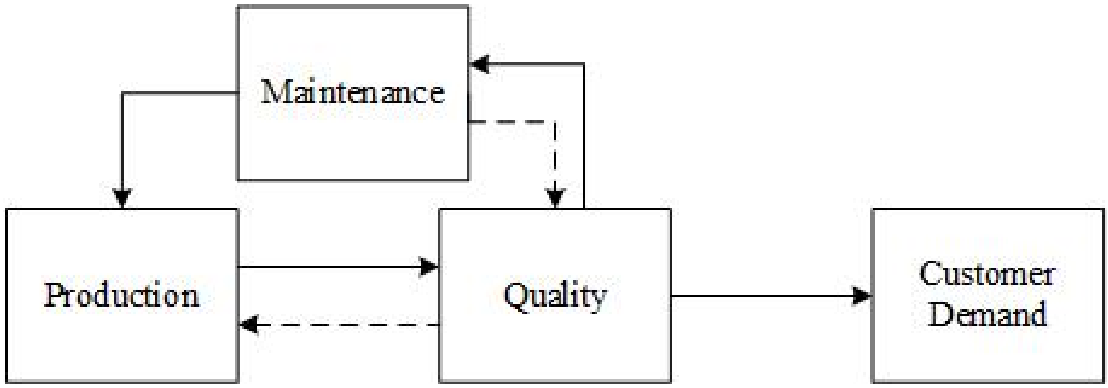

Figure 4.1: Production, maintenance and quality relationship

A company that has quality as its strategy should strive for effective production scheduling and planned maintenance in order to have high quality products and meet customer demand at the right time.

The goal of this chapter is to develop an integrated optimization model that minimizes the costs associated with the integration of production, maintenance and quality characteristics all at once for a single machine. The problem under consideration has three major parts. The first part is the planning of maintenance for the machine and the second part is the scheduling of the batches for production. The third part is the quality part that deals with the monitoring and control of the production proses. The elements of the integrated model are formulated to determine the cost function of each part and then added together to obtain the total cost. However the solution of the integrated model is developed as follows:

1. Find the optimal ideal PM interval and the number of PM batches to be included in the sequence.

2. Integrate the PM interval with the production schedule.

3. Determine the optimal integrated PM and production schedule.

4. Develop the cost functions associated with maintenance, production and quality.

5. Determine the optimal PM interval, production and quality parameters that minimizes the total cost of the integrated model.

The final output of the proposed methodology is the solution of the integrated model.

The coming parts of the chapter are organized as follows: section 4.2 presents the statement of the problem followed by the model development is section 4.3. Section 4.4 contains the formulation of the integrated model. Section 4.5 describes the results and analysis.

4.2 Statement of The Problem

Consider the production system explained in chapter 3 where the machine is assumed to be producing products of the same type in batches of size $N_{[i]}$ at a constant average rate on a continuous basis unless a failure occurs during batch processing. The processing time for each batch i is $P_{[i]}$ and the due date is $d_{[i]}$. It is assumed the machine breakdowns are divided into two failure styles similarly to the classification used by **Lad and Kulkarni (2008)**:

1. A machine failure that leads to a total breakdown and immediately stops the machine is referred to as failure mode I (FM_I). This type of failure is

obviously detected immediately. A corrective maintenance action will take place to repair the tool to the condition prior to it's breakdown with no improvement. Furthermore, the job that was disrupted by the error should continue with the remaining portion of it, after machine reform. This will result in an expected corrective action cost(CMC_{FM_I}).

2. A process failure that disturb the performance of the machine, resulting in a raise in the rejection level in terms of process rejection rate is referred to as failure mode II (FM_{II}). Whenever this failure is detected, the process is stopped instantly and corrective steps are utilized to repair the process back to the same state before failure. This will result in an expected corrective maintenance cost ($CMC_{FM_{II}}$). In addition, the process may also deteriorate and shift to an out-of-control state due to some external reasons (E) such as environmental effects, operator's mistakes and use of wrong tool. Whenever it's detected, the procedure is brought back to the in control case. The process time to failure is supposed to follow an exponential distribution as assumed in **Duncan (1956)**.

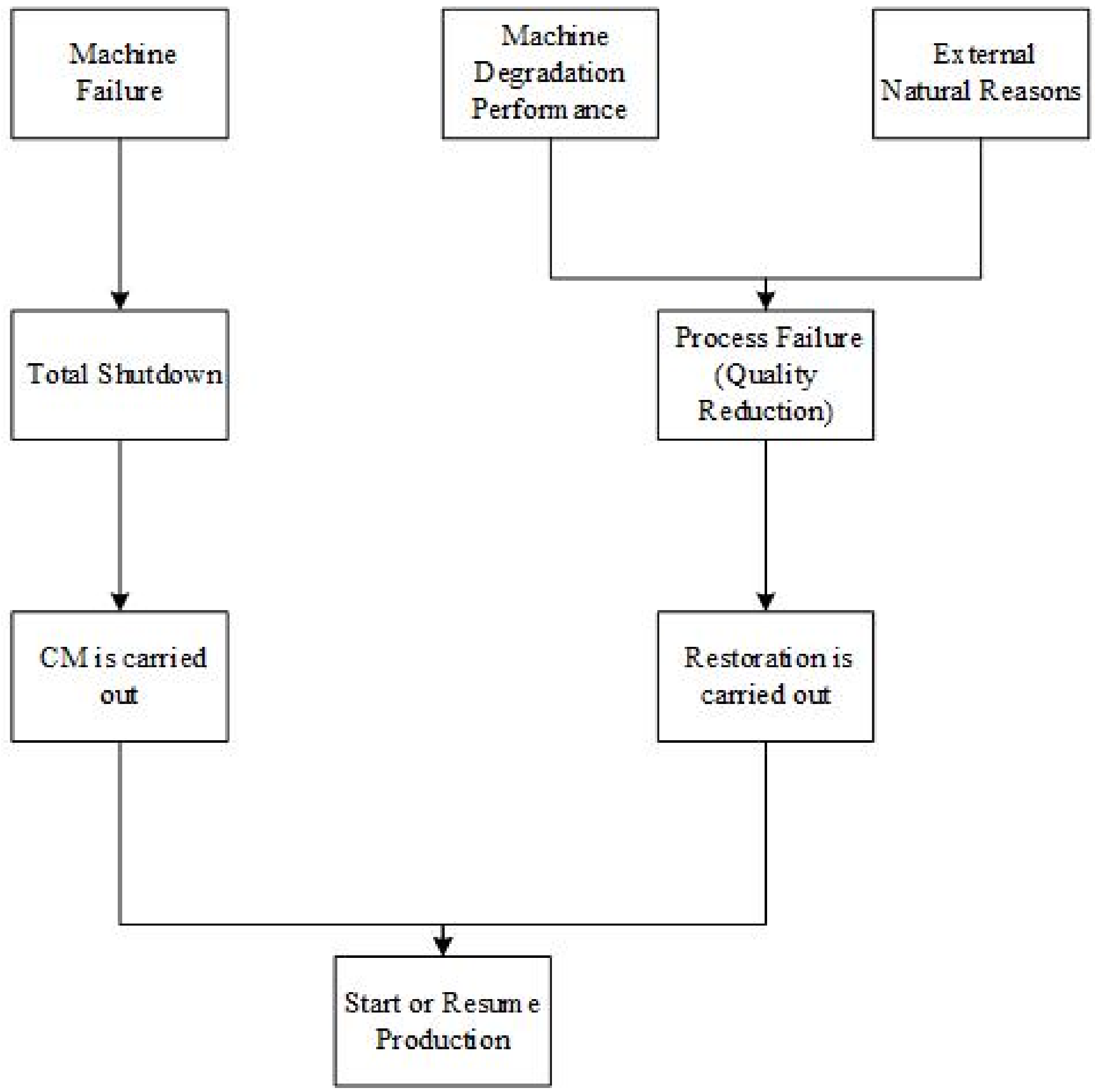

Figure 4.2: Types of failure

Identifying these types of failure (FM_{II}) and (E) will take time, since they don't directly stop the machine. Therefore, they are detected by monitoring the process. A quality control chart mechanism is considered for process monitoring. The $\overline{X}$ chart is used to monitor the quality characteristic of the finished product. The design variables of the chart are:

1. The time (length) between samples (h).

2. The sample size (n).

3. The number of standard deviations of the sample allocation that determines the distance between the middle of the chart and it's limits (k).

This will result in an expected total quality cost of process failure (TQC) owning to (FM_{II}) and (E).

Each failure mode FM_I and FM_{II} will delay the completion times of successive batches by the needed time to perform corrective maintenance actions t_{CM} (which assumed to be constant) and will cause a fixed cost of performing repair actions (FC_{CM}).

Now, apart from the above corrective actions, preventive maintenance action is implemented to lower the frequency of failures occurrence. It is considered to be perfect which means it restores the machine to a new condition. This will result in an expected cost per preventive maintenance (PMC). Each PM batch we introduce will delay sequential batches by the time required to perform preventive maintenance actions t_{PM} (which assumed to be constant) and will cause a fixed cost of performing preventive maintenance action (FC_{PM}).

For all the batches produced its assumed that the raw materials are freed at the start of the sequence, raw material inventory for a batch is at hold till it starts processing. Therefore, the inventory carrying (holding) cost for this period is computed based on the entire batch size and consists of the setup time and processing times of all the previous batches (if any) as well as the setup time of the current batch. After the processing of a batch starts, raw material will consume at a constant rate and accordingly the inventory carrying (holding) cost will be computed for this area based on half the batch size (average inventory). Each batch ($i \neq PM\ batch$) await on the production line will cause a holding cost H per unit of time till the completion time i.e. $E\left(C_{[i]}\right)$. Given that the average inventory for a batch is $\overline{N}_{[i]}$, then the total holding cost will be

$$H \cdot \sum_{i=1}^{n} E\left(C_{[i]}\ \right)\ \overline{N}_{[i]} \tag{4.1}$$

Ahead of developing the model, the following symbols are presented.

$\mathbf{n}$	number of jobs to be scheduled
$\mathbf{N_{[i]}}$	batch size
$\mathbf{x_{i\mathit{j}}}$	job sequencing decision variable
$\mathbf{p_{[i]}}$	processing time of i^{th} job in the sequence
$\mathbf{d_{[i]}}$	due date of the i^{th} job in the sequence
$\mathbf{P}N_{\mathbf{[i]}}$	penalty of the i^{th} job in the sequence
$\mathbf{C_{[i]}}$	completion time of the i^{th} job in the sequence
$\mathbf{y_{[i]}}$	PM batch decision variable
$\theta_{\mathbf{[i]}}$	lateness of the i^{th} job in the sequence
η	Weibull scale parameter for probability distribution of T
β	Weibull shape parameter for probability distribution of T
$\mathbf{t_{C\mathit{M}}}$	time required to perform corrective maintenance
$\mathbf{t_{P\mathit{M}}}$	time required to perform preventive maintenance
τ	ideal PM interval

τ^*	optimal value of τ
$\mathbf{F}C_{\mathbf{S}}$	fixed cost per sample
$\mathbf{F}C_{\mathbf{J}}$	fixed cost per job
$\mathbf{C}_{\mathbf{R}}$	cost of rejection
$\mathbf{F}C_{\mathbf{C}M}$	fixed cost of corrective maintenance
$\mathbf{C}_{\mathbf{r}eset}$	cost of resetting
$\mathbf{F}C_{\mathbf{P}M}$	fixed cost per preventive maintenance
ϵ	mean elapse time from the last sample before the assignable cause to the occurrence of assignable cause
$\mathbf{L}PC$	lost production cost
$\mathbf{L}C$	labor cost
$\mathbf{P}R$	production rate
$\mathbf{T_0}$	expected time consumed searching for a false alarm
$\mathbf{T_S}$	time to sample and chart a single component
$\mathbf{T_1}$	expected time to locate the appearance of assignable cause
$\mathbf{T}_{\mathbf{r}eset}$	time consumed to retest the process that moved to an out of control status as a result of an external reason
$\mathbf{T}_{\mathbf{S}ched}$	scheduling period
$\mathbf{T}_{\mathbf{e}val}$	evaluation period

Table 4.1: The integrated model symbols

4.3 Model Development

In this part we explain in details the development of the objective function that integrates the costs associated with performing maintenance planning, quality and production scheduling on the system. The model includes the following expected costs:

1. Corrective maintenance cost.
2. Preventive maintenance cost.
3. Total cost of quality loss.
4. Inventory holding cost.
5. Total penalty cost due to batch tardiness.

