Integrating Production and Maintenance Scheduling Under Stochastic Production Conditions

BY

Laith Awni Abdul-Fattah Al-Hadidi

A Dissertation 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

DOCTOR OF PHILOSOPHY

In

Industrial & Systems Engineering

May 2011

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS
DHAHRAN 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This dissertation, written by **Laith Awni Abdul-Fattah Al-Hadidi** 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 **DOCTOR OF PHILOSOPHY** IN **Industrial & Systems Engineering**.

Dissertation Committee

Dr.Umar Al-Turki
Dissertation Advisor

m. a. Rahim
Dr.Mohammed Adur-Rahim
Dissertation Co-Advisor

Dr.Salih Duffuaa
Member

Dr.Abdulbasit Andijani
Member

Dr.Bekir Sami Yilbas
Member

for
Dr.Fouad Al-Sunni
Department Chairman

Dr.Salam Zummo
Dean of Graduate Studies

Date 9/7/2011

Dedication

To my
Dear parents, brothers & sisters,
I dedicate this work

Acknowledgment

I sincerely thank King Fahd University of Petroleum & Minerals for supporting this research, and especially the Systems Engineering Department for providing the help and facility to carry it out.

I wish to express my profound gratitude to my advisor, **Dr. Umar Al-Turki**, and my co-advisor **Dr. Mohammed Abdur-Rahim**, who supervised this research. I highly appreciate their valuable suggestions, continuous encouragement, extraordinary support, and patience in correcting my writing. They were always kind, understanding and sympathetic to me. I also wish to thank other members of my dissertation committee **Dr. Salih Duffuaa, Dr. Abdulbasit Andijani** and **Dr. Bekir Sami Yilbas** for their cooperation and guidance. A great thanks goes to **Dr. Christopher Garris** for his careful proofreading.

I wish to extend my thanks to the anonymous referees of **International Journal of Industrial and Systems Engineering (IJISE), International Journal of Mathematics in Operational Research (IJMOR)** and, **International Journal of Operational Research (IJOR)** for their comments and insights which improved the content of this dissertation.

It goes without saying, I truly appreciate the love, sacrifices, prayers and understanding i received from my parents Dr. Awni & Mrs. Rima, brothers and sisters Sawsan, Hashem, Dr. Moayyed and Bushra. They were always supporting me and encouraging me with their best wishes.

Contents

List of Tables

List of Figures

DISSERTATION ABSTRACT

FULL NAME: LAITH AWNI ABDUL-FATTAH AL-HADIDI

TITLE OF STUDY INTEGRATING PRODUCTION AND MAINTENANCE SCHEDULING UNDER STOCHASTIC PRODUCTION CONDITIONS

MAJOR FIELD INDUSTRIAL & SYSTEMS ENGINEERING

DATE OF DEGREE JUNE, 2011

The goal of this dissertation is the integration between maintenance and production scheduling. The dissertation starts with a structured and comprehensive review of the literature on modelling the integration between maintenance and production scheduling. The review makes a distinction between interrelated and integrated models. Interrelated models superimpose the solution of one element on the model of the other element, while integrated models consider two or more elements of the production system simultaneously. Integrated models are proven to provide significant savings in operational cost and higher production system efficiency.

The second part of the dissertation models the integration of production scheduling and preventive maintenance scheduling on a single machine that is subject to random failures. Preventive maintenance that restores the machine to 'as good as new' condition is should be performed, if needed, before the start of job processing. The objective is to determine a schedule that

combines job processing and preventive maintenance activities that minimizes the total weighted expected jobs completion times. A mixed integer programming model is developed for the problem. Solving this model results in the optimum schedule.

The third part of the dissertation studies the previous problem taking into account the total cost of maintenance and production. Total cost includes costs of preventive maintenance, minimal repair and work in process inventory. Again the problem is formulated as a mixed integer programming model.

The dissertation concludes with suggestions for some future directions for research in this area. In addition, a preliminary investigation is presented regarding models that add quality to the integrated model, resulting in a three way joint determination of an integrated schedule and an optimum quality control chart design.

ملخص بحث

درجة الدكتوراة في الفلسفة

الإسم :	ليث عوني عبدالفتاح الحديدي
عنوان الإطروحة:	الجدولة الشاملة للصيانة والإنتاج تحت ظروف إنتاجية متغيرة
التخصص الدقيق:	هندسة صناعية ونظم
تاريخ التخرج:	يونيو ٢٠١١

الموضوع الرئيسي لهذه الإطروحة هو الجدولة الشاملة المتزامنة للعمليات الصناعية و عمليات الصيانة الدورية بغرض زيادة الإنتاجية و الكفاءة التشغيلية. الجزء الأول من هذه الأطروحة يقدم مراجعة شاملة ذات بناء محدد لجدولة الصيانة والعمليات الصناعية. قامت هذه المراجعة بالتفريق بين النماذج المتداخلة والنماذج المتزامنة. النماذج المتداخلة تقوم باعتبار أحد عناصر الإنتاج كشرط يقيد عمليات الإنتاج الأخرى . النماذج المتزامنة تقوم بنمذجة عنصرين أو أكثر من عناصر الإنتاج. أثبتت النماذج المتزامنة وفرا لتكلفة الإنتاج و كفاءة أعلى لنظام الإنتاج.

الجزء الثاني من هذه الأطروحة يقوم بنمذجة العمليات الصناعية و الصيانة الوقائية لآلة صناعية واحدة معرضة لأعطال غير متوقعة و المطلوب هو جدولة تشمل العمليات الصناعية وعمليات الصيانة الوقائية بما يضمن الكلفة الأقل من حيث مجموع أوقات إكمال المهام الإنتاجية. تقوم الصيانة الوقائية بإعادة حالة الآلة للحالة

الإبتدائية إذا تم عمل الصيانة الوقائية. تم في هذه الأطروحة تطوير نموذج رياضي لإيجاد الجدول الزمني الأمثل للعمليات الصناعية وعمليات الصيانة الوقائية.

يقوم الجزء الثالث من هذه الأطروحة بدراسة المسألة السابقة من حيث كلفة الإنتاج و كلفة الصيانة الوقائية. تتكون الكلفة الكاملة من الصيانة الوقائية، الإصلاح و كلف التخزين. يقوم هذا الجزء من الأطروحة بتقديم نموذج رياضي مشابه للنموذج السابق.

هذه الأطروحة تنتهي بتقديم مقترحات لأفكار بحثية مستقبلية لهذه المسألة و كذلك بتقييم أولي لبحث إمكانية إضافة التصميم الأمثل لأدوات ضبط الجودة للنموذج المتزامن لينتج نموذج ثلاثي بين جدولة العمليات الصناعية، الصيانة الوقائية و ضبط الجودة.

Chapter 1

INTRODUCTION

1.1 INTRODUCTION

Production scheduling, maintenance and quality are the fundamental elements for any production system. Since the 1950's, research in these elements has sustained a growing attention of researchers, as well as practitioners. This interest was driven by the increasing competition in global markets. As such, the theory in this area has nurtured and became mature. Many researchers believe that treating these elements independently would result in a suboptimal solution. Hence, research in the integrated models has recently gained momentum.

Modern production systems rely on optimal and effective planning and scheduling for their operations. It is a usual practice to plan for one element of the production system, independent of the others and, to ignore their possible mutuality. Furthermore, this independent planning is done through separate functional teams. As a result, plans of a specific function may disrupt other function plans. For example, the maintenance function schedules a major shutdown and communicates it to the production. The suggested maintenance may maximize the machine availability, but will disrupt production plans. Similarly, production schedulers may have the tendency to utilize machines to their full capacity to meet demand disregarding maintenance requirements. In this case, productivity may increase, but machine availability will decrease due to more frequent breakdowns. Figure 1.1 shows the possible interactions between different elements of a production system that will be clearly visible at the shop floor level where conflicts between the three plans arise.

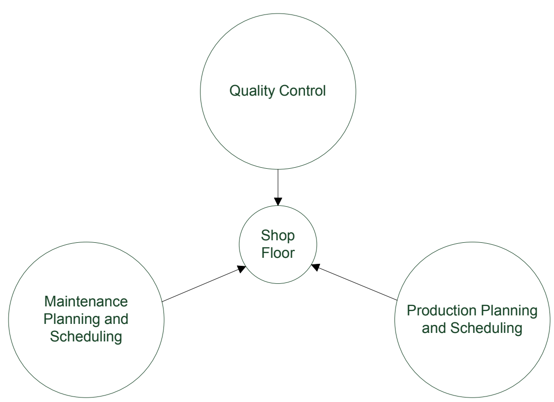

Figure 1.1: Classical disjoint planning for production, maintenance and quality

Independent planning may provide optimal performance at the level of a specific function. A global optimal can only be achieved by models integrating all functional elements of the system. Integrated production models are expected to deal with multiple elements of conflicting nature; hence, planning these elements independently will cause conflicts between their corresponding functions. This disturbance can be reduced through coordination between two or more elements of the production system. Figure 1.2 shows functional coordination in real life practice at the two levels of planning and scheduling, where production planning is done and then that plan goes to the shop floor and quality planning for implementation. Meanwhile, maintenance planning and scheduling develop their own plans and schedules to be implemented on the shop floor.

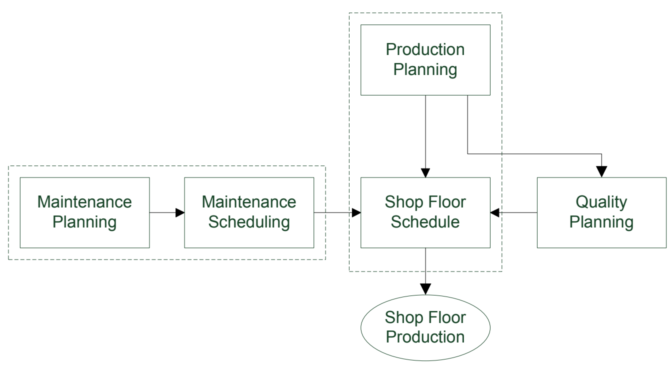

Figure 1.2: Interrelation between planning of production, quality and maintenance on the shop floor

Integrated models are usually not easy to develop, because of their multi-dimensional complexity. As such, the level of integration in planning between functional elements in production setting is minimal. Planners may give higher priority to a certain function and plan for that solely. The output plan will be taken as an input to the second in priority function. For that function, a plan will be built taking the input of the other function as a constraint. For example, production schedules can be generated given that the machine will be out of service for a specific duration. This situation can be seen as coordination or superimposition rather than real integration. These types of models can be referred to as interrelated models.