The objective function for the integrated model is formulated as

$$\mathrm{ETC} = \frac{\mathrm{TPC}_{\text{Scheduling and Maintenance}} + \mathrm{HC} + \mathrm{CMC}_{\mathrm{FM_I}} + \mathrm{PMC} + \mathrm{E[TQC]}_{\text{process failure}}}{\mathrm{T}_{\text{eval}}} \tag{4.2}$$

Next, the derivation for developing each component of the integrated objective function is provided.

4.3.1 Model For The Expected Corrective Maintenance Cost Due To F$M_{\mathbf{I}}$

To generate the expected cost of CM due to FM_I , the following parameters has to be considered:

1. The amount of time the machine is anticipated to be down every time CM is needed (t_{CM}).

2. The down time cost during the repair of the machine.

$$t_{CM}\,(LPC * PR + LC)$$

3. The fixed cost of performing corrective maintenance (FC_{CM}).

4. The probability that the tool will break down owing to the FM_I, calculated as

   Since that failures are randomly distributed over the machine and the time to failure follows a two parameters Weibull probability distribution having the shape and scale as B and η . The probability that the machine fails due to FM_I in a given planning period T_{eval} can be expressed as

$$P_{\,FM_I} = F\,(T_{eval}; \mathrm{B}, \eta) = 1 - e^{\left(\frac{T_{eval}}{\eta}\right)^{\mathrm{B}}} \tag{4.3}$$

5. The number of failures during the period $(0, PM_I)$, denoted by $N(t)$, calculated as

   For the Weibull distribution the failure rate/hazard function is

$$r\,(t) = \frac{\mathrm{B}}{\eta^{\mathrm{B}}}\, t^{\mathrm{B}-1}$$

Then, the expected number of machine failures during$(0, PM_I)$, is calculated as

$$E\left(N\left(PM_I\right)\right) = \int_0^{PM_I} r\left(t\right)\ dt = \int_0^{PM_I} \frac{\mathrm{B}}{\eta^{\mathrm{B}}}\ t^{\mathrm{B}-1}\ dt = \left(\frac{PM_I}{\eta}\right)^{\mathrm{B}} \quad (4.4)$$

Therefore, considering the above parameters the CM cost due to FM_I for a given interval of time can be expressed as

$$CMC_{FM_I} = P_{\ FM_I} * E\left[N\left(PM_I\right)\right] *\ \left[t_{CM}\left(LPC * PR + LC\right) + FC_{CM}\right] \quad (4.5)$$

4.3.2 Model For The Expected Preventive Maintenance Cost

Preventive maintenance is assumed perfect, so the machine will be maintained to a better state but not as being new. To estimate the expected cost that each PM action incurs, the following parameters must be considered:

1. The amount of time the machine is expected to be down each time PM is performed (t_{PM}).

2. The down time cost during the PM

$$t_{PM}\left(LPC * PR + LC\right)$$

3. The fixed cost of performing preventive maintenance (FC_{PM}).

4. The number of preventive maintenances (N_{PM})

Therefore, the expected cost per preventive maintenance can be expressed as

$$PMC = N_{PM} * [t_{PM} (LPC * PR + LC) + FC_{PM}] \tag{4.6}$$

4.3.3 Model For The Expected Total Cost of Quality Loss Due To Process Failure

In order to get the expected total cost of quality loss, the process cycle length and the process quality cost expressions will be derived. The process mean can instantly deviant due to (FM_{II}) or (E) to an out of control state in which the machine will be producing products with a lower quality or even defected items. When the process moves out of limits, we assume that it can't come back to the in control condition without interference. Since (FM_{II}) and (E) cannot be directly detected, the reason of failure can't be specified without closing down the operation and carrying out a close inspection on the tool. A quality control chart $\overline{X}$ is used to monitor the process behavior by calculating one key quality characteristic of the completed product. Let x be a normal random variable that indicates the estimation of this characteristic for a given product having μ as the process mean and σ as the procedure standard deviation. While being in control, the process mean is at its target value. Following a shift the process is considered out of limits and the updated mean is calculated as:

$$\mu = \mu_0 + \delta\sigma_0$$

$$where\ \delta\ is\ a\ nonzero\ real\ number$$

For the parameters of the $\overline{X}$ chart $(h, n\ and\ k)$ the resulting upper and lower control limits are:

$$UCL = \mu_0 + k\frac{\sigma}{\sqrt{n}} \qquad , \qquad LCL = \mu_0 - k\frac{\sigma}{\sqrt{n}}$$

In the coming sections the process cycle length and quality cost expressions are developed.

4.3.3.1 Model Developed For The Expected Process Cycle Length

The expected procedure cycle time includes the process in control time, the process out of control time and the repair time, illustrated as follows:

1. **The process in-control time**

   During this period the failure rate is constant. Therefore, we assume that the in control period follows an exponential distribution having a mean time to failure $\frac{1}{\lambda}$ and a process failure rate $r(t) = \lambda$. The operation might break down due to machine deterioration or as a result of some external reasons. So, let the failure rate as a result of machine deterioration (FM_{II})

be $(\lambda_{FM_{II}})$ and because of external reason (E) be (λ_E). Then,

$$\lambda_{FM_{II}} = \frac{P_{\ FM_{II}} * \ E\left(N\left(PM_I\right)\right)}{T_{eval}} \qquad , \quad \lambda_E = \frac{1}{mean\ time\ to\ failure}$$

Where, the probability that the machine fails due to FM_{II} is

$$P_{\ FM_{II}} = F\left(h;;\lambda\right) = 1 - e^{\left(\frac{T_{eval}}{\eta}\right)^{\mathrm{B}}} \tag{4.7}$$

Thus, the total process failure rate λ as a result of (FM_{II}) and (E) is

$$\lambda = \lambda_{FM_{II}} + \lambda_E \tag{4.8}$$

Now, the expected in control period composed of the following:

(a) The mean time to failure $(\frac{1}{\lambda})$.

(b) The expected time spent searching and inspecting for false alarms, which includes:

   i. The expected number of samples (NS) taken while being in control, calculated as (**Lorenzen & Vance, 1986**):

   Since, $PDF \quad f\left(h, \lambda\right) = \lambda e^{-\lambda h}$

$$NS = \sum_{i=0}^{\infty} i\ Pr\left(assinable\ cause\ happens\ between\ the\ ith\ and\ \left(i+1\right)st\ samples\right)$$

$$= \sum_{i=0}^{\infty} i\ \left(e^{-\lambda hi} - e^{-\lambda h(i+1)}\right) = -\left(1 - e^{-\lambda h}\right) \frac{d}{d\left(\lambda h\right)} \sum_{i=0}^{\infty} e^{-\lambda hi} = \frac{e^{-\lambda h}}{\left(1 - e^{-\lambda h}\right)}$$

ii. The average run length while the procedure being control (ARLI), calculated as

$$ARLI = \frac{1}{\alpha}$$

Where,

$$\alpha = \Pr\left(out - of - ontrol \quad | \ process\ is\ in\ control\right) = 2F(-k)$$

Then, the expected number of false alarms throughout this period, is calculated by

$$E\left[Nf_{alarm}\right] = \frac{NS}{ARLI} \tag{4.9}$$

Thus, the expected amount of time spent searching and inspecting for false alarms is

$$T_0 \ E\left[Nf_{alarm}\right] \tag{4.10}$$

Therefore, the expected in-control time until the appearance of an assignable cause can be expressed as

$$E\left[IT\right] = \frac{1}{\lambda} + T_0 \ E\left[Nf_{alarm}\right] \tag{4.11}$$

2. **The process out of control time**

The expected out of control period consist of the following times:

(a) The expected time ahead of having a sample statistic falling beyond the control limit, calculated as:

Let ϵ be the mean time between the last sample prior to the assignable cause to the happening of the assignable cause where it take place between the ith and $(i+1)st$ samples. Then ϵ can be calculated as in (**Duncan, 1956**)

$$\epsilon = \frac{\int_h^{h(i+1)} \lambda(x-hi)e^{-\lambda x}dx}{\int_h^{h(i+1)} \lambda e^{-\lambda x}dx} = \frac{\left[1-(1+\lambda h)e^{-\lambda h}\right]}{\left[\lambda(1-e^{-\lambda h})\right]} = \frac{h}{2} \tag{4.12}$$

Now, the average run length after the process shifts to an out of control state is

$$ARLO = \frac{1}{1-\beta}$$

Where,

$$\beta = Pr\left(in - control\ signal\ \mid\ process\ is\ out - of - control\right)$$

$$\beta = Pr\left(LCL \leq \overline{X} \leq UCL\ \mid\ \mu = \mu_0 = \mu_0 + \delta\sigma_P\right)$$

Since that

$$\overline{X}\ \sim N\left(\mu\ , \frac{\sigma_P^2}{n}\right)$$

The upper and lower control limits will be

$$UCL = \mu_0 + k\frac{\sigma_P}{\sqrt{n}} \qquad , \qquad LCL = \mu_0 - k\frac{\sigma_P}{\sqrt{n}}$$

Given that F denote the standard normal cumulative distribution function, then

$$\beta = F\left(\frac{UCL - \mu_0 + \delta\sigma_P}{\frac{\sigma_P}{\sqrt{n}}}\right) - F\left(\frac{LCL - \mu_0 + \delta\sigma_P}{\frac{\sigma_P}{\sqrt{n}}}\right)$$

$$\beta = F\left(k - \delta\sqrt{n}\right) - F\left(-k - \delta\sqrt{n}\right)$$

Let the $ARLO$ due to machine degradation (FM_{II}) be ($ARLO_{FM_{II}}$), then

$$ARLO_{FM_{II}} = \frac{1}{1 - \beta_{FM_{II}}}$$

$$= \frac{1}{1 - [F\,(k - \delta_{FM_{II}}\sqrt{n}) - F\,(-k - \delta_{FM_{II}}\sqrt{n})]}$$

And due to external reasons (E) let it be ($ARLO_E$), then

$$ARLO_E = \frac{1}{1 - \beta_E}$$

$$= \frac{1}{1 - [F\,(k - \delta_E\sqrt{n}) - F\,(-k - \delta_E\sqrt{n})]}$$

Therefore, the expected time ahead of having a sample statistic falling beyond the control limit is

$$\left[h\,\left(ARLO_{FM_{II}}\,\left(\frac{\lambda_{FM_{II}}}{\lambda}\right) + ARLO_E\,\left(\frac{\lambda_E}{\lambda}\right)\right)\right] - \epsilon \qquad (4.13)$$

(b) The expected time to design and map a sample $n\ T_S$.

(c) The anticipate time to investigate the assignable cause occurrence T_1.

(d) The anticipate time to renew the process, calculated as

The restoration after detecting the assignable cause depends on the type of failure. The process is repaired as a result of FM_{II} and restarted as a result of E, thus

$$E\left[T_{restore}\right] = \left[t_{CM}\left(\frac{\lambda_{FM_{II}}}{\lambda}\right) + T_{reset}\left(\frac{\lambda_E}{\lambda}\right)\right] \tag{4.14}$$

Therefore, the expected out of control time can be presented as

$$E\left[OT\right] = \left[h\;\left(ARLO_{FM_{II}}\;\left(\frac{\lambda_{FM_{II}}}{\lambda}\right) + ARLO_E\;\left(\frac{\lambda_E}{\lambda}\right)\right)\right] - \epsilon + n\,T_S + T_1 + E\left[T_{restore}\right] \tag{4.15}$$

In conclusion from equations (4.11) and equation (4.15), the model for the expected process cycle length is

$$E\left[T_{Cycle}\right] = E\left[IT\right] + E\left[OT\right] \tag{4.16}$$

4.3.3.2 Model Developed For The Expected Process Quality Control Cost

The operation quality cost composed of the costs generated during the in control period and the costs generated during the out of control period owning to false alarms, sampling the process, producing defective (non-conforming) units, searching for assignable alarm, restoring (repair or reset) the system and downtime cost. In this part we derive expressions for the expected cost of process quality control which contain the following costs:

1. The expected cost of false alarms, calculated as

$$E\left[C_{false}\right] = C_{false}\ \left(T_0\ E\left[Nf_{alarm}\right]\right) \tag{4.17}$$

   Where, C_{false} is the cost for inspecting a false alarm per unit time.

2. The expected cost of sampling per cycle, is calculated as

   Let FC_S be the fixed cost per sample and FC_J be the fixed cost per job, then

$$E\left[C_S\right] = \frac{(FC_S + n\ FC_J)}{h}\left[\frac{1}{\lambda} + T_0\ E\left[Nf_{alarm}\right] + \left[h\ \left(ARLO_{FM_{II}}\ \left(\frac{\lambda_{FM_{II}}}{\lambda}\right) + ARLO_E\ \left(\frac{\lambda_E}{\lambda}\right)\right)\right] - \epsilon + n\ T_S\right] \tag{4.18}$$

3. The expected cost of non conforming components (rejects) while running within control, calculated as:

   Let R_I be the proportion of non conforming components while running within control. The type II error probability is given by

$$\beta = F\left(k - \delta\sqrt{n}\right) - F\left(-k - \delta\sqrt{n}\right)$$

   Since the process is in-control state, the shift parameter $\delta = 0$. Then,

$$R_I = 1 - F\left(k\right) - F\left(-k\right)$$

Therefore, the expected quality loss cost of non-conforming units when the process is in-control is

$$E\left[C_I\right] = \left(R_I \ \cdot \ C_R \ \cdot PR\right)\left(E\left[IT\right]\right) \tag{4.19}$$

4. The expected cost of non-conforming units (rejections) while running beyond control due to FM_{II}, is calculated as follows

   Let $\left(R_\delta\right)_{FM_{II}}$ be the proportion of non-conforming units when the process shifts $\delta_{FM_{II}}$ to an out of control position owning to FM_{II}. The process capability of the in control case is assumed to be 1. So the upper and lower quality limits will be at $\pm 3\sigma_P$. Then the type II error probability will be

$$\beta_{FM_{II}} = F\left(3 - \delta_{FM_{II}}\right) - F\left(-3 - \delta_{FM_{II}}\right)$$

   And the proportion of non-conforming components when the process shifts $\delta_{FM_{II}}$ to an out of control state owning to FM_{II} is given by

$$\left(R_\delta\right)_{FM_{II}} = 1 - F\left(3 - \delta_{FM_{II}}\right) - F\left(-3 - \delta_{FM_{II}}\right)$$

   Therefore, the expected cost of operating while being beyond control due to

FM_{II} is given as

$$E\left[C_O\right]_{FM_{II}} = \left(\left[\frac{(R_\delta)_{FM_{II}}}{1-\beta_{FM_{II}}}\right] \cdot PR \cdot \ C_R\right)\left(\frac{\lambda_{FM_{II}}}{\lambda}\right)$$
$$\left[\left[h\ \left(ARLO_{FM_{II}}\ \left(\frac{\lambda_{FM_{II}}}{\lambda}\right) + ARLO_E\ \left(\frac{\lambda_E}{\lambda}\right)\right)\right] - \epsilon + n\ T_S + T_1\right] \tag{4.20}$$

5. The expected cost of non-conforming units (rejections) when the process moves to out of control state due to E , is calculated as follows

   Let $(R_\delta)_E$ be the proportion of non-conforming units when the process shifts δ_E beyond control owning to E. It's assumed that the procedure capability of the monitored state is 1. Thus, the upper and lower quality limits will be at $\pm 3\sigma_P$. The type II error probability will be

$$\beta_E = F\left(k - \delta_E\sqrt{n}\right) - F\left(-k - \delta_E\sqrt{n}\right)$$

   And the proportion of non-conforming units when the process shifts δ_E to an out of-of-control state owning to E is

$$\left(R_\delta\right)_E = 1 - F\left(3 - \delta_E\right) - F\left(-3 - \delta_E\right)$$

   Therefore, the expected quality cost of operating while being in out-of-control state due to E is given as

$$E\left[C_O\right]_E = \left(\left[\frac{(R_\delta)_E}{1-\beta_E}\right] \cdot PR \cdot \ C_R\right)\left(\frac{\lambda_E}{\lambda}\right) \\ \left[\left[h\ \left(ARLO_{FM_{II}}\ \left(\frac{\lambda_{FM_{II}}}{\lambda}\right) + ARLO_E\ \left(\frac{\lambda_E}{\lambda}\right)\right)\right] - \epsilon + n\ T_S + T_1\right] \tag{4.21}$$

6. The expected cost of CM activity owning to FM_{II} for locating and correcting the assignable cause, calculated as

$$CMC_{FM_{II}} = \left[t_{CM}\left(LPC * PR + LC\right) + FC_{CM}\right]\left(\frac{\lambda_{FM_{II}}}{\lambda}\right) \tag{4.22}$$

7. The expected cost of finding and resetting the assignable cause owing to E, is calculated as

$$E\left[C_{reset}\right]_E = \left[T_{reset} \cdot C_{reset}\right]\left(\frac{\lambda_E}{\lambda}\right) \tag{4.23}$$

In conclusion, the expected process quality control cost is

$$E\left[PQC\right] = E\left[C_{false}\right] + E\left[C_S\right] + E\left[C_I\right] + E\left[C_O\right]_{FM_{II}} + E\left[C_O\right]_E + CMC_{FM_{II}} + E\left[C_{reset}\right]_E \tag{4.24}$$

Therefore, the expected total cost of quality loss due to process failure for the evaluation period is

$$E[TQC]_{process\ failure} = E\left[PQC\right]\ \left(\frac{T_{eval}}{E\left[T_{Cycle}\right]}\right) \tag{4.25}$$

4.3.4 Model For The Expected Inventory Holding Cost

Since we assumed that raw materials for every batch are freed to the shop floor at the beginning of the sequence, raw material inventory for each batch are at hold till it begins processing. The manufacturer should consider the holding cost during the scheduling horizon. One batch of size $N_{[i]}$ consists of processing a set of jobs. Hence the batch size is

$$N_{[i]}=\sum_{j=1}^{n} N_j \; x_{ij} \qquad\qquad i = 1, 2, \; .. \; ., n$$

Two periods are there, one is before the processing of a batch in which the raw materials inventory for it are carried for the duration of the current batch setup time as well as the setup and running times of all the previous batches (if any). Therefore the inventory holding cost will be calculated during this period for the whole batch size. While the batch is being processed, raw materials of the batch consumes at a constant rate and accordingly the inventory carrying (holding) cost will be computed for this area based on half the batch size (average inventory). Shown in figure 4.3 the inventory holdings for batch i.

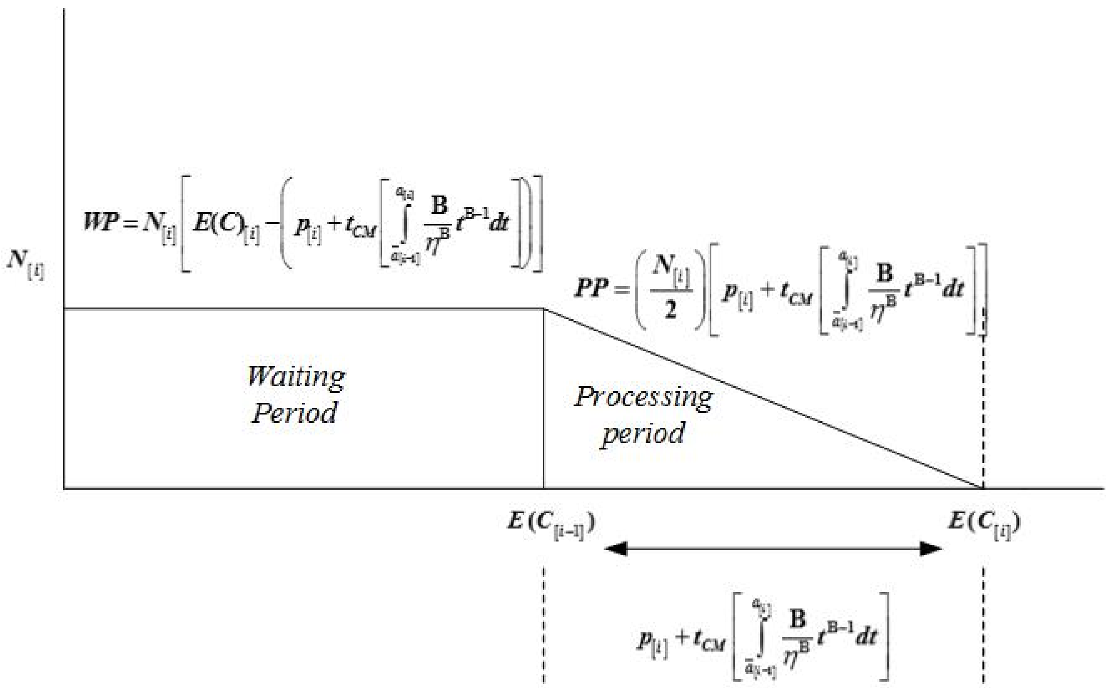

Figure 4.3: Inventory holdings for a single batch i.

Then, the average inventory quantity is calculated as

$$\overline{N}_{[i]} = \frac{WP + PP}{E(C_{[i]})}$$

$$\overline{N}_{[i]} = \frac{N_{[i]}\left[E(C_{[i]}) - \frac{\left[p_{[i]} + t_{CM}\left(m\left(a_{[i]}\right) - m\left(\overline{a}_{[i-1]}\left[1 - \left(y_{[i]}\right)\right]\right)\right)\right]}{2}\right]}{E(C_{[i]})}$$

$$\overline{N}_{[i]} = N_{[i]}\left[1 - \frac{\left[p_{[i]} + t_{CM}\left(m\left(a_{[i]}\right) - m\left(\overline{a}_{[i-1]}\left[1 - \left(y_{[i]}\right)\right]\right)\right)\right]}{2E(C_{[i]})}\right]$$

$$\overline{N}_{[i]} = N_{[i]}\left[1 - \frac{\left[p_{[i]} + t_{CM}\left(m\left(a_{[i]}\right) - m\left(\overline{a}_{[i-1]}\left[1 - \left(y_{[i]}\right)\right]\right)\right)\right]}{2\left[\sum_{k=1}^{i} t_{PM}\left(y_{[k]}\right) + \left(p_{[k]}\right) + t_{CM}\left[m\left(a_{[k]}\right) - m\left(\overline{a}_{[k-1]}\left[1 - \left(y_{[k]}\right)\right]\right)\right]\right]}\right] \tag{4.26}$$

In conclusion, the model for the expected inventory holding cost is given as

$$HC = H \cdot \sum_{i=1}^{n} E\left(C_{[n]}\ \right)\ \overline{N}_{[n]} \tag{4.27}$$

4.4 The Integrated Model

The integrated model consists of the objective function representing the production scheduling, maintenance and quality cost derived a above. The model has few constraints.