1.2 AN OVERVIEW

The objective of production planning is to identify the optimal production plan that satisfies demand with a minimum cost. This cost is usually composed of inventory holding and production setup costs. Production planning usually assumes a perfect environment in terms of resource availability and process quality. Resource unavailability during the production process will increase production costs and affect inventory levels needed to satisfy customer demand. Production planning is done as part of a hierarchical planning process, where the production plan is cascaded down to a more detailed production schedule. The objective of scheduling is to sequence production tasks, in order to minimize a certain performance measure of customer satisfaction. Performance measures may include average flow time, maximum production time or meeting due dates. These measures are minimized under different configurations of production resources, such as single machine, parallel machines, flowshop or jobshop. For each configuration, different scheduling rules are presented to optimize different performance measures. These rules are used to schedule production tasks on machines over time. Available production scheduling models are mostly deterministic models based on methodologies varying from traditional integer programming to Branch-Bound techniques to Lagrangean relaxation and optimization-based heuristics. These models and techniques have been implemented in a variety of manufacturing systems.

Customers' satisfaction of delivery, offered by successful production planning and scheduling, can be affected by quality deterioration resulting from shifts in process mean, variance or both. Preventive Maintenance (PM) is utilized to delay or prevent these shifts, which can be detected by Statistical Process Control (SPC) tools. To control a production process, proper planning is needed for PM activities as well as effective quality control tools. PM studies focus on inspection and replacement intervals or address equipment condition. PM planning models are typically stochastic in nature (either mathematical or simulation) accompanied by optimization techniques designed to maximize equipment availability or minimize equipment maintenance costs.

Preventive maintenance is usually done in two different ways. The first is time-based or preventive, where maintenance tasks are scheduled for the production unit when it reaches a certain age. The second is condition-based or predictive where maintenance is scheduled based on machine conditions.

The ultimate goal of condition-based maintenance is to perform maintenance when the maintenance activity is most appropriate and before the equipment loses optimum performance. This is in contrast to time-based maintenance, where a piece of equipment gets maintained at predetermained points of time whether it needs it or not.

1.3 DISSERTATION OBJECTIVES AND MOTIVATION

Although, the interest in integrated modeling is increasing, review papers on integrated models are limited (Pandey et al., 2010*a*; Budai et al., 2008; Ben-Daya and Rahim, 2001). Motivated by the lack in review papers, this dissertation provides, at first, a state of the art model for the integration between planning and scheduling of production, maintenance, and quality. It is proven that integrated models offer savings in operating costs and a higher utilization of resources.

After reviewing the literature, this dissertation considers three integrated problems:

1. Integrating job scheduling and preventive maintenance on a single machine to minimize expected total job completion times.

2. Integrating job scheduling and preventive maintenance on a single machine to minimize costs associated with maintenance, minimal repair

and work in process inventory.

3. Investigating the effect of quality rejection rate on delaying job completion time and its effect on decisions related to job scheduling and preventive maintenance.

This chapter only provides a brief introduction for each problem. A detailed introduction is given at the beginning of each of the coming chapters.

The motivation to study the integrated job scheduling and preventive maintenance problem, in addition to cost savings, comes from the need to overcome conflicts arising between production and maintenance functions in most manufacturing systems. While the production unit has an interest in keeping a continuous production run to satisfy customer needs, the maintenance function is committed to long life asset management and optimum maintenance tasks and activities. These two objectives, in many cases, cause conflicts when planned or unplanned shutdowns cause a serious delay in production schedules. Solving the production scheduling and PM planning problems independently ignores these inherent conflicts. Even when the conflict is managed, the result is not usually optimized globally, because both schedules are developed independently from each other and then combined over the planning horizon.

To our knowledge, there are no integrated models between job scheduling and quality control in the literature. Meanwhile, the integration between preventive maintenance and quality control is well established in the literature.

Fewer models exist in the integration between job scheduling and preventive maintenance. The three way integration between job scheduling, preventive maintenance and quality control is highly challenging. This dissertation attempts to address this gap in the literature, which simultaneously captures the effect of job scheduling, preventive maintenance and quality control on the overall system performance.

1.4 ORGANIZATION OF THE DISSERTATION

Chapter 2 provides a literature review focusing on the integration between planning and scheduling of production, maintenance and quality. The review identifies some of the gaps that needed to be addressed. As a result, Chapters 3 and 4 discuss integration between job scheduling and preventive maintenance for two different objectives. Chapter 3 addresses the minimization of expected total weighted job completion times. Chapter 4 addresses the objective of minimizing total costs associated with maintenance and inventory.

Finally, Chapter 6 summarizes the research in this dissertation, and briefly discusses some potential future work.

Chapter 2

LITERATURE REVIEW OF INTEGRATED MODELS IN PRODUCTION PLANNING AND SCHEDULING, MAINTENANCE AND QUALITY

2.1 INTRODUCTION

In recent years, researchers have enriched the literature in integrated planning. Much research has investigated integrating production and maintenance planning (Aghezzaf et al., 2007; Chelbi et al., 2008; El-Ferik, 2008). Research also has investigated integration production and maintenance scheduling (Sortrakul and Cassady, 2007; Kuo and Chang, 2007; Yulan et al., 2008; Naderi et al., 2009*a*,*b*; Berrichi et al., 2009, 2010). Integrating maintenance and quality control was investigated too (Zhou and Zhu, 2008; Yeung et al., 2008; Wu and Makis, 2008; Panagiotidou and Tagaras, 2007, 2008; Panagiotidou and Nenes, 2009; Radhoui et al., 2010).

Despite increasing interest, existing work reviewing integrated models are limited (Pandey et al., 2010*a*; Budai et al., 2008; Ben-Daya and Rahim, 2001). This chapter can be seen as an extension to their work. The key feature distinguishing the work in this chapter from other reviews is the differentiation between the concept of interrelation and integration. In addition, this review considers the integrated models of production scheduling. In section 2.2, interrelated models are presented in production planning and scheduling, maintenance and quality. Section 2.3 discusses two way integration between production elements. Section 2.4 discusses production planning, maintenance and quality integrated models. Section 2.5, presents gaps in the literature. Finally, section 2.6 presents conclusions.

2.2 INTERRELATED MODELS

Interrelated models consider optimizing a certain component of a production system, taking the requirement of another component as a constraint. For example, models exist for scheduling jobs with machine unavailability due to maintenance operations (arrow 4 in Figure 2.1). The inverse is also common where maintenance operations are scheduled while taking into consideration the production schedule (arrow 3 in Figure 2.1). Production schedules and maintenance schedules are cascaded down from production plans and maintenance plans. In this example, interrelation can occur at the planning level (arrows 1 and 2 in Figure 2.1). Section 2.2.1 presents interrelated models between production and maintenance scheduling. Section 2.2.2 presents interrelated models between maintenance and inventory control. Section 2.2.3 presents interrelated models between quality control and inventory control where EMQ is assumed to have defectives.

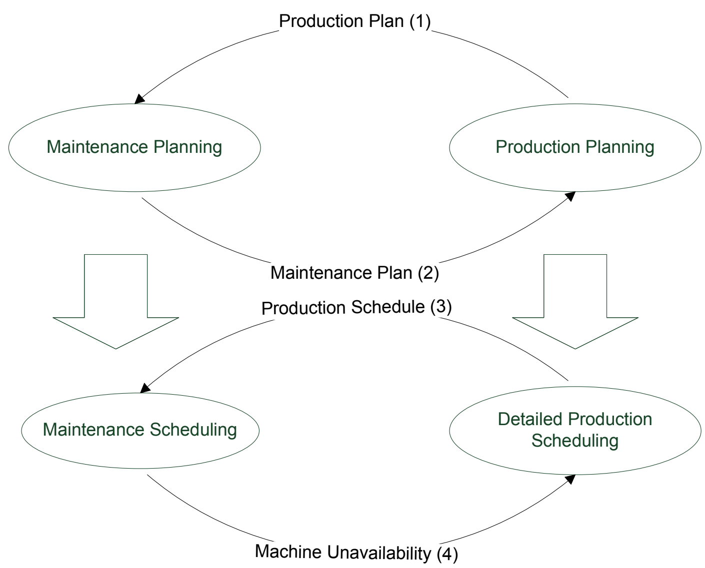

Figure 2.1: Interrelated models between production and maintenance

2.2.1 PRODUCTION AND MAINTENANCE SCHEDULING INTERRELATED MODELS

Most papers in the scheduling field are based on the assumption that machines are continuously available. Adiri et al. (1989) studied the single machine nonpreemptive scheduling problem of minimizing total completion time of jobs for both stochastic and deterministic cases. The single machine is not available for the entire scheduling horizon. To solve the problem, a shortest processing time (SPT) heuristic algorithm was proposed. In Schmidt (2000), a review was presented, related to deterministic scheduling problems, where machines are not continuously available for processing. Sadfi et al. (2005) studied the single machine total completion scheduling problem subject to a period of maintenance. In Ji et al. (2007), the objective was to find a schedule that minimizes the makespan, subject to periodic maintenance and nonresumable jobs. Low et al. (2008) studied a single machine scheduling problem, with an availability constraint, under simple linear deterioration for both preemptive and nonpreemptive cases. The objective was to minimize the makespan in the system.

The maintenance task can be seen as a special job that should not be processed with longer than a predefined interval. Qi et al. (1999) studied scheduling maintenance on a machine that must be maintained after it continuously works for a period of time. The objective was to minimize total completion time of jobs. They presented two metaheuristics to solve the problem. Raza et al. (2007) extended this work with the objective to minimize total earliness and tardiness with a common due date. In Low et al. (2010), a several maintenance periods modeled on a single machine. The machine should be stopped for maintenance after a periodic time interval or to change tools after a fixed amount of jobs are processed simultaneously. Yang et al. (2002) scheduled flexible maintenance on a single machine, where the machine should be stopped for a constant maintenance time interval, during the scheduling period. Liao and Chen (2003) studied scheduling periodic maintenance jobs on a single machine. Several maintenance periods were deliberated, where each maintenance type was required after a periodic time interval. Specifically, the problem was to minimize the maximum tardiness with periodic maintenance and nonresumable jobs. Chen (2009) scheduled periodic maintenance to minimize the number of tardy jobs. Based on the Moores algorithm, an effective heuristic was developed to provide a near-optimal schedule for the problem.