The objective function for the integrated cost model for joint optimization of maintenance planning, quality and production scheduling is minimized as follows

$$\text{Minimize } \frac{\text{TPC}_{\text{Scheduling and Maintenance}}+\text{HC} + \text{CMC}_{\text{FM}_\text{I}}+\text{PMC}+\text{E[TQC]}_{\text{process failure}}}{\text{T}_{\text{eval}}}$$

Subject to

$$\sum_{i=1}^{n} x_{ij} = 1 \qquad j = 1, 2, 3, ..n$$

$$\sum_{j=1}^{n} x_{ij} = 1 \qquad i = 1, 2, 3, ..n$$

$$p_{[i]} = \sum_{j=1}^{n}\ p_j\ x_{ij} \qquad i = 1, 2,\ .. ., n$$

$$N_{[i]}=\sum_{j=1}^{n} N_j \; x_{ij} \qquad i=1,2,\;..,n$$

$$E\left(\Theta_{[i]}\right)=\sum_{k=0}^{i}\theta_{[i,k]}\;\pi_{[i,k]} \qquad k=0,1,2,\;..\;i$$

$$E\left(C_{[i]}\;\right)=\sum_{k=1}^{i}t_{PM}\left(y_{[k]}\right)+\left(p_{[k]}\right)+t_{CM}\left[m\left(a_{[k]}\right)-m\left(\overline{a}_{[k-1]}\left[1-\left(y_{[k]}\right)\right]\right)\right]$$

$$x_{ij} \quad binary \qquad i=1,2,3,..n$$

$$y_{[i]} \quad binary \qquad i=1,2,3,..n$$

4.5 Results and Sensitivity Analysis

In this section, an illustrative example for the model developed above is presented. This is followed by sensitivity analysis and a number of experimental cases for the model decision variables (parameters) to discover their influence on the results. Previous studies assumed three batches of jobs to be scheduled on a single machine, in this section we extend that to the possibility of scheduling up to n batches of jobs. First the solution methodology algorithm is described. Then, the utility of the model will be demonstrated using an example from the literature for the case of three batches. For the numerical analysis, a program is developed to solve any n number of batches using Maple 18 software.

4.5.1 Solution Methodology

The proposed solution algorithm consists of the following main steps

1. For a given set of batches n find the number of PM batches to be inserted in the sequence and the optimal ideal PM interval τ^* then generate all the possible production schedules $n!$. Such as

$$\tau^* = \eta \left[\frac{t_{PM}}{t_{CM} (\beta - 1)} \right]^{\frac{1}{\beta}}$$

$$N_{PM} = \frac{\sum_{i=1}^{n} p_i}{\tau^*}$$

2. Compute the costs of production and maintenance scheduling for each PM plan, which includes

3. Penalty cost due to tardiness.

4. Inventory holding cost.

5. Corrective maintenance cost.

6. Preventive maintenance cost.

7. Reduce the model to the quality cost and solve it using Maple 18 global optimization tool for the decision variables $(n,\ h,\ k)$.

8. Compute the total cost of integrating production, maintenance and quality for each production schedule.

9. Compare the total cost obtained from each schedule and select the minimum.

4.5.2 Numerical Example For Scheduling Three Batches

Consider a production system with a single machine, assuming that the machine follows a two parameter Weibull distribution as the normal shape and life parameter respectively $\beta = 2$ and $\eta = 100$. The age of the machine at the beginning is $a_0 = 68$. The expected time required performing a corrective maintenance $t_{CM} = 15$ units of time and the repair is assumed to be minimal in which the machine will be repaired to its same age before the failure and the restoration factor $RF_{CM} = 0$. The expected time required to perform preventive maintenance $t_{PM} = 5$ units of time, assuming a perfect PM in which the machine will be restored to its new state. The $\overline{X}$ quality control chart is used to monitor the quality characteristic of the production process that produces items. The process in-control state quality characteristic is normally distributed with $\mu = 0$ and process standard deviation of $\sigma = 0.01$ and will shift to an out-of-control state due to random machine failure be $\delta_{FM_{II}} = 0.8$ or due to external reasons $\delta_E = 1$, which will result in a shift of process mean from μ_0 to $(\mu_0 + \delta\sigma)$.

The initial values for all the parameters used in the example are shown in Table 4.4.

Table 4.2: Initial Cost Parameters

Cost Parameters	Value
FC_S	40
FC_J	10
C_R	5000
FC_{CM}	10 000
C_{reset}	1500
FC_{PM}	800
C_{false}	1200
LPC	40
LC	500
PR	20

Table 4.3: Initial Time Parameters

Time Parameters (in hours)	Value
T_0	1
T_S	20/60
T_1	1
T_{reset}	2
$\delta_{FM_{II}}$	0.8
δ_E	1

Table 4.4: Initial values for all the model parameters

The machine will be processing a set of 3 batches having the following parameters.

Batch	**Batch size**	**Processing time**	**Due Date**	**Penalty**	**Release time**	**Inventory holding cost**	**Setup times**
1	500	23	67	10	0	1.71	3
2	500	28	114	2	0	1.71	1
3	500	43	65	5	0	1.71	2

Table 4.5: Parameters for processing the set of three batches

The first step in our current solution is to determine the optimal idle preventive maintenance intervals i.e. the due dates of the PM batches and the number of PM batches to be introduced to the sequence.

$$\tau^* = \eta \left[\frac{t_{PM}}{t_{CM}(\beta - 1)} \right]^{\frac{1}{\beta}} = 100 \left[\frac{5}{15(2-1)} \right]^{\frac{1}{2}} = 57.7$$

$$N_{PM} = \frac{\sum_{i=1}^{n} p_i}{\tau^*} = \frac{94}{57.7} = 1.629 \approx 1$$

Therefore, only one preventive maintenance action has to be performed on the machine as another batch added to the schedule, with the following parameters

Batch	Processing time	Due Date	Penalty
1	23	67	10
2	28	114	2
3	43	65	5
PM	5	57.7	0

Table 4.6: PM batch parameters

The integration model is solved using enumeration technique. The feasible sequences for this example are $n!$ enumerated as follows

Batch sequence	$\mathbf{P}M_{\mathbf{I}}$	h	k	n	**ETC**
$\mathbf{B_1}$–$\mathbf{B_2}$–$\mathbf{B_3}$–$\mathbf{P}M$	222.9	5.34	3.49	32.84	3210.67
$\mathbf{B_1}$–$\mathbf{B_2}$–$\mathbf{P}M$–$\mathbf{B_3}$	133.3	4.69	3.57	27.66	2132.21
$\mathbf{B_1}$–$\mathbf{B_3}$–$\mathbf{B_2}$–$\mathbf{P}M$	222.9	5.24	3.49	32.34	3133.28
$\mathbf{B_1}$–$\mathbf{B_3}$–$\mathbf{P}M$–$\mathbf{B_2}$	154	4.74	3.55	28.61	2346.78
$\mathbf{B_1}$–$\mathbf{P}M$–$\mathbf{B_2}$–$\mathbf{B_3}$	96.4	4.67	3.61	25.85	1816.96
$\mathbf{B_1}$–$\mathbf{P}M$–$\mathbf{B_3}$–$\mathbf{B_2}$	96.4	4.67	3.61	25.85	1895.97
$\mathbf{B_2}$–$\mathbf{B_1}$–$\mathbf{B_3}$–$\mathbf{P}M$	229.3	5.34	3.49	32.87	3216.64
$\mathbf{B_2}$–$\mathbf{B_1}$–$\mathbf{P}M$–$\mathbf{B_3}$	133.3	4.68	3.57	27.51	2132.06

$\mathbf{B_2}-\mathbf{B_3}-\mathbf{B_1}-\mathbf{P}M$	229.3	5.22	3.5	32.24	3121.75
$\mathbf{B_2}-\mathbf{B_3}-\mathbf{P}M-\mathbf{B_1}$	161	4.75	3.55	28.73	2403.74
$\mathbf{B_2}-\mathbf{P}M-\mathbf{B_1}-\mathbf{B_3}$	102.8	4.67	3.61	26.07	1884.74
$\mathbf{B_2}-\mathbf{P}M-\mathbf{B_3}-\mathbf{B_1}$	102.8	4.67	3.61	26.07	1982.86
$\mathbf{B_3}-\mathbf{B_1}-\mathbf{B_2}-\mathbf{P}M$	249	5.28	3.49	32.58	3173.03
$\mathbf{B_3}-\mathbf{B_1}-\mathbf{P}M-\mathbf{B_2}$	154	4.71	3.56	28	2310.61
$\mathbf{B_3}-\mathbf{B_2}-\mathbf{B_1}-\mathbf{P}M$	249	5.26	3.49	32.44	3153.76
$\mathbf{B_3}-\mathbf{B_2}-\mathbf{P}M-\mathbf{B_1}$	161	4.72	3.55	28.28	2369.70
$\mathbf{B_3}-\mathbf{P}M-\mathbf{B_1}-\mathbf{B_2}$	122.5	4.66	3.59	26.74	2108.22
$\mathbf{B_3}-\mathbf{P}M-\mathbf{B_2}-\mathbf{B_1}$	122.5	4.66	3.59	26.74	2128.15
$\mathbf{P}M-\mathbf{B_1}-\mathbf{B_2}-\mathbf{B_3}$	**68**	**4.73**	**3.65**	**24.68**	**1466.62**
$\mathbf{P}M-\mathbf{B_1}-\mathbf{B_3}-\mathbf{B_2}$	68	4.73	3.65	24.68	1587.59
$\mathbf{P}M-\mathbf{B_2}-\mathbf{B_1}-\mathbf{B_3}$	68	4.73	3.65	24.65	1492.15
$\mathbf{P}M-\mathbf{B_2}-\mathbf{B_3}-\mathbf{B_1}$	68	4.73	3.65	24.65	1651.55
$\mathbf{P}M-\mathbf{B_3}-\mathbf{B_1}-\mathbf{B_2}$	68	4.74	3.65	24.55	1661.27
$\mathbf{P}M-\mathbf{B_3}-\mathbf{B_2}-\mathbf{B_1}$	68	4.74	3.65	24.55	1699.01

Table 4.7: Solution for the integrated model

Once this search has been executed for all sequences of jobs, the tasks sequence with the most lowest objective function value is determined as the global optimal solution. The optimal solution is $ETC = 1466.6$ for this example. The optimal batch sequence is to use $B_1 - B_2 - B_3$ with PM plan performed prior to batch 1.

4.5.3 Sensitivity Analysis and Experimentation

Through a collection of numerical examinations, we investigate the conclusions and advantages of implementing the integrated model. A comparison of all possible compensations of the scheduling, quality and maintenance concepts versus the integrated model and its interrelated objective function value was conducted.

Benchmark	**ETC**	**Profit of the proposed Integration**
Joint Maintenance and quality +scheduling	1505	2.6%
Joint scheduling and maintenance + quality	1539	4.7%
Joint quality and scheduling +maintenance	1566	6.4%
Separate consideration	1552	5.4%

Table 4.8: Comparison between the integrated model and the independent considerations

A systematic sensitivity analysis was developed using some of the cost and time symbols to estimate the required model parameters. In Table 4.9, level 1 is the essential level that was considered to solve the model in Section 4.5.2. Level 2 and 3 show the values of these symbols at +10 and +20% of the essential level respectively. Since the process and cost symbols cannot estimated be approximated with certainty, it is substantial to know the consequence of imprecision on the quality of the optimal solution attained from the proposed integrated model.

Parameters	**Level 1**	**ETC**	**Level 2**	**ETC**	**Level 3**	**ETC**
$\mathbf{F}C_{\mathbf{S}}$	40	1466.6	44	1467.4	48	1468.1
$\mathbf{F}C_{\mathbf{J}}$	10	1466.6	11	1471.5	12	1476.2
$\mathbf{C}_{\mathbf{R}}$	5000	1466.6	5500	1495.3	6000	1523.8
$\mathbf{F}C_{\mathbf{C}M}$	10 000	1466.6	11000	1468.8	12000	1471.1
$\mathbf{F}C_{\mathbf{P}M}$	800	1466.6	880	1467.2	960	1467.7
$\mathbf{C}_{\mathbf{f}alse}$	1200	1466.6	1320	1466.6	1440	1466.6
$\mathbf{L}PC$	40	1466.6	44	1471.8	48	1477.1
$\mathbf{T_0}$	1	1466.6	1.1	1466.6	1.2	1466.6
$\mathbf{T_1}$	1	1466.6	1.1	1468.4	1.2	1470.2
$\mathbf{T}_{\mathbf{r}eset}$	2	1466.6	2.2	1468.3	2.4	1469.9
$\delta_{\mathbf{F}M_{\mathbf{I}I}}$	0.8	1466.6	.88	1463.5	.96	1461.7
$\delta_{\mathbf{E}}$	1	1466.6	1.1	1460.8	1.2	1458.2

Table 4.9: Sensitivity analysis for three levels of integration

The results show that the ETC value will increase at every level affected by the change in the rejection cost and will decrease at every level affected by the change in the process shift after an external cause. Therefore, the solution is particularly sensitive to faults occurring while estimating the quantity of the procedure shift as a result of external reasons δ_{E} and the rejection cost $\mathrm{C_R}$. Consequently, all the effort should be put on the perfect approximation of them.

The scope of optimum values for the decision variables corresponding to the results of the objective function at the multiple levels of the tested symbols are shown in Table 4.10.

Decision variable	$\mathbf{P}M_{\mathbf{I}}$	**n**	**h**	**k**
Range	68	23.2 – 24.8	4.2 – 5.1	3.6 – 3.7

Table 4.10: Scope of optimum values for decision variables

CHAPTER 5

CONCLUSION

5.1 Introduction

This chapter outlines the research don in the thesis. A short summary of the developed models is given in section 5.2. Section 5.3 recommends suggestion for furthermore investigation.

5.2 Summary

This thesis proposes a model for integrating production scheduling, maintenance planning and quality control decisions. The model allows joint optimization of PM interval, jobs scheduling and quality control charts design parameters to decrease the expected total cost per unit time. A program was developed using Maple modeling and optimization tool to solve up to ten batches of jobs. We proposed a number of experimental cases to investigate the benefits from the integrated model. Sensitivity analysis is conducted on various model parameters to investigate the influence of them on the attitude of the system. This will assist the industrialist to determine the most sensitive parameters from the ones that are not.

A clear understanding of the relationship between the leading elements of the manufacture system, that are scheduling, quality and maintenance can be applied to develop an inclusive model for their overall optimization.

The study shows that the least profitable case is when the schedule of the optimal jobs sequence is found first separately considering no preventive maintenance or quality control. Then, the preventive maintenances is linked with the quality control to find the optimal joint PM interval and quality control chart decisions. The most profitable case is when the optimal PM interval is found first separately considering no scheduling or quality control. Then, the jobs sequence is linked with the quality control to obtain the optimal joint jobs schedule and quality control chart parameters.

Its clear that the quality control relationship with maintenance and scheduling respectively has the greatest impact on the model developed.

5.3 Future Extensions

As a future development and improvement to this research different objective functions can be targeted such as the maximizing the system availability, operation efficiency and more. Researchers can try different quality representation to monitor the process behavior and status other than the chart implemented in this search and further more compare the charts and identify the advantages.

The study offered in this thesis is bounded to a single machine system, yet it would be more reasonable and practical to extend the system to contain more than one machine with different flow patterns and sequence dependent/independent setup times.

REFERENCES

Abboud, N. and Salameh, M.K., 1987. How machine unavailability affects optimal production quantity for the finite production inventory model. Prod. Inventory Management, 28(1), pp.38-45.

Abboud, N.E., Jaber, M.Y. and Noueihed, N. A., 2000. Economic lot sizing with the consideration of random machine unavailability time. Computers and Operations Research, 27(4), pp.335-351.

Abid, C. and Tadj, L., 2011. An integrated productioninventory model with raw material, production and final product deteriorations. International Journal of Industrial and Systems Engineering, 8(3), pp.366-385.

Adiri, I. et al., 1989. Single machine flow-time scheduling with a single breakdown. Acta Informatica, 26(7), pp.679-696.

Aggoune, R., 2004. Minimizing the makespan for the flow shop scheduling problem with availability constraints. European Journal of Operational Research, 153(3), pp.534-543.

Aghezzaf, E.H., Jamali, M. a. and Ait-Kadi, D., 2007. An integrated production and preventive maintenance planning model. European Journal of

Operational Research, 181(2), pp.679-685.

Alaoui-Selsouli, M., Mohafid, A. and Najid, N.M., 2012. Lagrangian relaxation based heuristic for an integrated production and maintenance planning problem. International Journal of Production Research, 50(13), pp.3630-3642.

Allaoui, H. et al., 2008. Simultaneously scheduling n jobs and the preventive maintenance on the two-machine flow shop to minimize the makespan. International Journal of Production Economics, 112(1), pp.161-167.

Allaoui, H. and Artiba, A., 2004. Integrating simulation and optimization to schedule a hybrid flow shop with maintenance constraints. Computers and Industrial Engineering, 47(4), pp.431-450.

Allaoui, H. and Artiba, A., 2006. Scheduling two-stage hybrid flow shop with availability constraints. Computers and Operations Research, 33(5), pp.1399-1419.

Anily, S., Glass, C. A. and Hassin, R., 1998. The scheduling of maintenance service. Discrete Applied Mathematics, 82(1-3), pp.27-42.

Asano, M. and Ohta, H., 1999. Scheduling with shutdowns and sequence dependent set-up times. International Journal of Production Research, 37(7), pp.1661-1676.

Asano, M. and Ohta, H., 1999. Single machine scheduling to meet due times under shutdown constraints. International Journal of Production Economics, 60, pp.537-547.

Ben Ali, M. et al., 2011. Simultaneous scheduling of production and maintenance tasks in the job shop. International Journal of Production Research, 49(13), pp.3891-3918.

Bandyopadhyay, S. and Bhattacharya, R., 2013. Solving multi-objective parallel machine scheduling problem by a modified NSGA-II. Applied Mathematical Modelling, 37(10-11), pp.6718-6729.

Banerjee, A. and Burton, J.S., 1990. Equipment utilization based maintenance task scheduling in a job shop. European Journal of Operational Research, 45(2), pp.191-202.

Banerjee, P. and Rahim, M., 1988. Economic Design ofControl Charts Under Weibull Shock Models. Technometrics, 30(4), pp.pp.407-414.

Ben-Daya, M., 1999. Integrated production maintenance and quality model for imperfect processes. IIE Transactions (Institute of Industrial Engineers), 31(6), pp.491-501.

Ben-Daya, M., 2002. The economic production lot-sizing problem with imperfect production processes and imperfect maintenance. International Journal of Production Economics, 76(3), pp.257-264.

Ben-Daya, M. and Duffuaa, S.O., 1995. Maintenance and quality: the missing link. Journal of Quality in Maintenance Engineering, 1(1), pp.20-26.

Ben-Daya, M. and Hariga, M., 2000. Economic lot scheduling problem with imperfect production processes. Journal of the Operational Research Society, 51(7), pp.875-881.

Ben-Daya, M. and Makhdoum, M., 1998. Integrated production and quality model under various preventive maintenance policies. Journal of the Operational Research Society, pp.840-853.

Ben-Daya, M. and Noman, S.A., 2006. Lot sizing, preventive maintenance, and warranty decisions for imperfect production systems. Journal of Quality in Maintenance Engineering, 12(1), pp.68-80.

Ben-Daya, M. and Rahim, M.., 2000. Effect of maintenance on the economic design of x-control chart. European Journal of Operational Research, 120(1), pp.131-143.

Ben-Daya, M. and Rahim, M.., 2001. Integrated production, quality and maintenance models: an overview. Integrated Models in Production Planning, Inventory, Quality, and Maintenance, pp.3-28.

Benmansour, R. et al., 2014. Minimizing the weighted sum of maximum earliness and maximum tardiness costs on a single machine with periodic preventive maintenance. Computers and Operations Research, 47, pp.106-113.

Berrade, M.D., Cavalcante, C. a. V. and Scarf, P. a., 2012. Maintenance scheduling of a protection system subject to imperfect inspection and replacement. European Journal of Operational Research, 218(3), pp.716-725.

Berrichi, a. et al., 2010. Bi-Objective Ant Colony Optimization approach to optimize production and maintenance scheduling. Computers and Operations Research, 37(9), pp.1584-1596.

Berrichi, A. et al., 2009. Bi-objective optimization algorithms for joint production and maintenance scheduling: application to the parallel machine problem. Journal of Intelligent Manufacturing, 20(4), pp.389-400.

Berrichi, A. and Yalaoui, F., 2013. Efficient bi-objective ant colony approach to minimize total tardiness and system unavailability for a parallel machine scheduling problem. International Journal of Advanced Manufacturing Technology, 68(9-12), pp.2295-2310.

Berthaut, F., Gharbi, A. and Dhouib, K., 2011. Joint modified block replacement and production/inventory control policy for a failure-prone manufacturing cell. Omega, 39(6), pp.642-654.

Bishop, P., 1995. Optimal short-term scheduling of maintenance and production for multipurpose plants. Industrial and engineering chemistry research, 34(1), pp.192-201.

Blazewicz, J. et al., 2001. Heuristic algorithms for the two-machine flowshop with limited machine availability. Omega, 29(6), pp.599-608.

Brandolese, M., Franci, M. and Pozzetti*, A., 1996. Production and maintenance integrated planning. International Journal of Production Research, 34(7), pp.2059-2075.

Budai, G., Dekker, R. and Nicolai, R.P., 2008. Maintenance and production: a review of planning models. Handbook In Complex System Maintenance, pp.321-344.

Burton, J.S., Banerjee, A. and Sylla, C., 1989. A simulation study of sequencing and maintenance decisions in a dynamic job shop. , 17(1), pp.447-452.

Caballero Morales, S.O., 2013. Economic Statistical Design of Integrated X-bar-S Control Chart with Preventive Maintenance and General Failure Distribution. PLoS ONE, 8(3).

Cai, X., Sun, X. and Zhou, X., 2004. Stochastic scheduling subject to machine breakdowns: The preemptive-repeat model with discounted reward and other criteria. Naval Research Logistics, 51(6), pp.800-817.

Cassady, C.R. and Kutanoglu, E., 2005. Integrating preventive maintenance planning and production scheduling for a single machine. IEEE Transactions on Reliability, 54(2), pp.304-309.

Cassady, C.R. and Kutanoglu, E., 2003. Minimizing job tardiness using integrated preventive maintenance planning and production scheduling. IIE transactions, 35(6), pp.503-513.

Cassady, R.C. et al., 2000. Combining preventive maintenance and statistical process control: a preliminary investigation. IIE Transactions, 32(6), pp.471-478.

Cavory, G., Dupas, R. and Goncalves, G., 2001. A genetic approach to the scheduling of preventive maintenance tasks on a single product manufacturing production line. International Journal of Production Economics, 74(1-3), pp.135-146.

Chakraborty, T. and Giri, B.C., 2013. Lot sizing in a deteriorating production system under inspections, imperfect maintenance and reworks. Operational

Research, 14(1), pp.29-50.

Chan, F.T.S. et al., 2006. Solving distributed FMS scheduling problems subject to maintenance: Genetic algorithms approach. Robotics and Computer-Integrated Manufacturing, 22(5-6), pp.493-504.

Chand, S., 1989. Lot sizes and setup frequency with learning in setups and process quality. European Journal of Operational Research, 42(2), pp.190-202.

Charongrattanasakul, P. and Pongpullponsak, A., 2011. Minimizing the cost of integrated systems approach to process control and maintenance model by EWMA control chart using genetic algorithm. Expert Systems with Applications, 38(5), pp.5178-5186.

Chelbi, A., Rezg, N. and Radhoui, M., 2008. Simultaneous determination of production lot size and preventive maintenance schedule for unreliable production system. Journal of Quality in Maintenance Engineering, 14(2), pp.161-176.

Chen, J., 2006. Single-machine scheduling with flexible and periodic maintenance. Journal of the Operational Research Society, 57(6), pp.703-710.

Chen, J., Lin, Y. and Chen, Y., 2010. Economic optimisation for an imperfect production system with rework and scrap rate. International Journal of Industrial and Systems Engineering, 6(1), pp.92-109.

Chen, J.F., 2006. Minimization of maximum tardiness on unrelated parallel machines with process restrictions and setups. International Journal of Advanced Manufacturing Technology, 29(5-6), pp.557-563.

Chen, J.-S., 2008. Scheduling of nonresumable jobs and flexible maintenance activities on a single machine to minimize makespan. European Journal of Operational Research, 190(1), pp.90-102.

Chen, W. et al., 2011. Economic design of x-bar control charts under preventive maintenance and Taguchi loss functions. Journal of Applied Research, 3(2), pp.103-109.

Chen, W., 2006. Minimizing total flow time in the single-machine scheduling problem with periodic maintenance. Journal of the Operational Research Society, 57(4), pp.410-415.