The multiple machine scheduling problems with unavailability constraints have also been studied. Schmidt (1988) studied the parallel machine preemptive scheduling problem, where each job had a deadline and each machine had different availability intervals. Lee (1991) considered the problem of minimizing the makespan for parallel machines, where machines may not be available in a certain time interval. To solve this problem, he proposed a modified longest processing time (LPT) algorithm and showed a tight worst-case bound. Kellerer (1998) introduced an algorithm for a parallel machine problem with different starting times. Ho and Wong (1995) studied minimizing makespan on m parallel machines and proposed a two machine optimization (TMO) algorithm. Liao et al. (2005, 2007) introduced a fixed known unavailable period for the TMO. Their objective was to minimize makespan on two machines, where only one machine has a fixed known unavailable period. Lin and Liao (2007) extended previous work and presented a model minimizing makespan on two machines, where each machine has a fixed and known unavailable period. Lee and Liman (1993) studied minimizing total completion time for two parallel machines where one machine is available for some period, after which the machine is no longer available. Their work was extended by Mosheiov (1994) to m parallel machines with different starting times. Lee and Chen (2000) studied minimizing total completion time on m parallel machines, where each machine should be maintained at least once in the planning horizon. They identified the problem as having two versions. In first, more than one machine can be maintained simultaneously. In second, no more than one machine can be maintained at a time.

The flowshop problem with unavailability constraint was also studied in the literature (Lee, 1997; Espinouse et al., 1999; Blazewicz et al., 2001; Espinouse et al., 2001; Kubiak et al., 2002; Aggoune, 2003; Allaoui and Artiba, 2004; Kubzin and Strusevich, 2005; Aggoune and Portmann, 2006; Allaoui and Artiba, 2006; Yang et al., 2008; Allaoui et al., 2008; Liao and Tsai, 2009; Gholami et al., 2009).

Table 2.1: Maintenance and scheduling interrelated models

Category	Models
Single machine	Adiri et al. (1989), Qi et al. (1999), Schmidt (2000), Yang et al. (2002), Liao and Chen (2003), Sadfi et al. (2005), Raza et al. (2007), Low et al. (2008), Chen (2009), Low et al. (2010)
Parallel machines	Schmidt (1988), Burton et al. (1989), Banerjee and Burton (1990), Lee (1991), Lee and Liman (1992), Lee and Liman (1993), Mosheiov (1994), Chakravarty and Balakrishnan (1995), Suresh and Chaudhuri (1996), Lee (1996), Brandolese et al. (1996), Kellerer (1998), Asano and Ohta (1999*a*), Asano and Ohta (1999*b*), Holthaus (1999), Lee (1999), Graves and Lee (1999), O'Donovan et al. (1999), Lee and Chen (2000), Rabinowitz et al. (2000), Chan (2001), Lee and Lin (2001), Blazewicz and Formanowicz (2002), Wu and Lee (2003), Breit et al. (2003), Leung and Pinedo (2004), Cai et al. (2004), Liao et al. (2005), Chen and Liao (2005), Chen (2006*a*), Chen (2006*b*), Chen (2006*c*), Gao et al. (2006), Chan et al. (2006), Liao et al. (2007), Cheng (2007), Chen (2007*c*), Chen (2007*b*), Lin and Liao (2007), Lee and Wu (2008), Xu et al. (2008), Chen and Tsou (2008), Sbihi and Varnier (2008), Gurela and Akturk (2008), Chen (2008), Mosheiov and Sarig (2009), Mellouli et al. (2009), Sun and Li (2010), Pan et al. (2010)
Flowshop	Lee (1997), Espinouse et al. (1999), Blazewicz et al. (2001), Espinouse et al. (2001), Kubiak et al. (2002), Aggoune (2003), Allaoui and Artiba (2004), Kubzin and Strusevich (2005), Aggoune and Portmann (2006), Allaoui and Artiba (2006), Ji et al. (2007), Allaoui et al. (2008), Yang et al. (2008), Liao and Tsai (2009), Gholami et al. (2009)

2.2.2 PRODUCTION AND MAINTENANCE PLANNING INTERRELATED MODELS

In the following, we consider maintenance models under the direct effect of production requirements model but that don't provide changes to the original production plan. The production system may be planned to have an excess amount of production (buffer) to overcome shortages due to unexpected production interruption due to machine breakdowns. There are a number of models that explored production systems with buffer (Das and Sarkar, 1999; Iravani and Duenyas, 2002; Yao et al., 2005; Kyriakidis and Dimitrakos, 2006; Chelbi and Ait-Kadi, 2004).

Some models in the literature presented the economic manufacturing quantity (EMQ) or lot sizing with the presence of stochastic machine breakdowns and corrective maintenance (Groenevelt et al., 1992*a*,*b*; Sarper, 1993; Anily et al., 1998; Vassiliadis and Pistikopoulos, 2001; Cavory et al., 2001; Ben-Daya, 2002; Chung, 2003; Lee, 2005; Lin and Gong, 2006; Kenné et al., 2006; Lodree and Geiger, 2010).

Finch and Gilbert (1986) presented an integrated conceptual framework for maintenance and production, in which they focus especially on manpower issues during corrective and preventive work. Duffuaa and Al-Sultan (1997, 1999), extended Finch and Gilbert (1986) and casted the maintenance scheduling problem in a stochastic framework. For a multipurpose plant, Lou et al. (1992) and Dedopoulos and Shah (1995) considered a multi-product manufacturing system, with random breakdowns and random repair time. They offered an interrelated production and maintenance model that determines the relationship between failure and profitability, as well as the costs of different maintenance policies. Vaurio (1999) developed unavailability and cost rate functions for components whose failures can occur randomly. Dijkhuizen (2001) discussed the problem of clustering preventive maintenance jobs in a multi-component production system that has multiple setups. Cassady et al. (2000) presented the concept of selective maintenance, where production systems are required to perform a sequence of operations with finite breaks between each operation. Rishel and Christy (1996) studied the impact of incorporating maintenance policies into the material requirement planning (MRP) system. Four performance measures were used to evaluate the impact of merging maintenance policies with the MRP system: number of on-time orders, number of scheduled maintenance actions, number of equipment failures and the total maintenance costs. Six different MRP systems were used to determine if integrating scheduled maintenance with the production schedule would improve the performance measures. Brandolese et al. (1996) considered the problem of planning a multi-product made up for flexible machines operating in parallel. They developed a model that determined the optimal schedule for both production and maintenance check points. Cheung et al. (2004) considered a plant with several units of different types, where there are different shutdown periods for maintenance. The problem was to allocate units to these periods in a way that production was least affected. Maintenance was not modeled in detail, but incorporated through frequency or period restrictions.

Table 2.2: Maintenance and inventory control interrelated models

Category	Models
Buffer inventory models	Das and Sarkar (1999), Iravani and Duenyas (2002), Chelbi and Ait-Kadi (2004), Yao et al. (2005), Kyriakidis and Dimitrakos (2006)
EMQ models	Groenevelt et al. (1992*a*), Groenevelt et al. (1992*b*), Sarper (1993), Anily et al. (1998), Vassiliadis and Pistikopoulos (2001), Cavory et al. (2001), Ben-Daya (2002), Chung (2003), Lee (2005), Lin and Gong (2006), Kenné et al. (2006), Lodree and Geiger (2010)
Other models	Finch and Gilbert (1986), Lou et al. (1992), Dedopoulos and Shah (1995), Sanmarti et al. (1995), Duffuaa and Al-Sultan (1997), Duffuaa and Al-Sultan (1999), Weinstein and Chung (1999), Vaurio (1999), Rishel and Christy (1996), Abboud et al. (2000), Dijkhuizen (2001), Cassady et al. (2001), Sudiarso and Labib (2002), Coudert et al. (2002), Sloan (2004), Cheung et al. (2004), Guo et al. (2007), Chen (2007*a*)

2.2.3 PRODUCTION AND QUALITY INTERRELATED MODELS

Classical production planning models assume all produced items have an acceptable quality level (i.e. production process mean and variance) remains in-control during the entire production time. In the literature, some of the production planning models can be found with the assumption to have rejected items. This type of production is called an imperfect production process (Rosenblatt and Lee (1986*a*,*b*) and Lin et al. (1991) and Hariga and

Ben-Daya (1998) and Salameh and Jaber (2000)).

Porteus (1986) studied the relationship between lot size and quality. Keller and Noori (1988) evaluated quality investments under uniform and exponential lead time demand. Chand (1989) investigated learning effect in process quality on the optimal setup frequency. Cheng (1989) modeled the relationship between production setup and process reliability and flexibility. Cheng (1991) modeled an EPQ with imperfect production process and demand dependent unit production cost. Mehraz et al. (1991) considered the lot size and quality issue in the context of the news-boy problem. Khouja and Mehraz (1994) dealt with economic production lot size, where the production rate is a decision variable. Hong (1995) determined optimal lot size with lead time and quality improvement. Kim and Hong (1999) presented an EMQ model, which determines an optimal production run length in three deteriorating production processes: constant, linear and exponentially increasing. Voros (1999) developed a model that relates lot size, quality improvement and setup time reduction. Ben-Daya and Hariga (2000) studied the economic lot scheduling problem under imperfect production process.

Lee and Zipkin (1992) considered quality issues in Kanban production systems. Rahim and Banerjee (1988) and Schneider et al. (1990) developed an optimal decision rule for tool re-setting for a process with random linear drift to minimize the cost of rejected items. Gunasekaran et al. (1995) addressed issues related to optimal investments and lot sizing policies for improved productivity and quality. For a deteriorating production system, Yeh et al. (2000) studied optimal run length where products are sold under warranty.

Table 2.3: Quality control and inventory control interrelated models

Category	Models
Imperfect EPQ	Porteus (1986), Rosenblatt and Lee (1986*a*), Rosenblatt and Lee (1986*b*), Keller and Noori (1988), Chand (1989), Cheng (1989), Lin et al. (1991), Cheng (1991), Mehraz et al. (1991), Khouja and Mehraz (1994), Hong (1995), Hariga and Ben-Daya (1998), Kim and Hong (1999), Voros (1999), Salameh and Jaber (2000), Ben-Daya and Hariga (2000), Chiu et al. (2007), Charles-Owaba et al. (2008*b*), Charles-Owaba et al. (2008*a*), Chen (2010), Faria et al. (2010), Sana and Chaudhuri (2010)
Other	Rahim and Banerjee (1988), Schneider et al. (1990), Lee and Zipkin (1992), Gunasekaran et al. (1995), Yeh et al. (2000)

2.3 INTEGRATED MODELS

Integrated models between inventory control, maintenance and quality control are models where decision variables are simultaneously serving more than one of them as shown in Figure 2.2 (areas 1, 2, 3, 4 and 5) . Section 2.3.1 discusses integration between maintenance and inventory control (area 1 in Figure 2.2). Section 2.3.2 discusses integration between maintenance and scheduling (area 2 in Figure 2.2). Section 2.3.3 discusses integration between quality control and inventory control (area 3 in Figure 2.2). Section 2.3.4 discusses integration between quality control and maintenance (area 4 in Figure 2.2).