Chen, W.J., 2009. Minimizing number of tardy jobs on a single machine subject to periodic maintenance. Omega, 37(3), pp.591-599.

Chen, W.J., 2007. Scheduling of jobs and maintenance in a textile company. International Journal of Advanced Manufacturing Technology, 31(7-8), pp.737-742.

Chen, W.J. and Liao, C.J., 2005. Scheduling with different maintenance policies in a textile company. Journal of Quality in Maintenance Engineering, 11(1), pp.43-52.

Chen, W.J. and Tsou, J.C., 2008. Sequencing Heuristic for Scheduling Jobs with Periodic Maintenance. International Journal of Information and Management Sciences, 19, pp.635-649.

Cheng, T., 1991. An economic order quantity model with demand-dependent unit production cost and imperfect production processes. IIE transactions, 23(1),

pp.23-28.

Cheng, T.C.., 1989. An economic production quantity model with flexibility and reliability considerations. European Journal of Operational Research, 39(2), pp.174-179.

Cheung, K.-Y. et al., 2004. Short-term site-wide maintenance scheduling. Computers and Chemical Engineering, 28(1-2), pp.91-102.

Chiu, H. and Huang, B., 1996. The economic design of x control charts with repair cost depending on detection delay. Computers and industrial engineering, 30(4), pp.707-718.

Chiu, H.-N. and Huang, B.-S., 1995. The economic design of x and S2 control charts with preventive maintenance and increasing hazard rate. Journal of Quality in Maintenance Engineering, 1(4), pp.17-40.

Chiu, S.W., Wang, S.L. and Chiu, Y.S.P., 2007. Determining the optimal run time for EPQ model with scrap, rework, and stochastic breakdowns. European Journal of Operational Research, 180(2), pp.664-676.

Chung, K.-J., 2003. Approximations to production lot sizing with machine breakdowns. Computers and Operations Research, 30(10), pp.1499-1507.

Collani, E. von, 1999. Control of production processes subjectto random shocks. Annals of Operations Research, 91, pp.289-304.

Colledani, M. and Tolio, T., 2012. Integrated quality, production logistics and maintenance analysis of multi-stage asynchronous manufacturing systems with degrading machines. CIRP Annals - Manufacturing Technology, 61(1), pp.455-

458.

Coudert, T., Grabot, B. and Archimde, B., 2002. Production/maintenance cooperative scheduling using multi-agents and fuzzy logic. International Journal of Production Research, 40(18), pp.4611-4632.

Cui, W.-W., Lu, Z. and Pan, E., 2014. Integrated production scheduling and maintenance policy for robustness in a single machine. Computers and Operations Research, 47, pp.81-91.

Darwish, M.A., Abdulmalek, F. and Alkhedher, M., 2013. Optimal selection of process mean for a stochastic inventory model. European Journal of Operational Research, 226(3), pp.481-490.

Dhouib, K., Gharbi, A. and Ben Aziza, M.N., 2012. Joint optimal production control/preventive maintenance policy for imperfect process manufacturing cell. International Journal of Production Economics, 137(1), pp.126-136.

Dieulle, L. et al., 2003. Sequential condition-based maintenance scheduling for a deteriorating system. European Journal of Operational Research, 150(2), pp.451-461.

Duffuaa, S.O. and Al-Sultan, K.S., 1999. A stochastic programming model for scheduling maintenance personnel. Applied Mathematical Modelling, 23(5), pp.385-397.

Duffuaa, S.O. and Al-Sultan, K.S., 1997. Mathematical programming approaches for the management of maintenance planning and scheduling. , 3(3), pp.163-176.

Duncan, A., 1956. The economic design of X charts used to maintain current control of a process. Journal of the American Statistical Association, 51(274), pp.228-242.

El-Ferik, S., 2008. Economic production lot-sizing for an unreliable machine under imperfect age-based maintenance policy. European Journal of Operational Research, 186(1), pp.150-163.

Espinouse, M., Formanowicz, P. and Penz, B., 2001. Complexity results and approximation algorithms for the two machine no-wait flow-shop with limited machine availability. Journal of the Operational Research Society, pp.pp.116-121.

Espinouse, M.L., Formanowicz, P. and Penz, B., 1999. Minimizing the makespan in the two-machine no-wait flow-shop with limited machine availability. Computers and Industrial Engineering, 37(1-2), pp.497-500.

Fakher, H.B. and Gendreau, M., 2014. Profit Maximization by Integrating Production Planning , Maintenance Scheduling , Quality Aspects and Sale Decisions. International Conference on Industrial Engineering and Operations Management.

Faria, J. a., Nunes, E. and Matos, M. a., 2010. Cost and quality of service analysis of production systems based on the cumulative downtime. International Journal of Production Research, 48(6), pp.1653-1684.

Finch, B.J. and Gilbert, J.P., 1986. Developing maintenance craft labor efficiency through an integrated planning and control system: a prescriptive model. Journal of Operations Management, 6(3), pp.449-459.

Fitouhi, M.-C. and Nourelfath, M., 2012. Integrating noncyclical preventive maintenance scheduling and production planning for a single machine. International Journal of Production Economics, 136(2), pp.344-351.

Fitouhi, M.-C. and Nourelfath, M., 2014. Integrating noncyclical preventive maintenance scheduling and production planning for multi-state systems. Reliability Engineering and System Safety, 121, pp.175-186.

Gao, J. et al., 2007. A hybrid of genetic algorithm and bottleneck shifting for multiobjective flexible job shop scheduling problems. Computers and Industrial Engineering, 53(1), pp.149-162.

Gholami, M., Zandieh, M. and Alem-Tabriz, A., 2009. Scheduling hybrid flow shop with sequence-dependent setup times and machines with random breakdowns. International Journal of Advanced Manufacturing Technology, 42(1-2), pp.189-201.

Ghosh, S. and Khanra, S., 2011. An EOQ model for a deteriorating item with time-varying demand and time-dependent partial backlogging. International Journal of Mathematics in Operational Research, 3(3), pp.pp.264-279.

Goel, H.D., Grievink, J. and Weijnen, M.P.C., 2003. Integrated optimal reliable design, production, and maintenance planning for multipurpose process plants. Computers and Chemical Engineering, 27(11), pp.1543-1555.

Goyal, S.K. et al., 1993. Integrating production and quality control policies: A survey. European Journal of Operational Research, 69(1), pp.1-13.

Groenevelt, H., Pintelon, L. and Seidmann, A., 1992. Production lot sizing with machine breakdowns. Management Science, 38(1), pp.104-123.

Gunasekaran, A. et al., 1995. Optimal investment and lot-sizing policies for improved productivity and quality. The International Journal of Production Research, 33(1), pp.261-278.

Guo, Y. et al., 2007. Machine scheduling performance with maintenance and failure. Mathematical and Computer Modelling, 45(9-10), pp.1067-1080.

Gurel, S. and Akturk, M.S., 2007. Scheduling parallel CNC machines with time/cost trade-off considerations. Computers and Operations Research, 34(9), pp.2774-2789.

Hadidi, L. a., Turki, U.M. Al and Rahim, M.A., 2011. An integrated cost model for production scheduling and perfect maintenance. International Journal of Mathematics in Operational Research, 3(4), p.395.

Hadidi, L. a., Turki, U.M. Al and Rahim, M.A., 2012. Joint job scheduling and preventive maintenance on a single machine. International Journal of Operational Research, 13(2), p.174.

Hadidi, L. and Al-Turki, U., 2011. Integrated models in production planning and scheduling, maintenance and quality: a review. International Journal of Industrial and Systems Engineering, 10(1), pp.21-50.

Hajji, A. et al., 2012. Dynamic pricing models for ERP systems under network externality. International Journal of Production Economics, 135(2), pp.708-715.

Haoues, M., Dahane, M. and Mouss, N., 2013. Optimization of single-manufacturer multiple-contractors outsourcing relationship in integrated approach of production, maintenance and quality. IEEE International Conference In Systems, Man and Cybernetics (SMC), pp.935-940.

Hariga, M. and Ben-Daya, M., 1998. The economic manufacturing lot sizing problem with imperfect manufacturing process: bounds and optimal solutions. Naval Research Logistics, 45(4), pp.423-433.

Ho, J. and Wong, J., 1995. Makespan minimization for m parallel identical processors. Naval Research Logistics (NRL), 42(6), pp.935-948.

Holthaus, O., 1999. Scheduling in job shops with machine breakdowns: an experimental study. Computers and Industrial Engineering, 36(1), pp.137-162.

HONG, J., 1995. The effects of manufacturing lead time and process quality in a multi-process production system. Production Planning and Control, 6(4), pp.311-319.

Horenbeek, A., Bur, J., et al., 2013. Joint maintenance and inventory optimization systems: A review. International Journal of Production Economics, 143(2), pp.499-508.

Horenbeek, A., Scarf, P.A., et al., 2013. The effect of maintenance quality on spare parts inventory for a fleet of assets. IEEE Transactions on Reliability, 62(3), pp.596-607.

Hsu, C. and Chen, H., 2013. Single-Machine Scheduling to Minimize Makespan with Deterioration Jobs and Multi-Maintenance Activities. Advanced

Materials Research, 690(7), pp.3007-3013.

Huang, B. and Chiu, H., 1995. The quality management of the imperfect production process under two monitoring policies. International Journal of Quality and Reliability Management, 12(3), pp.19-31.

Huang, Y.S., Lin, Y.J. and Ho, J.W., 2013. A study on negative binomial inspection for imperfect production systems. Computers and Industrial Engineering, 65(4), pp.605-613.

Hyun Kim, C. and Hong, Y., 1999. An optimal production run length in deteriorating production processes. International Journal of Production Economics, 58(2), pp.183-189.

Jain, M. and Naresh, P., 2012. A multi-state degraded system with inspection and maintainability. International Journal of Industrial and Systems Engineering, 12(2), pp.165-187.

Jeang, A., 2012. Simultaneous determination of production lot size and process parameters under process deterioration and process breakdown. Omega, 40(6), pp.774-781.

Kazaz, B. and Sloan, T.W., 2013. The impact of process deterioration on production and maintenance policies. European Journal of Operational Research, 227(1), pp.88-100.

Keller, G. and Noori, H., 1988. Impact of investing in quality improvement on the lot size model. Omega, 16(6), pp.595-601.

Kellerer, H., 1998. Algorithms for multiprocessor scheduling with machine release times. IIE Transactions (Institute of Industrial Engineers), 30(11), pp.991-999.

Kenn, J.-P., Gharbi, A. and Beit, M., 2007. Age-dependent production planning and maintenance strategies in unreliable manufacturing systems with lost sale. European Journal of Operational Research, 178(2), pp.408-420.

Kubiak, W. et al., 2002. Two-machine flow shops with limited machine availability. European Journal of Operational Research, 136(3), pp.528-540.

Kubzin, M.A. and Strusevich, V.A., 2005. Two-machine flow shop no-wait scheduling with machine maintenance. 4OR, 3(4), pp.303-313.

Kuo, Y. and Chang, Z., 2007. Integrated Production Scheduling and Preventive Maintenance Planning for a Single Machine Under a Cumulative Damage Failure Process. Naval Research Logistics, 54(6), pp.602-614.

Lad, B.K. and Kulkarni, M.S., 2008. Integrated reliability and optimal maintenance schedule design: a Life Cycle Cost based approach. International Journal of Product Lifecycle Management, 3(1), pp.78-90.

Lee, C.Y., 1996. Machine scheduling with an availability constraint. Journal of Global Optimization, 9(3-4), pp.395-416.

Lee, C.-Y., 1997. Minimizing the makespan in the two-machine flowshop scheduling problem with an availability constraint. Operations Research Letters, 20(3), pp.129-139.

Lee, C.-Y., 1991. Parallel machines scheduling with nonsimultaneous machine available time. Discrete Applied Mathematics, 30(1), pp.53-61.

Lee, C.-Y. and Chen, Z.-L., 2000. Scheduling jobs and maintenance activities on parallel machines. Naval Research Logistics, 47(2), pp.145-165.

Lee, C.-Y. and Danusaputro Liman, S., 1993. Capacitated two-parallel machines scheduling to minimize sum of job completion times. Discrete Applied Mathematics, 41(3), pp.211-222.