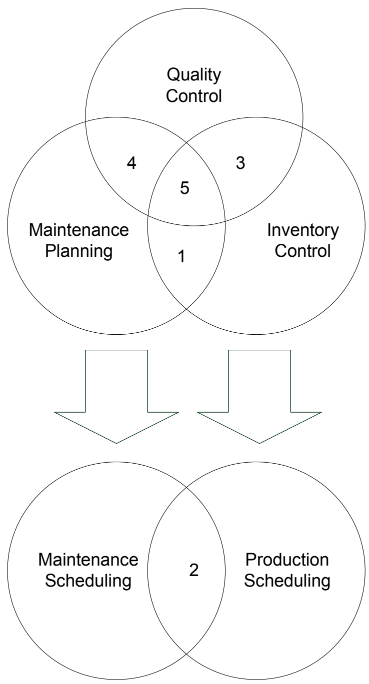

Figure 2.2: Integrated models in production, maintenance and quality

2.3.1 INTEGRATING MAINTENANCE AND INVENTORY CONTROL

Srinivasan and Lee (1996) modeled PM as a decision of the inventory level. PM operation is initiated when inventory reaches a certain level then it restores production system to an 'as-good-as new' condition. After the PM operation, the production system will remain without production until the inventory level drops down to or below a predefined value. At that inventory level, the facility continues to produce stock until inventory is raised back to the inventory level where maintenance is applied. A minimal repair is conducted if the facility breaks down. Okamura et al. (2001) generalized the model with the assumption that both the demand and the production process are a continuous-time renewal counting process. Machine breakdowns follow non-homogeneous Poisson process. Pistikopoulos et al. (2000) described an optimization framework for general multi-purpose process models, which determines both the optimal design as well as the production and maintenance plans simultaneously. Goel et al. (2003) presented a reliability allocation model coupled with the existing design, production and maintenance optimization framework. The aim was to identify the optimal size and initial reliability for each unit of equipment at the design stage.

A properly integrated production and maintenance plan can be achieved by optimizing the production rate and maintenance intervals for a production system. This system consists of multiple identical machines with random breakdowns, repairs and PM activities. The objective of the control problem is to find the production rate and PM frequency of the machines, so as to minimize the total cost of inventory/backlog, repair and PM. This line of research can be found (Gharbi and Kenné, 2000; Kenné and Boukas, 2003; Kenné et al., 2003; Gharbi and Kenné, 2005).

Production and maintenance planning were integrated for a given set of items that must be produced in lots on a capacitated production system throughout a specified finite planning horizon (Aghezzaf et al., 2007; Dieulle et al., 2003). Ben-Daya and Noman (2006) developed an integrated model that considers simultaneous inventory production decisions, maintenance schedule, and warranty policy. This model was presented for a deteriorating system that experiences quality shifts. El-Ferik (2008) dealt with the problem of joint determination for both economic production quantity and imperfect PM schedules. The production system undergoes PM, either upon failure or after having reached a predetermined age, whichever occurs first.

Production planning is affected by machine breakdowns due to aging. Proper PM planning will reduce the age of the production unit and, hence, number of defective items produced in the lot. Chelbi et al. (2008) focused on finding, simultaneously, the optimal values of the lot size Q and the age T at which preventive maintenance must be performed. They considered a single unit production system, which must satisfy a constant and continuous demand D, shifts to an out-of-control state and produces non-conforming units at a given rate, after a random period of operation. The system is submitted to an age-based preventive maintenance policy. A PM action is performed as soon as the system reaches age T without having shifted to the out-of-control state. If the shift to the out-of-control state is detected, a restoration action of the system is planned for L time units later.

$$Total\ Cost\ Rate = \frac{Production\ Cost + Maintenance\ Cost}{Expected\ Cycle\ Time}$$

$$\begin{aligned} Production\ Cost =& Inventory\ Cost + Nonconforming\ Items\ Cost \\ & + Shortage\ Cost + Setup\ Cost \end{aligned}$$

Table 2.4: Maintenance and inventory control integrated models

Category	Models
Maintenance and inventory control	Srinivasan and Lee (1996) PM cost, a repair cost, a setup cost, a holding cost, and a backorder cost. Pistikopoulos et al. (2000) introduced a system effectiveness optimization framework. Goel et al. (2003) extended a combined design, production and maintenance planning formulation for multipurpose process plants. Dieulle et al. (2003) A maintenance scheduling function determines random inspecting times. Ben-Daya and Noman (2006) Integrates inventory production decisions, PM schedule, and warranty policy for a deteriorating system that experiences shifts to an out of control state. Aghezzaf et al. (2007) considered a set of items that must be produced in lots on a capacitated production system throughout a specified finite planning horizon. El-Ferik (2008) proposed a model for the joint determination of economic production quantity and PM schedules under imperfect maintenance.
Optimizing the production rate and maintenance intervals	Gharbi and Kenné (2000) considered a multiple-identical-machine manufacturing system with random breakdowns, repairs and PM activities. Kenné and Boukas (2003) dealt with the production and PM planning control problem for a multimachine flexible manufacturing system (FMS). Kenné et al. (2003) presented the analysis of the optimal production control and corrective maintenance planning problem for a failure prone manufacturing system consisting of several identical machines, Gharbi and Kenné (2005) presented a two-level hierarchical control model that find the production and PM rates minimize the total cost of inventory/backlog, repair and PM.

2.3.2 INTEGRATING MAINTENANCE AND SCHEDULING

Production planning is very dependent on machine conditions. Machine breakdowns may disturb the production process and cause delay in schedules. Despite this dependency, classical scheduling models ignored machine breakdowns. However, recently, researchers spot out the need to integrate planning for production and maintenance. This integration is justified by expected cost savings and better resource utilization. Maintenance scheduling might delay the production schedule, but will reduce expected number of machine failures.

For the objective of total weighted tardiness, Cassady and Kutanoglu (2003) investigated the benefits of integration through a numerical study of small problems. In Yulan et al. (2008) five objectives were simultaneously considered to optimize the integrated problem of PM and production scheduling. The five objectives included minimizing maintenance cost, makespan, total weighted completion time (TWC) of jobs, total weighted tardiness (TWT), and maximizing machine availability. Sortrakul et al. (2005) developed three algorithms to solve the integrated problem. Algorithms performance was evaluated using multiple instances of small, medium, and large size. Sortrakul and Cassady (2007) developed heuristics based on genetic algorithms to solve the integrated model. In order to minimize the total tardiness, Kuo and Chang (2007) proposed a solution method to find the optimal integrated production schedule and preventive maintenance plan for a single machine under a cumulative damage process. Naderi et al. (2009*a*) presented a job shop scheduling environment that has sequence-dependent setup times, which is subjected to preventive maintenance policies. The optimization criterion was to minimize the makespan.

Cassady and Kutanoglu (2005) investigated the value of integrating production and PM scheduling. This model was developed for a single machine that has increasing hazard rate and is subject to failure. Each time the machine fails, it needs a fixed time to repair t_r. Expected number of failures can be minimized by performing preventive maintenance before the start of the job which will restore the machine to an 'as-good-as-new' condition. This PM will delay the start of the job by fixed time to maintain t_p, nevertheless. If the machine is required to process n jobs with the objective to minimize their expected total completion times then the scheduler is required to provide simultaneously, optimal sequence and, when to perform PM's. To represent the problem in the form of mathematical program, a binary variable $y_{[i]}$ is defined where $y_{[i]} = 1$ if PM is conducted and $y_{[i]} = 0$ if PM is not conducted. Let $P_{[i]}$ be the processing time for job i. The expected completion time for job i will be

$$E(c_{[i]}) = \sum_{k=1}^{i} [y_{[k]} \times t_p + P_{[k]} + t_r \times number\ of\ failures]$$

If each job has a given weight $w_{[i]}$ then the objective function would be to minimize the total weighted expected completion time

$$Total\ Weighted\ Expected\ completion\ Time = \sum_{i=1}^{n} (w_{[i]} E(c_{[i]}))$$

Identifying the sequence, mathematically, can be done by introducing job assignment binary variable x_{ij}. This variable is two dimensional; one is for jobs domain $i = \{1, 2 \cdots, n\}$ and the other is for position domain $j = \{1, 2, \cdots, n\}$.

$$x_{ij} = \begin{cases} 1 & \text{if job } i \text{ is assigned to position } j \\ 0 & \text{if job } i \text{ is not assigned to position } j \end{cases}$$

Two logical sets of constraints will constrain the objective function; first set of constraints states that job i can not seize two positions at the same time i.e.

$$\sum_{j=1}^{n} x_{ij} = 1 \quad \forall \quad i = 1, \cdots, n$$

second set of constraints states that one position can not hold more than one job i.e.

$$\sum_{i=1}^{n} x_{ij} = 1 \quad \forall \quad j = 1, \cdots, n$$

Table 2.5: Maintenance and scheduling integrated models

Category	Models
Single machine	Cassady and Kutanoglu (2003) formulated the integrated problem for a single machine with the objective to minimize expected total weighted tardiness, Sortrakul et al. (2005) developed heuristics based on genetic algorithms to solve Cassady and Kutanoglu (2003), Cassady and Kutanoglu (2005) formulated the integrated problem for a single machine with the objective to minimize expected total weighted completion times, Sortrakul et al. (2005) developed heuristics based on genetic algorithms to solve Cassady and Kutanoglu (2005), Kuo and Chang (2007) developed an integrated model to minimize total tardiness for a single machine under a cumulative damage process, In Yulan et al. (2008), five objectives where examined on a single machine,
Flowshop	Naderi et al. (2009*b*) investigated flexible flow line problems with sequence dependent setup times and different PM policies to minimize the makespan,
Parallel machines	Berrichi et al. (2009) proposed a model to simultaneously optimize two criteria: the makespan for the production part and the system unavailability, Berrichi et al. (2010) presented an algorithm based on Ant Colony optimization paradigm to solve the joint production and maintenance scheduling problem,
Jobshop	Naderi et al. (2009*a*) considered job shop scheduling with sequence-dependent setup times and PM policies to minimize the makespan. Four metaheuristics based on simulated annealing and genetic algorithms were employed to solve the problem.

2.3.3 INTEGRATING QUALITY CONTROL AND INVENTORY CONTROL

In classical production planning, it is a common assumption that the start of production will be in an in-control state. After some time the production process may then shift to an out-of-control state. Lee and Rosenblatt (1987, 1989) and Tseng (1996) showed that the derived optimal lot size was smaller than the classical EMQ if the in-control-state time follows an exponential distribution. Wang and Sheu (2003) extended Lee and Rosenblatt (1987) in which they assumed that periodic inspections were imperfect with two types of error: Type I and Type II. They used a Markov chain to jointly determine the production cycle, process inspection intervals and maintenance levels.

For the economic design of control charts, Rahim (1994) developed an economic model for joint determination of production quantity, inspection schedule and control chart design for a production process which is subject to a non-Markovian random shock. Rahim and Ben-Daya (1998) generalized the previous model by assuming that the production stops for a fixed amount of time, not only for a true alarm, but also whenever there is a false alarm during the in-control state. Liou et al. (1994) and Ohta and Ogawa (1991) determined optimal EPQ and inspection frequency for a single item, where there is an inspection error. Peters et al. (1988) determined a joint optimal inventory and quality control policy for a production system. Goyal et al.

(1993) reviewed models that integrate production, lot sizing, inspection and rework. Ben-Daya and Makhdoum (1998) studied joint optimization of the economic production quantity (EPQ) and the economic design of control chart under different preventive maintenance policies.

The integrated model's objective is to minimize the expected cost rate for production and quality costs. Sampling cost, cost of running the process under out-of-control state, cost of false alarm and cost of repairing the process are the four components of quality costs. Production costs are composed of setup cost, average holding cost and shortage costs. Since production system may be disrupted by sampling and repairing then production cycle time is a stochastic variable that $E[T_c]$

$$\begin{aligned} Total\ Cost\ Rate = & \quad Production\ Cost + Quality\ Cost = \\ = & \quad \tfrac{K}{E[T_c]} + K_1\bar{I} + K_2\bar{S} \\ & \quad + \tfrac{f(n,f)+C_2 f(f,P_f)+C_3 f(f,\alpha)+C_4 f(P_f)}{E[T_c]} \end{aligned}$$

Where K is setup cost, K_1 is holding cost, $\bar{I}$ is the average inventory,K_2 is cost of shortage and $\bar{S}$ is the average shortage. For the quality cost let n be the sample size and let f the number of samples taken during production time, α is probability of type I error, C_2 is cost per unit time of running process under out-of-control, C_3 is cost per false alarm, C_4 is cost of detecting and correcting process. P_f probability system will shift out-of-control.

2.3.4 INTEGRATING QUALITY CONTROL AND MAINTENANCE

The production process is usually considered to follow a deteriorating scheme where the in-control period follows a general probability distribution with increasing hazard rate. Ben-Daya and Duffuaa (1995) pointed out possibility of integration between PM and quality control in two ways. In the first approach, proper maintenance is expected to increase the time between failures that the machine can have. The second approach is based on Taguchi's approach for quality where a quadratic function (called Taguchi loss function) is defined (Taguchi, 1986). This function measures deviation of product quality characteristics. The economic design of control charts and the optimization of preventive maintenance policies are two research areas that have recently received increasing attention in the quality and reliability literature. More and more researchers recognize the strong relationship between product quality, process quality and equipment maintenance.

Pate-Cornell et al. (1987) addressed the inspection-maintenance problem which was extended by Tagaras (1988). Chiu and Huang (1996, 1995) developed models that introduce preventive maintenance into the design of control charts. In Cassady et al. (2000), a combined control chart-preventive maintenance strategy is defined. The process can shift to an out-of-control condition due to a manufacturing equipment failure. Collani (1999) addressed the relationship between tool wear and continuous monitoring process. He assumed the quality to be a function of a machine's degradation state. He developed an economic model that incorporates both process control and maintenance policies. Linderman et al. (2005) demonstrated the value of integrating statistical process control and maintenance by jointly optimizing their policies to minimize the total costs associated with quality, maintenance, and inspection. Zhou and Zhu (2008) discussed the integration of statistical process control and maintenance, and provides an integrated model of control chart and maintenance management. A mathematical model is given to analyze the cost of the integrated model and the grid-search approach is used to find the optimal values of policy variables that minimize hourly cost. Yeung et al. (2008) formulated a combined preventive maintenance and SPC policy using partially observable, discrete-time Markov decision process. Wu and Makis (2008) considered the economic-statistical design of a control chart for a maintenance application. The machine deterioration process is described by a three-state continuous time Markov chain. The machine state is unobservable, except for the failure state. Panagiotidou and Tagaras (2008) developed an economic model for the optimization of maintenance procedures in a production process with two quality states. In addition to deteriorating with age, the equipment may experience a jump to an out-of-control state (quality shift), which is characterized by lower production revenues and higher tendency to failure. Panagiotidou and Nenes (2009) proposed a model for the economic design of a variable-parameter Shewhart control chart. This model is used to monitor the process mean, where, apart from quality shifts, failures may also occur.

A new cost named obsolescence cost was incorporated in Sun and Xi (2010) where the impact of tool-degraded state on the product quality was studied. The degraded state of a tool is set back to its nominal value through preventive or corrective maintenance. In general, most maintenance policies assume the replacement occurs with identical parts to the replaced tools but a new technology may appear and replace the old part even if this part was functioning well. The replacement can be done each time a corrective maintenance is undertaken. The old technology can be salvaged and the incurred cost for it and the new technology is called obsolescence cost. The Sun and Xi (2010) model minimized costs of maintenance, quality loss, and tool obsolescence cost.

Ben-Daya and Rahim (2000) developed a model that jointly optimize the economic design of process mean control chart, and the optimal maintenance level. The objective was to minimize the total cost rate.

$$Total\ Cost\ Rate = \frac{E(PM) + E(QC)}{E(T)}$$

In the formula, $E(PM)$ is the expected preventive maintenance cost, $E(QC)$ is the expected quality cost and $E(T)$ is the expected cycle time. The problem is then to simultaneously determine the optimal production run time, the optimal preventive maintenance level, and the optimal design parameters of the process mean control chart (namely $h_1; h_2; \cdots; h_m$, the sample size n, and the control limit coefficient k).

2.4 INTEGRATING MAINTENANCE, INVENTORY CONTROL AND QUALITY CONTROL

Three way integration between production, maintenance and quality comes as a natural extension to the two way integration. In the literature, some attempts have been made to model the integration of the three functions, production planning, maintenance and quality. Many models discussed joint integration between production and quality under different PM policies (Huang and Chiu, 1995; Makis and Fung, 1995; Tseng et al., 1998). Makis and Fung (1995) presented a model for the joint determination of the lot size, inspection interval and preventive replacement time for a production facility that was subject to a random failure. The time when the system was in-control was exponentially distributed and once it was out-of-control, a certain amount of defective items were produced. Inspecting the unit on a periodic basis was done to review the production process. After a certain number of production-runs, the production facility was replaced. This model was studied under the effect of machine failures in Makis and Fung (1998). Rahim and Ben-Daya (1998) presented a generalized model for a continuous production process for simultaneous determination of production quantity, inspection schedule and control chart design, with a non-zero inspection time for false alarms. Rahim and Ben-Daya (2001) looked at the effect of deteriorating products and a deteriorating production process, on the optimal production quantity, inspection schedule and control chart design parameters. Radhoui et al. (2010) developed a joint quality control and preventive maintenance policy for a production system producing conforming and nonconforming units. Chelbi et al. (2008) proposed an integrated production-maintenance strategy for unreliable production systems producing conforming and non-conforming items that links EMQ, quality and an age-based preventive maintenance policy. Ben-Daya (1999) developed an integrated model for the joint optimization of the economic production quantity, the economic design of process mean control chart, and the optimal maintenance level. The system is a deteriorating process with increasing hazard rate and the in-control period follows a general probability distribution.

$$Total\ Cost\ Rate = \frac{Production\ Cost + Maintenance\ Cost + Quality\ Cost}{Expected\ Cycle\ Time} =$$

$$Total\ Cost\ Rate = \frac{S_0 + E(HC) + E(PM) + E(QC)}{E(T)}$$

In the formula, S_0 is the setup cost, $E(HC)$ is the expected holding cost, $E(PM)$ is the expected preventive maintenance cost, $E(QC)$ is the expected quality cost, $E(T)$ is the expected cycle time. The problem is then to simultaneously determine the optimal production run time, the optimal preventive maintenance level, and the optimal design parameters of the process mean control chart (namely sampling frequencies $h_1; h_2; \cdots; h_m$, the sample size n, and the control limit coefficient k).

2.5 MISSING INTEGRATED MODELS

In the literature, production scheduling was integrated with maintenance scheduling resulting in cost savings. Also, quality was integrated with maintenance. As observed, there is a missing gap in the literature of integrating production scheduling and quality. The suggested integrated modeling will provide, simultaneously, optimal schedule for inspection and production. Inspectors may spend some time in testing products. This time will affect the production schedule. The higher number of inspections, the more delay production schedule will have. Moreover, scheduling models can be studied under the effect of deteriorating jobs, where the machine have the probability to shift to an out-of-control state during job processing.

As a natural evolution in the integrated models literature, researchers can look into the models where production, PM scheduling and quality can be integrated. In these models job processing times can be deteriorated due to the probability that system can shift to out-of control state. PM should be scheduled before the start of a job and will reduce the age of the machine.

This reduction in age will reduce probability of the machine to shift to out-of-control state during job processing. However, it will delay the start of the job due to the time needed to perform PM. This suggested integrated model will provide production, maintenance and inspection schedules.

2.6 CONCLUSIONS

This review emphasizes providing a better understanding of the interrelation and integration between production, maintenance and quality models. The key feature distinguishing this chapter from other reviews is the differentiation between the concept of interrelation and integration. Interrelated models are meant to describe models that optimize solely one function taking other function as a constraint. Another feature distinguishing this review is the inclusion of production scheduling in addition to production planning, maintenance and quality. To the best of our knowledge, there is no integrated model between scheduling and quality or scheduling, quality and maintenance.