Lee, C.Y. and Liman, S.D., 1992. Single machine flow-time scheduling with scheduled maintenance. Acta Informatica, 29(4), pp.375-382.

Lee, H. and Rosenblatt, M., 1989. A production and maintenance planning model with restoration cost dependent on detection delay. IIE transactions, 21(4), pp.368-375.

Lee, H. and Rosenblatt, M., 1987. Simultaneous determination of production cycle and inspection schedules in a production system. Management science, 33(9), pp.1125-1136.

Lee, H.-H., 2005. A cost/benefit model for investments in inventory and preventive maintenance in an imperfect production system. Computers and Industrial Engineering, 48(1), pp.55-68.

Lee, W.C., 2014. Single-machine scheduling with past-sequence-dependent setup times and general effects of deterioration and learning. Optimization Letters, 8(1), pp.135-144.

Lee, W.-C. and Wu, C.-C., 2008. Multi-machine scheduling with deteriorating jobs and scheduled maintenance. Applied Mathematical Modelling, 32(3), pp.362-373.

Lee, Y.-J. and Zipkin, P.H., 1992. Production control in a kanban-like system with defective outputs. International Journal of Production Economics, 28(2), pp.143-155.

Leung, J.Y.T. and Pinedo, M., 2004. A note on scheduling parallel machines subject to breakdown and repair. Naval Research Logistics, 51(1), pp.60-71.

Liao, C., Chen, C. and Lin, C., 2007. Minimizing makespan for two parallel machines with job limit on each availability interval. Journal of the Operational Research Society, 58(7), pp.938-947.

Liao, C.J. and Chen, W.J., 2003. Single-machine scheduling with periodic maintenance and nonresumable jobs. Computers and Operations Research, 30(9), pp.1335-1347.

Liao, C.J., Shyur, D.L. and Lin, C.H., 2005. Makespan minimization for two parallel machines with an availability constraint. European Journal of Operational Research, 160(2), pp.445-456.

Liao, G.L., 2012. Joint production and maintenance strategy for economic production quantity model with imperfect production processes. Journal of Intelligent Manufacturing, 24(6), pp.1229-1240.

Liao, L.M. and Tsai, C.H., 2009. Heuristic algorithms for two-machine flowshop with availability constraints. Computers and Industrial Engineering, 56(1),

pp.306-311.

Lin, G.C. and Gong, D.C., 2006. On a production-inventory system of deteriorating items subject to random machine breakdowns with a fixed repair time. Mathematical and Computer Modelling, 43(7-8), pp.920-932.

Linderman, K., McKone-Sweet, K.E. and Anderson, J.C., 2005. An integrated systems approach to process control and maintenance. European Journal of Operational Research, 164(2), pp.324-340.

Liou, M., Tseng, S. and Lin, T., 1994. The effects of inspection errors to the imperfect EMQ model. IIE transactions, 26(2), pp.42-51.

Liu, L. et al., 2013. Economic and economic-statistical designs of an X control chart for two-unit series systems with condition-based maintenance. European Journal of Operational Research, 226(3), pp.491-499.

Lodree, E.J. and Geiger, C.D., 2010. A note on the optimal sequence position for a rate-modifying activity under simple linear deterioration. European Journal of Operational Research, 201(2), pp.644-648.

Lou, S., Sethi, S. and Sorger, G., 1992. Stability of real-time lot scheduling policies for an unreliable machine. Automatic Control, IEEE, 37(12), pp.1966-1970.

Low, C. et al., 2010. Minimizing the makespan in a single machine scheduling problems with flexible and periodic maintenance. Applied Mathematical Modelling, 34(2), pp.334-342.

Lu, Z., Zhang, Y. and Han, X., 2013. Integrating run-based preventive maintenance into the capacitated lot sizing problem with reliability constraint. International Journal of Production Research, 51(5), pp.1379-1391.

Madhavi, N. and Rao, K.S., 2011. Optimal pricing policies of an inventory model for deteriorating items with discounts. International Journal of Operational Research, 12(4), pp.464-480.

Makis, V., Fung, J., 1995. Optimal preventive replacement, lot sizing and inspection policy for a deteriorating production system. Quality in Maintenance Engineering, 1(4), pp.41-55.

Manna, S., Lee, C. and Chiang, C., 2009. EOQ model for non-instantaneous deteriorating items with time-varying demand and partial backlogging. International Journal of Industrial and Systems Engineering, 4(3), pp.241-254.

May, R., 1996. The efficient set is nothing but a collection of such dominant schedules . Industrial Engineering, 30(1), pp.77-82.

Mehdi, R., Nidhal, R. and Anis, C., 2010. Integrated maintenance and control policy based on quality control. Computers and Industrial Engineering, 58(3), pp.443-451.

Mehrafrooz, Z. and Noorossana, R., 2011. An integrated model based on statistical process control and maintenance. Computers and Industrial Engineering, 61(4), pp.1245-1255.

Mehrez, A., Myers, B.L. and Khouja, M.J., 1991. Quality and inventory issues within the newsboy problem. Computers and Operations Research, 18(5),

pp.397-410.

Mellouli, R. et al., 2009. Identical parallel-machine scheduling under availability constraints to minimize the sum of completion times. European Journal of Operational Research, 197(3), pp.1150-1165.

Mirabedini, S.N. and Iranmanesh, H., 2014. A scheduling model for serial jobs on parallel machines with different preventive maintenance (PM). International Journal of Advanced Manufacturing Technology, 70(9-12), pp.1579-1589.

Mokhtari, H., Mozdgir, A. and Kamal Abadi, I.N., 2012. A reliability/availability approach to joint production and maintenance scheduling with multiple preventive maintenance services. International Journal of Production Research, 50(20), pp.5906-5925.

Moradi, E., Fatemi Ghomi, S.M.T. and Zandieh, M., 2011. Bi-objective optimization research on integrated fixed time interval preventive maintenance and production for scheduling flexible job-shop problem. Expert Systems with Applications, 38(6), pp.7169-7178.

Mosheiov, G., 1994. Minimizing the Sum of Job Completion Times on Capacitated Parallel Machines. Mathematical and Computer Modelling, 20(6), pp.91-99.

Moskowitz, H. and Plante, R., 1994. Using Runlength Distributions of Control Charts to Detect False Alarms. Production and Operations Management, 3(3), pp.217-239.

Naderi, B., Khalili, M. and Tavakkoli-Moghaddam, R., 2009. A hybrid artificial immune algorithm for a realistic variant of job shops to minimize the total completion time. Computers and Industrial Engineering, 56(4), pp.1494-1501.

Naderi, B., Zandieh, M. and Fatemi Ghomi, S.M.T., 2009. A study on integrating sequence dependent setup time flexible flow lines and preventive maintenance scheduling. Journal of Intelligent Manufacturing, 20(6), pp.683-694.

Najid, N.M., Alaoui-Selsouli, M. and Mohafid, A., 2011. An integrated production and maintenance planning model with time windows and shortage cost. International journal of production research, 49(8), pp.2265-2283.

Nourelfath, M. and Chatelet, E., 2012. Integrating production, inventory and maintenance planning for a parallel system with dependent components. Reliability Engineering and System Safety, 101, pp.59-66.

Nourelfath, M. and Fitouhi, M., 2010. An integrated model for production and preventive maintenance planning in multi-state systems. IEEE Transactions on Reliability, 59(3), pp.496-506.

ODonovan, R., Uzsoy, R. and McKay, K.N., 1999. Predictable scheduling of a single machine with breakdowns and sensitive jobs. International Journal of Production Research, 37(1), pp.4217-4233.

Ohta, H. and Ogawa, S., 1991. Joint determination of production cycle and inspection schedules under inspection errors. Production Research: Approaching the 21st Century. Taylor and Francis: London, pp.179-188.

Okamura, H., Dohi, T. and Osaki, S., 2001. Computation algorithms of cost-effective EMQ policies with PM. Integrated Models in Production Planning, Inventory, Quality, and Maintenance, pp.31-65.

Oke, S., Oluleye, A. and Oyawale, F., 2008a. A facility maintenance scheduling model incorporating opportunity and inflationary costs. International Journal of Industrial and Systems Engineering, 3(4), pp.423-466.

Oke, S., Oluleye, A. and Oyawale, F., 2008b. Sensitivity analysis of a preventive maintenance scheduling model. International Journal of Industrial and Systems Engineering, 3(3), pp.298-323.

Operational, O.F., 1995. Impact of job-sequence on the down-time of a deteriorating flexible machine. European journal of operational research, 87(2), pp.299-315.

Pan, E. et al., 2012. An integrated EPQ model based on a control chart for an imperfect production process. International Journal of Production Research, 50(23), pp.6999-7011.

Pan, E., Liao, W. and Xi, L., 2010. Single-machine-based production scheduling model integrated preventive maintenance planning. The International Journal of Advanced Manufacturing Technology, 50(1-4), pp.365-375.

Panagiotidou, S. and Nenes, G., 2009. An economically designed, integrated quality and maintenance model using an adaptive Shewhart chart. Reliability Engineering and System Safety, 94(3), pp.732-741.

Panagiotidou, S. and Tagaras, G., 2008. Evaluation of maintenance policies for equipment subject to quality shifts and failures. International Journal of Production Research, 46(1), pp.5761-5779.

Panagiotidou, S. and Tagaras, G., 2012. Optimal integrated process control and maintenance under general deterioration. Reliability Engineering and System Safety, 104, pp.58-70.

Panagiotidou, S. and Tagaras, G., 2007. Optimal preventive maintenance for equipment with two quality states and general failure time distributions. European Journal of Operational Research, 180(1), pp.329-353.

Pandey, D., Kulkarni, M.. and Vrat, P., 2012. A methodology for simultaneous optimisation of design parameters for the preventive maintenance and quality policy incorporating Taguchi loss function. International Journal of Production Research, 50(7), pp.2030-2045.

Pandey, D., Kulkarni, M.S. and Vrat, P., 2011. A methodology for joint optimization for maintenance planning, process quality and production scheduling. Computers and Industrial Engineering, 61(4), pp.1098-1106.

Pandey, D., Kulkarni, M.S. and Vrat, P., 2010. Joint consideration of production scheduling, maintenance and quality policies: a review and conceptual framework. International Journal of Advanced Operations Management, 2(1-2), pp.1-24.

Panesar, S.S. and Markeset, T., 2008. Development of a framework for industrial service innovation management and coordination. Journal of Quality in Maintenance Engineering, 14(2), pp.177-193.

Pat-Cornell, M. and Lee, H., 1987. Warnings of malfunction: the decision to inspect and maintain production processes on schedule or on demand. Management Science, 33(10), pp.1277-1290.

Peters, M., Schneider, H. and Tang, K., 1988. Joint determination of optimal inventory and quality control policy. Management Science, 34(8), pp.991-1004.

Pistikopoulos, E.N., Vassiliadis, C.G. and Papageorgiou, L.G., 2000. Process design for maintainability: an optimization approach. Computers and Chemical Engineering, 24(2), pp.203-208.

Porteus, E., 1986. Optimal lot sizing, process quality improvement and setup cost reduction. Operations research, 34(1), pp.137-144.

Portioli-Staudacher, A. and Tantardini, M., 2012. Integrated maintenance and production planning: a model to include rescheduling costs. Journal of Quality in Maintenance Engineering, 18(1), pp.42-59.

Prakash, O., Roy, A. and Goswami, A., 2013. Manufacturing inventory model with discrete random machine breakdown and discrete stochastic corrective and preventive repair time. International Journal of Procurement Management, 6(4), pp.394-406.

Qi, X., Chen, T. and Tu, F., 1999. Scheduling the maintenance on a single machine. Journal of the Operational Research Society, 50(10), pp.1071-1078.

Rabinowitz, G., Goren, S. and Mehrez, A., 2000. Scheduling two machines that require multiple types of maintenance, for a single operation. European Journal of Operational Research, 127(3), pp.546-564.

Rahim, A. and Fareeduddin, M., 2011. Optimal production run length for products sold with warranty in a deteriorating production system with a time varying defective rate under allowable shortages. International Journal of Industrial and Systems Engineering, 8(3), pp.298-325.