Chapter 3

JOINT JOB SCHEDULING AND PREVENTIVE MAINTENANCE ON A SINGLE MACHINE

3.1 INTRODUCTION

Production scheduling focuses on allocating machine capacity to job processing, while maintenance scheduling focuses on maintaining machine capacity. These two problems are interrelated, in that machine interruptions cause delay in production schedules. However, this interrelatedness seems to be overlooked in the literature. Classical production models assume continuous machine availability, which might not be true in most real life manufacturing systems. A machine may become unavailable during the production process, due to preventive maintenance (PM), which can be scheduled in advance or due to random breakdowns. Recently, researchers addressed the need to integrate the scheduling of both production and maintenance. Kenne et al. (2009) stated that the integrated production planning and preventive maintenance problem is concerned with coordinating production and maintenance operations to meet customer demand with the aim of minimizing cost. Pandey et al. (2010*a*) pointed out that production scheduling and maintenance have been treated as separate issues. In real life situations, machines do fail or need to be maintained and hence may become unavailable during certain periods. Thus, the interdependency of scheduling and maintenance has resulted in a considerable amount of interest in developing models.

In recent years, few researchers have addressed this conflict by developing integrated models of production and maintenance scheduling. Many models have discussed the integrated optimization problem of production scheduling and PM for a single machine. Cassady and Kutanoglu (2003) compared the optimal total weighted tardiness under integrated production scheduling and PM planning. Their results indicated that there was an average of a 30% reduction in the expected total weighted tardiness when the production scheduling and PM were integrated. Thus, the need to integrate production scheduling with PM planning was clearly demonstrated. Similarly, Cassady and Kutanoglu (2005) considered an integrated model of job scheduling on a single machine and its preventive maintenance. The objective was to minimize the total weighted expected completion times. They assumed that the uptime of a machine follows a Weibull distribution such that the machine is minimally repaired when it fails and the maintenance restores the machine to an 'as good as new' state. Using weighted shortest processing time (WSPT) they minimized the total weighted expected completion times for large size problems. An optimal maintenance interval was provided by maximizing the availability of the machine. They integrated job scheduling and PM on a single machine by introducing a binary variable representing whether or not to schedule PM before each job. The above mentioned-papers (Cassady and Kutanoglu, 2003, 2005) used the total enumeration method as the optimization technique. Aghezzaf et al. (2007) presented an integrated lot sizing and preventive maintenance strategy of the system that satisfies the demand for all items over the entire time horizon without backlogging, and which minimizes the expected sum of production and maintenance costs. They assumed that any maintenance action carried out on the system, within a period, reduces the system's available production capacity during that period. Berrichi et al. (2009, 2010) introduced a new bi-objective approach for the joint production and maintenance-scheduling problem. Their aim was to simultaneously optimize two criteria: the minimization of the makespan for the production part and the minimization of the system unavailability for the maintenance side.

Clearly, integrated models have proven expected cost reductions over independent solutions of the two problems. Similar to Cassady and Kutanoglu (2005), this chapter finds the optimal integrated production schedule and PM plan to minimize the total weighted expected completion times of a fixed number of jobs processed on a single machine, and investigates how the optimal PM plan interacts with the optimal production schedule. Cassady and

Kutanoglu (2005) used the full enumeration procedure to solve the integrated problem. In their procedure, they fixed a production job sequence and then enumerated all possible maintenance schedules, which are 2^n maintenance schedules (where n is the number of jobs). The minimum maintenance cost was found for the given job sequence. Then, the job sequence was altered and again all maintenance schedules were evaluated for the new job sequence to find the minimum maintenance cost. They continued in the previous method until all production sequences are evaluated. The minimum of all evaluated job sequences was considered to be the optimal solution. However, they did not fully utilize the integrated model developed in their paper.

The model in this chapter provides, simultaneously, the optimal schedules for production jobs and PM. The key feature distinguishing our model is the development of an explicit mathematical formulation for the problem that jointly integrates production scheduling and preventive maintenance scheduling. The decision variables of the model include both scheduling problems, which once solved, yield an optimum solution of the whole problem.

3.2 PROBLEM DEFINITION

Consider n independent jobs ready for processing on a single machine that is subject to interruptions due to preventive maintenance and unexpected random failures. PM policy is adopted to increase machine availability that restores the machine to an 'as good as new' state. When the machine fails, it is assumed that it is minimally repaired, i.e. the machine is restored to an operating condition, but the machine age is not altered. This implies that, upon machine failure, the machine operator does just enough maintenance to resume machine function. The assumption that PM restores the machine to 'as good as new' implies that PM is a more comprehensive action than repair. This may include the replacement of many key parts in the machine. It is assumed that jobs are not interrupted by PM. However, jobs interrupted by failure can be resumed after repair without any additional time penalty. The maintenance and repair times are assumed to be constant, t_p and t_r respectively. Time to failure for the machine T is assumed to follow a Weibull probability distribution having shaping parameter β greater than 1.

Some particular applications of the Weibull distributions associated with the process-failure mechanism can be seen in real life. The distribution of time to leakage failure of dry cell batteries can be approximated by a Weibull distribution (Berrittoni, 1964). For example, consider a typical manufacturing process with several mechanical and electrical control devices. Certain control devices require the continuous direct current output of dry cell batteries. When the battery fails, the process can drift into an out-of-control state and needs a repair that is assumed to be minimal. When choosing a job sequence, a decision is made whether or not to perform PM prior to each job. The integrated problem is further complicated by the fact that completion times for the jobs are stochastic, because the machine may or may not fail during each job and PM decisions change the stochastic process governing machine failure.

3.3 FORMULATION

The single machine scheduling, with the objective of minimizing the weighted mean completion times, is modeled in classical scheduling theory as follows:

$$Min \sum_{j=1}^{n} \left(\sum_{i=j}^{n} w_{[i]} \right) P_{[j]} \tag{3.1}$$

$$\sum_{j=1}^{n} x_{ij} = 1 \quad \forall \quad i = 1, \cdots, n \tag{3.2}$$

$$\sum_{i=1}^{n} x_{ij} = 1 \quad \forall \quad j = 1, \cdots, n \tag{3.3}$$

Where

$$x_{ij} = \begin{cases} 1 & \text{if the } i^{th} \text{ job performed is job } j \\ 0 & Otherwise \end{cases}$$

To introduce the effect of random machine failures and the scheduling of

PM activities we followed an approach similar to Cassady and Kutanoglu (2005).

$$y_i = \begin{cases} 1 & \text{if PM is performed before job } i \\ 0 & Otherwise \end{cases} \qquad i = 1, 2, \cdots, n$$

Let $N(\tau)$ be the number of failures that occur during a time interval τ and $E[N(P_i)]$ be the expected number of failures that occur while processing job i.

Figure 3.1 presents a Gantt chart for the sequence j_1, j_2 $\cdots$,j_{n-1},j_n with hatched area representing PM activity of times t_p and random machine breakdowns. It presents the notations used for modeling completion times in a schedule.

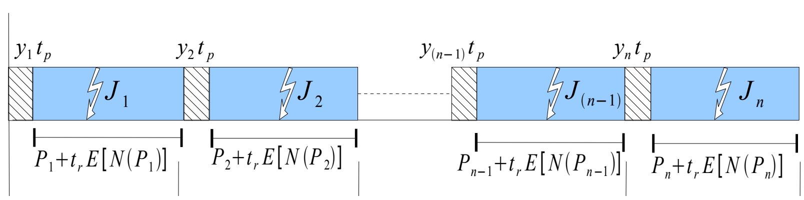

Figure 3.1: Gantt chart for the effect of preventive maintenance on a production schedule

Taking randomness into consideration for equation 3.1, the objective function becomes

$$\sum_{i=1}^{n} [w_i E(c_i)] = w_1 E(c_1) + w_2 E(c_2) \cdots + w_{n-1} E(c_{n-1}) + w_n E(c_n) \quad (3.4)$$

Since c_i is a function of machine breakdowns, which is in turn a function of the age of the machine, we need to introduce a variable $a_{[i]}$ to represent the age at the completion of the i^{th} job. Since PM renews the machine, the age of the machine at the end of processing the i^{th} job is

$$a_{[i]} = \quad (1 - y_i) a_{[i-1]} + P_{[i]} \quad i = 1, 2, \cdots, n \quad (3.5)$$

Given that job i starts at age $(1-y_i)a_{[i-1]}$ and ends at age $a_{[i]}$, the expected number of breakdowns during the processing of the i^{th} job, assuming Weibull hazard rate, is

$$E[N(P_{[i]})] = \quad \int_{(1-y_i)a_{[i-1]}}^{a_{[i]}} z(t)\, dt = \quad \int_{(1-y_i)a_{[i-1]}}^{a_{[i]}} \frac{\beta}{\eta^{\beta}} t^{\beta-1}\, dt$$

which can be simplified to be

$$= \quad m(a_{[i]}) - m((1 - y_i) a_{[i-1]}) = \left(\frac{a_{[i]}}{\eta}\right)^{\beta} - \left(\frac{(1-y_i) a_{[i-1]}}{\eta}\right)^{\beta}$$

The expected job completion time can be written as

$$E[c_{[i]}] = \sum_{k=1}^{i} \left\{ t_p y_k + P_{[k]} + t_r \left[m(a_{[k]}) - m((1-y_i)a_{[k-1]}) \right] \right\}$$
$$i = 1, 2, \cdots, n \tag{3.6}$$

The deterministic scheduling model presented earlier can now be modified to model the expected total completion time of the integrated problem as follows:

$$Minimize$$
$$\sum_{i=1}^{n} \left(w_{[i]} E\left[c_{[i]}\right] \right) = \sum_{i=1}^{n} \left\{ W_i \left(t_p y_i + \sum_{j=1}^{n} (P_j x_{ij}) + t_r \left[m(a_{[i]}) - m((1-y_i)a_{[i-1]}) \right] \right) \right\}$$

Subject to

$$
\begin{aligned}
\sum_{j=1}^{n} x_{ij} &= 1 \quad i = 1, 2, \cdots, n \\
\sum_{i=1}^{n} x_{ij} &= 1 \quad j = 1, 2, \cdots, n \\
W_i = & \textstyle\sum_{k=i}^{n} \left(\sum_{j=1}^{n} (w_j x_{ij}) \right) \quad i = 1, 2, \cdots, n \\
a_{[i]} &= (1 - y_i) a_{[i-1]} + \textstyle\sum_{j=1}^{n} (P_j x_{ij}) \quad i = 1, 2, \cdots, n \\
a_{[0]} &= C \\
x_{ij} & \text{ binary} \quad i = 1, 2, \cdots, n \; j = 1, 2, \cdots, n \\
y_i & \text{ binary} \quad i = 1, 2, \cdots, n
\end{aligned}
$$

Where C is an arbitrary constant that represents the initial age of the machine at the beginning of the scheduling period.

The model has $2n$ constraints and $n(n+1)$ variables. The solution of this model can be obtained using one of the available solvers that run under optimization programs such as GAMS and AMPL.

3.4 EXAMPLE FOR SOLVING THE INTEGRATED PROBLEM

Consider processing 3 jobs of processing times: 8, 48 and 41 units of time. Each job has a different weight: $w_1 = 2$, $w_2 = 10$, $w_3 = 10$. Processing starts when the machine has an age of $a_{[0]} = 88$, preventive maintenance time $t_p = 5$ and corrective maintenance time $t_r = 15$ units. The machine failure rate follows a Weibull distribution with parameters $\beta = 2, \eta = 100$. Upon failure a minimal repair is conducted with repair time $t_r = 15$.

GAMS language was used to input the model (12 variables and 6 constraints) and the BARON solver was used to find the optimal solution. The BARON solver is a computational system designed for solving non-convex NLP optimization problems to global optimality. As a result, the optimal joint solution will give $x_{13} = x_{21} = x_{32} = 1$ (corresponding to sequence $J_3 - J_1 - J_2$) and $y_1 = y_3 = 1$ (PM before first and last jobs) with $\sum_{i=1}^{3} w_{[i]} E[c_{[i]}] = 1740.993$ as shown in Figure 3.2.

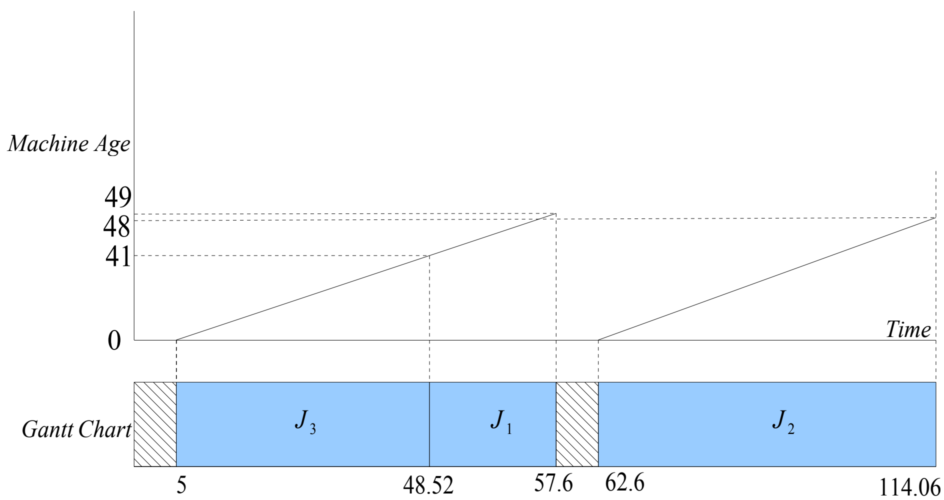

Figure 3.2: Gantt chart and the corresponding machine age for the optimal joint solution

In the following, we will solve the same problem independently by first solving for optimal PM timing and then superimpose the solution on the scheduling problem. First, we will find the optimal PM interval that would maximize the availability. Machine availability is defined as the ratio of machine uptime t to the total time that includes uptime, repair time and PM time.

$$\begin{aligned} Availability &= \frac{uptime}{\text{uptime+maintenance time+repair time}} \\ &= \frac{t}{t+t_p+t_r N(t)} \end{aligned} \tag{3.7}$$

For the Weibull distribution it can be shown that t^* (the optimal time for PM) is

$$t^* = \eta \left[\frac{t_p}{t_r\left(\beta - 1\right)} \right]^{\left(\frac{1}{\beta}\right)}$$

For the problem in the example, $t^* = 57.7$. This indicates that the machine should be maintained at age 57.7.

For the scheduling problem, it is well known that arranging jobs according to the weighted shortest processing time (WSPT) results in the optimal schedule (J_1, J_3, J_2). Since the machine initial age is 88, that is higher than

t^*, then PM is scheduled at time 0 and J_1 starts processing after the initial PM and completes at time 48.5. Similarly, J_3 and J_2 complete at 62.6 and 114.06, respectively. The total expected cost is 1746, which is higher than the integrated solution.

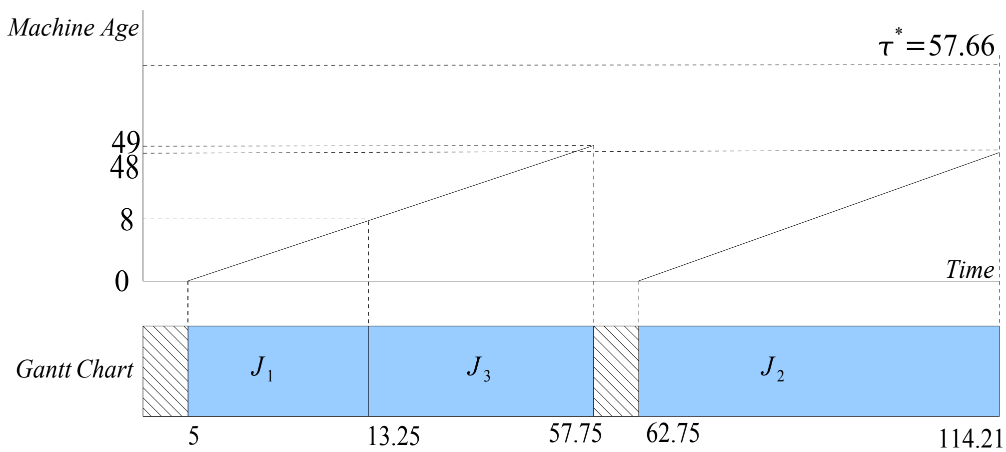

Figure 3.3: Gantt chart and the corresponding machine age for independent solution

Independent planning may provide optimal performance at the level of a specific function. Management usually looks at the production system as a whole, and separate optimal solutions may not provide an optimal solution for the whole system. Usually there is a global optimal that includes all major functions in the production system. This global optimal can only be achieved by integrating models for all different functions. Integrated production models are expected to deal with multiple objectives with a conflicting nature.

Hence, planning these elements independently will cause conflicts between functions. This disturbance can be avoided through integrated modeling.

3.5 CONCLUSIONS

Preventive maintenance is typically used to reduce random machine breakdowns while processing a scheduled job. Optimal scheduling of PM activities maximizes the availability of the machine for production process. However, PM schedules often conflict with the production schedule that is subject to adjustments. This yields a suboptimal schedule. The approach that emerged recently is to integrate these two scheduling problems to get a global optimal solution. In this work, production scheduling and maintenance operations, for a single machine, were integrated at the shop floor level. The objective was to find the job order sequence and maintenance decisions that would minimize the total expected weighted completion times.

A few researchers has developed an integrated model, including Cassady and Kutanoglu (2005). However, those models need to be further modified to give an integrated solution. The main contribution of this chapter is to develop a complete integrated model. An example is used to demonstrate the application of the model and the integrated solution. Research in integrated modeling still has great potential to contribute to, justified by the expected savings provided.

Chapter 4

AN INTEGRATED COST MODEL FOR PRODUCTION SCHEDULING AND PERFECT MAINTENANCE

4.1 INTRODUCTION

The integration between production elements has received attention in recent years. This integration is strongly justified by significant savings in operations costs; however, integrated models are not easy to solve. This difficulty is due the fact that integrated models deal with multiple conflicting objectives. In this work, production scheduling and maintenance operations, for a single machine, are integrated at the shop floor level. It is a common practice to schedule both of them independently, which is done through separate functional teams. The resulting plans of a specific function may disrupt the other function plans. For example, the maintenance function assigns scheduled shut-down intervals. These intervals will be communicated to the production unit. The suggested maintenance intervals may maximize the machine availability, but they will affect production plans. Similarly, production schedulers may have the tendency to utilize machines to their full capacity to meet demand. Under this condition, productivity may increase, but machine availability will decrease due to having more breakdowns.

This chapter integrates, simultaneously, the decisions of preventive maintenance and job order sequencing for a single machine. The motivation for this work is encouraged by the need of many real life applications, such as the automotive industry (Aksoy and Ozturk, 2010). In addition, this integration is expected to provide a reduction in the total expected cost. Each job order i consists of serving Q_i work pieces on a single machine. The manufacturer is expected to deliver n job orders with different processing times P_i. The machine is subjected, upon failure, to minimal repair action where each repair will cost the manufacturer c_m and restores the machine to work with no improvement in its condition. The manufacturer can do a preventive maintenance major action only before the start of serving a job order. This action will cost the manufacturer c_p and will restore the machine to an 'as good as new' condition, reducing the chance of machine breakdown during operation. All job order work pieces are released to the shop floor at time 0, hence; the manufacturer should consider the holding cost during the scheduling horizon. The holding cost (HC), minimal repair cost (MRC) and preventive maintenance cost (PMC) compromise the expected cost. Each job order sequence will change the average expected cycle costs. The objective is to find the job order sequence and maintenance decisions that would minimize the expected cost.

As observed in Cassady and Kutanoglu (2003), integrated models had proved an expected reduction in cost that might reach up to a 30% savings, over treating the two problems independently. However, no analytical solutions were provided for these integrated models. Instead, a full enumeration for small size problems was suggested to solve the integrated problem (Cassady and Kutanoglu, 2003, 2005). Hence, the need for more analytical or near optimal solutions is highly appreciated. The previous models do not capture the direct costs associated with machine downtime (e.g. labor, parts, etc.) of machine failures and machine maintenance. Hence, the need for cost based models of the integrated problem is justified (Gribkovskaia et al., 2010; Khanra et al., 2010; Goswami et al., 2010; Sun-Lee and Yoon, 2010; Karamatsoukis and Kyriakidis, 2010). The use of mathematical modeling for the purpose of production scheduling or preventive maintenance planning is well established in the literature (Diaby, 2010*a*,*b*). Typically, preventive maintenance planning models are stochastic models designed to either maximise equipment availability or minimize equipment maintenance costs.

The focus of this chapter is to formulate a cost model that simultaneously considers maintenance, minimal repair and holding costs for several production jobs, with the objective to minimize the expected total costs. Total expected cycle cost includes expected maintenance cost, expected minimal repair cost and expected holding cost. The organization of the rest of this article is as follows. Section 4.2 defines, in detail, the integrated problem and its assumptions. Sections 4.3 provide formulation of the integrated model as a mathematical program. Section 4.4 presents and solves an example for the integrated problem. Section 4.5 derives independent maintenance model and compares it with the integrated solution found in Section 4.4. Finally, concluding remarks are shown in Section 4.6.