Rahim, A. and Shakil, M., 2011. A tabu search algorithm for determining the economic design parameters of an integrated production planning, quality control and preventive maintenance policy. International Journal of Industrial and Systems Engineering, 7(4), pp.477-497.

Rahim, M., 1994. Joint determination of production quantity, inspection schedule, and control chart design. IIE transactions, 26(6), pp.2-11.

Rahim, M. and Ben-Daya, M., 1998. A generalized economic model for joint determination of production run, inspection schedule and control chart design. International Journal of Production Research, 36(1), pp.277-289.

Rahim, M. and Ben-Daya, M., 2001. Joint determination of production quantity, inspection schedule, and quality control for an imperfect process with deteriorating products. Journal of the Operational Research Society, 52(12), pp.1370-1378.

Rahim, M. and Banerjee, P., 1988. Optimal production run for a process with random linear drift. Omega, 16(4), pp.347-351.

Raza, S.A., Al-turki, U.M. and Selim, S.Z., 2007. Early-Tardy Minimization for Joint Scheduling of Jobs and Maintenance Operations on a Single Machin e. , 4(1), pp.32-41.

Rebai, M., Kacem, I. and Adjallah, K.H., 2013. Scheduling jobs and maintenance activities on parallel machines. Operational Research, 13(3), pp.363-383.

Reza Golmakani, H. and Namazi, A., 2012. Multiple-route job shop scheduling with fixed periodic and age-dependent preventive maintenance to minimize makespan. Journal of Quality in Maintenance Engineering, 18(1), pp.60-78.

Richard Cassady, C., Paul Murdock, W. and Pohl, E.A., 2001. Selective maintenance for support equipment involving multiple maintenance actions. European Journal of Operational Research, 129(2), pp.252-258.

Rishel, T. and Christy, D., 1996. Incorporating maintenance activities into production planning; integration at the master schedule versus material requirements level. International Journal of Production, 34(2), pp.421-446.

Rosenblatt, M. and Lee, H., 1986a. A comparative study of continuous and periodic inspection policies in deteriorating production systems. IIE transactions, 18(1), pp.2-9.

Rosenblatt, M. and Lee, H., 1986b. Economic production cycles with imperfect production processes. IIE transactions, 18(1), pp.48-55.

Sadfi, C. et al., 2005. An improved approximation algorithm for the single machine total completion time scheduling problem with availability constraints. European Journal of Operational Research, 161(1), pp.3-10.

Salameh, M.K. and Jaber, M.Y., 2000. Economic production quantity model for items with imperfect quality. International Journal of Production Economics, 64(1-3), pp.59-64.

Sana, S.. and Chaudhuri, K., 2010. An EMQ model in an imperfect production process. International Journal of Systems Science, 41(6), pp.635-646.

Sanmarti, E., Espuna, A. and Puigjaner, L., 1997. Batch production and preventive maintenance scheduling under equipment failure uncertainty. Computers and Chemical Engineering, 21(10), pp.1157-1168.

Sarper, H., 1993. Scheduling for the maintenance of completely processed low-demand large items. Applied Mathematical Modelling, 17(6), pp.321-328.

Sbihi, M. and Varnier, C., 2008. Single-machine scheduling with periodic and flexible periodic maintenance to minimize maximum tardiness. Computers and Industrial Engineering, 55(4), pp.830-840.

Schmidt, G., 1984. Scheduling on semi-identical processors. Zeitschrift fr Operations Research, 28(5), pp.153-162.

Schmidt, G., 2000. Scheduling with limited machine availability. European Journal of Operational Research, 121(1), pp.1-15.

Schneider, H., Tang, K. and OCinneide, C., 1990. Optimal control of a production process subject to random deterioration. Operations Research, 38(6), pp.1116-1122.

Shih, N. and Wang, C., 2013. An Extended Production and Inspection Model with Nonrigid Demand. The Scientific World Journal, p.7

Singh, N., Vaish, B. and Singh, S., 2012. An economic production lot-size (EPLS) model with rework and flexibility under allowable shortages. International

Journal of Procurement Management, 5(1), pp.104-122.

Sitayeb, F.B. et al., 2011. Joint scheduling of jobs and Preventive Maintenance operations in the flowshop sequencing problem: a resolution with sequential and integrated strategies. International Journal of Manufacturing Research, 6(1), pp.30-48.

Sloan, T., 2004. A periodic review production and maintenance model with random demand, deteriorating equipment, and binomial yield. Journal of the Operational Research Society, pp.647-656.

Sortrakul, N., Nachtmann, H.L. and Cassady, C.R., 2005. Genetic algorithms for integrated preventive maintenance planning and production scheduling for a single machine. Computers in Industry, 56(2), pp.161-168.

Srinivasan, M. and Lee, H., 1996. Production-inventory systems with preventive maintenance. IIE transactions, 28(11), pp.879-891.

Sudiarso, A. and Labib, A.W., 2002. A fuzzy logic approach to an integrated maintenance/production scheduling algorithm. International Journal of Production Research, 40(13), pp.3121-3138.

Suliman, S.M.A. and Jawad, S.H., 2012. Optimization of preventive maintenance schedule and production lot size. International Journal of Production Economics, 137(1), pp.19-28.

Sun, K. and Li, H., 2010. Scheduling problems with multiple maintenance activities and non-preemptive jobs on two identical parallel machines. International Journal of Production Economics, 124(1), pp.151-158.

Tagaras, G., 1988. An integrated cost model for the joint optimization of process control and maintenance. Journal of the Operational Research Society, pp.757-766.

Tsao, Y.C., 2014. A piecewise nonlinear model for a production system under maintenance, trade credit and limited warehouse space. International Journal of Production Research, 52(10), pp.3052-3073.

Tsao, Y.C., Chen, T.H. and Zhang, Q.H., 2013. Effects of maintenance policy on an imperfect production system under trade credit. International Journal of Production Research, 51(5), pp.1549-1562.

Tseng, S., 1996. Optimal preventive maintenance policy for deteriorating production systems. IIE transactions, 28(8), pp.687-695.

Tseng, S., Huei, R. and Ho, W., 1998. Imperfect maintenance policies for deteriorating production systems. International Journal of Production Economics, 55(2), pp.191-201.

Valliathal, M. and Uthayakumar, R., 2013. Designing and computing optimal policies on a production model for non-instantaneous deteriorating items with shortages. International Journal of Production Research, 51(1), pp.215-229.

Vassiliadis, C.G. and Pistikopoulos, E.N., 2001. Maintenance scheduling and process optimization under uncertainty. Computers and Chemical Engineering, 25(2-3), pp.217-236.

Vaurio, J.K., 1999. Availability and cost functions for periodically inspected preventively maintained units. Reliability Engineering and System Safety, 63(2),

pp.133-140.

Voros, J., 1999. Lot sizing with quality improvement and setup time reduction. European Journal of Operational Research, 113(3), pp.568-574.

Wang, C. and Sheu, S.H., 2003.— Determining the optimal productionmaintenance policy with inspection errors: using a Markov chain. Computers and Operations Research, 30(1), pp.1-17.

Wang, C.-H. and Tsai, W.C., 2012. Determining the production lot size with a heuristic inspection policy for controlling the quality of input materials and products. International Journal of Systems Science, 43(11), pp.2030-2039.

Wang, S. and Liu, M., 2012. A branch and bound algorithm for single-machine production scheduling integrated with preventive maintenance planning. International Journal of Production Research, 7543(FEBRUARY), pp.1-22.

Wang, S. and Liu, M., 2014. Two-stage hybrid flow shop scheduling with preventive maintenance using multi-objective tabu search method. International Journal of Production Research, 52(5), pp.pp.1495-1508.

Wang, W., 2012. A simulation-based multivariate Bayesian control chart for real time condition-based maintenance of complex systems. European Journal of Operational Research, 218(3), pp.726-734.

Wang, W.Y., 2013. Optimum production and inspection modeling with minimal repair and rework considerations. Applied Mathematical Modelling, 37(4), pp.1618-1626.

Weinstein, L. and Chung, C., 1999. Integrating maintenance and production decisions in a hierarchical production planning environment. Computers and operations research, 26(10), pp.1059-1074.

Wu, C.C. and Lee, W.C., 2003. Scheduling linear deteriorating jobs to minimize makespan with an availability constraint on a single machine. Information Processing Letters, 87(2), pp.89-93.

Wu, J. and Makis, V., 2008. Economic and economic-statistical design of a chi-square chart for CBM. European Journal of Operational Research, 188(2), pp.516-529.

Xiang, Y., 2013. Joint optimization of control chart and preventive maintenance policies: A discrete-time Markov chain approach. European Journal of Operational Research, 229(2), pp.382-390.

Xiang, Y. et al., 2014. Joint production and maintenance planning with machine deterioration and random yield. International Journal of Production Research, 52(6), pp.1644-1657.

Xu, D., Sun, K. and Li, H., 2008. Parallel machine scheduling with almost periodic maintenance and non-preemptive jobs to minimize makespan. Computers and Operations Research, 35(4), pp.1344-1349.

Yang, D.-L. et al., 2002. Minimizing the Makespan in a Single Machine Scheduling Problem With a Flexible Maintenance. Journal of the Chinese Institute of Industrial Engineers, 19(1), pp.63-66.

Yang, D.L., Hsu, C.J. and Kuo, W.H., 2008. A two-machine flowshop scheduling problem with a separated maintenance constraint. Computers and Operations Research, 35(3), pp.876-883.

Yang, S.L. et al., 2011. Minimizing total completion time on a single machine with a flexible maintenance activity. Computers and Operations Research, 38(4), pp.755-770.

Yeh, R.H., Ho, W.T. and Tseng, S.T., 2000. Optimal production run length for products sold with warranty. European Journal of Operational Research, 120(3), pp.575-582.

Yeung, T.G., Cassady, C.R. and Schneider, K., 2007. Simultaneous optimization of [Xbar] control chart and age-based preventive maintenance policies under an economic objective. IIE Transactions, 40(2), pp.147-159.

Yin, Z. and Makis, V., 2011. Economic and economic-statistical design of a multivariate Bayesian control chart for condition-based maintenance. IMA Journal of Management Mathematics, 22(1), pp.47-63.

Yoo, S.H., Kim, D. and Park, M.S., 2012a. Inventory models for imperfect production and inspection processes with various inspection options under one-time and continuous improvement investment. Computers and Operations Research, 39(9), pp.2001-2015.

Yoo, S.H., Kim, D. and Park, M.S., 2012b. Lot sizing and quality investment with quality cost analyses for imperfect production and inspection processes with commercial return. International Journal of Production Economics, 140(2),

pp.922-933.

Yu, X., Zhang, Y. and Steiner, G., 2014. Single-machine scheduling with periodic maintenance to minimize makespan revisited. Journal of Scheduling, 17(3), pp.263-270.

Yulan, J., Zuhua, J. and Wenrui, H., 2008. Multi-objective integrated optimization research on preventive maintenance planning and production scheduling for a single machine. International Journal of Advanced Manufacturing Technology, 39(9-10), pp.954-964.

Zhang, Y., Lu, Z. and Xia, T., 2014. A dynamic method for the production lot sizing with machine failures. International Journal of Production Research, 52(8), pp.2436-2447.

Zhao, S., Wang, L. and Zheng, Y., 2014. Integrating production planning and maintenance: an iterative method. Industrial Management and Data Systems, 114(2), pp.162-182.

Zhou, W.-H. and Zhu, G.-L., 2008. Economic design of integrated model of control chart and maintenance management. Mathematical and Computer Modelling, 47(11-12), pp.1389-1395.

Vitae

- Name: Ahmed Osmna EL-Khalifa
- Nationality: Sudanese
- Education:

  M.Sc. degree in Industrial and Systems Engineering, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia, October 2015

  B.Sc. degree in Statistics and Computer Science, University of Khartoum, Sudan, August 2007
- Participations:

  6th Symposium on Maintenance, Predictive and Intelligent Maintenance.
- Permenant Address: Khartoum, Sudan
- Current Address: Riyadh, Saudi Arabia
- Email: *ahmedalkalifa@gmail.com*