4.2 PROBLEM DEFINITION

Consider n job orders to be processed on a single machine that is subject to a preventive maintenance (PM) requirement. These job orders are available at time zero with no precedence constraints. Each job order consists of processing Q_i work pieces. Moreover, the machine is available continuously along the time horizon unless a machine breakdown occurs during job processing. If so, a minimum repair is conducted that restores the machine to its condition prior to breakdown. Also, the interrupted job should resume the job after machine repair. Each breakdown will delay completion time of successive jobs by the needed time to repair t_r (assumed to be constant). To reduce the chance for machine breakdown, a PM activity can be performed before starting any job. If so, it will restore machine condition to 'as good as new'. This PM activity will delay successive jobs by the time of PM t_p (assumed to be constant). The machine may or may not fail, causing the completion time for each job to be stochastic. The PM decisions affect the stochastic process governing machine failure and hence change the expected value of job completion time $E(c_i)$.

Each maintenance action costs a fixed PM cost c_p. Similarly, each break down will cost a fixed minimal repair cost c_m. It is assumed that all jobs are released to the shop floor ready to process at the start of the schedule. Hence, given that $\bar{Q}_i$ is the average work-in-process inventory, each job order i waiting on the shop floor will incur a holding cost per unit time $h\bar{Q}_i$ untill the time when the machine completes job order i that is, $E(c_i)$ and the total holding cost will be $hE(c_n)\sum_{i=1}^{n}\bar{Q}_i$. The details of these costs will be discussed in Section 4.3. The problem would be to identify a set of PM decisions, as well as a set of job sequencing decisions, in a way that reduces the expected total weighted completion times. Prior to the job starting, a decision has to be made whether to perform PM or not. If so, PM will take a constant time that will delay consequent jobs by such time t_p. If not, the job will start at the completion time of the previous job. However, the single machine can fail during job processing. The number of failures during job processing is strongly affected by the machine age, i.e. when the machine ages it has a higher probability to fail.

Furthermore, failures are randomly distributed over machine operation. Let $N(\tau)$ be the number of machine failures in τ time units of machine operation. Given that τ_{P_i} is the time units of machine operation over P_i, then $E[N(\tau_{P_i})]$ is the expected number of failures during machine operation for job i. For job i, the PM will reduce $E[N(\tau_{P_i})]$, but it will delay the start of job i by t_p. This situation can be represented by a binary variable y_i. Let

$$y_i = \begin{cases} 1 & \text{if PM is performed before job } i \\ 0 & Otherwise \end{cases} \qquad i = 1, 2, \cdots, n \tag{4.1}$$

Without loss of generality, Figure 4.1 represents a Gantt chart for job sequence j_1, j_2 $\cdots$,j_{n-1},j_n with hatched area representing PM decisions $y_i t_p$.

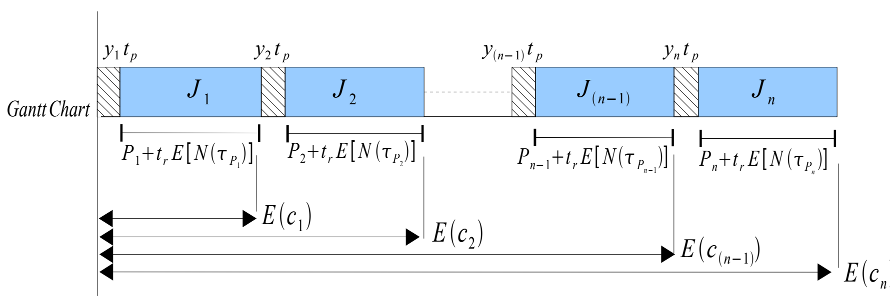

Figure 4.1: Gantt chart for the integrated problem

The following assumptions are considered in the problem

1. Jobs can not be preempted for PM.
2. Jobs interrupted by failure can be resumed after repair without additional time penalty.
3. The machine has increasing hazard rate.

4. Upon failure, minimum repair is conducted and machine will resume with the same age.

5. PM restores the machine to a 'as good as new' condition.

6. Repair times are deterministic and known in advance.

7. The number of machine breakdowns is unknown (random variable).

8. The number of breakdowns does not depend on job type.

9. Machine breakdowns are independent.

10. Raw material for all job orders are released at the start of the schedule.

4.3 FORMULATION

Consider a single machine in a manufacturing system that is required to process a set of n jobs, and suppose that preempting one job for another is not permitted. The purpose of production scheduling is to choose an optimal sequence for the jobs. Let

$$x_{ij} = \begin{cases} 1 & \text{if the } i^{th} \text{ job performed is job } j \\ 0 & Otherwise \end{cases} \tag{4.2}$$

$P_{[i]}$ *processing time of* i^{th} *job in the sequence*

then

$$P_{[i]} = \sum_{j=1}^{n} (P_j x_{ij}) \quad \forall \quad i = 1, \cdots, n \tag{4.3}$$

Two logical sets of constraints emerge, the first set of constraints states that job i can not seize two positions at the same time, i.e.

$$\sum_{j=1}^{n} x_{ij} = 1 \quad \forall \quad i = 1, \cdots, n \tag{4.4}$$

The second set of constraints states that one position can not hold more than one job, i.e.

$$\sum_{i=1}^{n} x_{ij} = 1 \quad \forall \quad j = 1, \cdots, n \tag{4.5}$$

Example

Suppose a single machine has two jobs needed to be scheduled with parameters $P_1 = 2$ and $P_2 = 4$ then the single machine can have two possible sequences: either J_1 following J_2 or J_2 following J_1.

- Sequence 1-2, where J_1 follows J_2 is expressed with following variables: $x_{11} = 1,\ x_{12} = 0,\ x_{21} = 0,\ x_{22} = 1\ P_{[1]} = 2\ P_{[2]} = 4$ (see Figure 4.2)

- Sequence 2-1, where J_2 follows J_1 is expressed with following variables:

$x_{11} = 0,\ x_{12} = 1,\ x_{21} = 1,\ x_{22} = 0\ P_{[1]} = 4\ P_{[2]} = 2$ (see Figure 4.3)

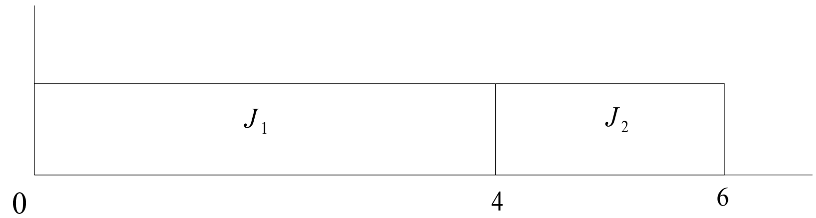

Figure 4.2: Gantt chart for the sequence $\{J_1, J_2\}$

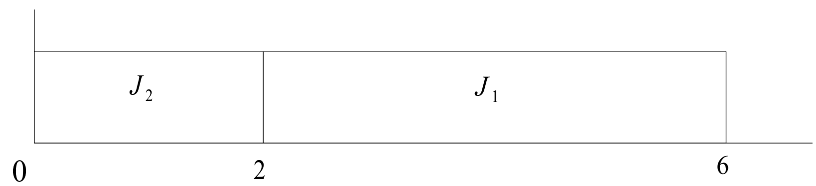

Figure 4.3: Gantt chart for the sequence $\{J_2, J_1\}$

In addition to choosing a job sequence, it is also necessary to decide whether or not to perform PM prior to each job. The integrated problem is further complicated by the fact that completion times for the jobs are stochastic, because the machine may or may not fail during each job, and PM decisions change the stochastic process governing machine failure. The completion time of a job is a random variable that depends on the following:

- the age of the machine prior to processing the job
- the completion time for previous jobs
- the time to complete PM, and the PM decision

- the job's processing, the minimal repair time
- the number of machine failures during the job

PM is assumed to restore the machine to an 'as good as new' condition i.e. machine age after PM will reduce to 0. Let

$a_{[i]}$ be the machine age at the completion of i^{th} job

then

$$a_{[i]} = (1 - y_i)a_{[i-1]} + P_{[i]} \quad i = 1, 2, \cdots, n$$

Suppose the machine used to process the jobs is subject to failure, and the time to failure for the machine is governed by a Weibull probability distribution, having shaping parameter β greater than 1. When the machine fails, it is assumed that the machine is minimally repaired, i.e. the machine is restored to an operating condition, but machine age is not altered. This implies that, upon machine failure, the machine operator does just enough maintenance to resume machine function. The assumption that PM restores the machine to 'as good as new' implies that PM is a more comprehensive action that may include the replacement of many key parts in the machine. Also, the operation and maintenance of the machine (between two successive PM's) can be modeled as a renewal process. Due to the minimal repair, the occurrence of failures during each cycle of the renewal process can be modeled using a non homogeneous Poisson process. Given that the job i starts at age $(1-y_i)a_{[i-1]}$ and ends at age $a_{[i]}$ then

$$
\begin{aligned}
E[N(\tau_{P_{[i]}})] = & \int_{(1-y_i)a_{[i-1]}}^{a_{[i]}} z(t)\, dt \\
= & \int_{(1-y_i)a_{[i-1]}}^{a_{[i]}} \frac{\beta}{\eta^{\beta}} t^{\beta-1}\, dt \\
= & \; m(a_{[i]}) - m((1-y_i)a_{[i-1]}) \\
= & \left(\frac{a_{[i]}}{\eta}\right)^{\beta} - \left(\frac{(1-y_i)a_{[i-1]}}{\eta}\right)^{\beta}
\end{aligned}
\tag{4.6}
$$

where $z(t)$ corresponds to the hazard function to the underlying Weibull probability distribution and $m(\tau) = \int_0^{\tau} z(t)\, dt = \int_0^{\tau} \frac{\beta}{\eta^{\beta}} t^{\beta-1}\, dt = \left(\frac{\tau}{\eta}\right)^{\beta}$. Figures 4.4 and 4.5 present the effect of maintenance decision y_i on the $E[N(\tau_{P_{[i]}})]$, where it will be reduced from $\int_{(1-y_i)a_{[i-1]}}^{a_{[i]}} z(t)dt = m(a_{[i]}) - m((1-y_i)a_{[i-1]})$ (if $y_i = 0$) down to $\int_0^{a_{[i]}} z(t)dt = m(P_{[i]})$ (if $y_i = 1$). However, the PM decision, $y_i = 1$, will delay completion time of *job i* by t_p time units.

The objective is to provide jobs sequence, as well as PM schedules to minimize the expected cost $E(Cost)$.

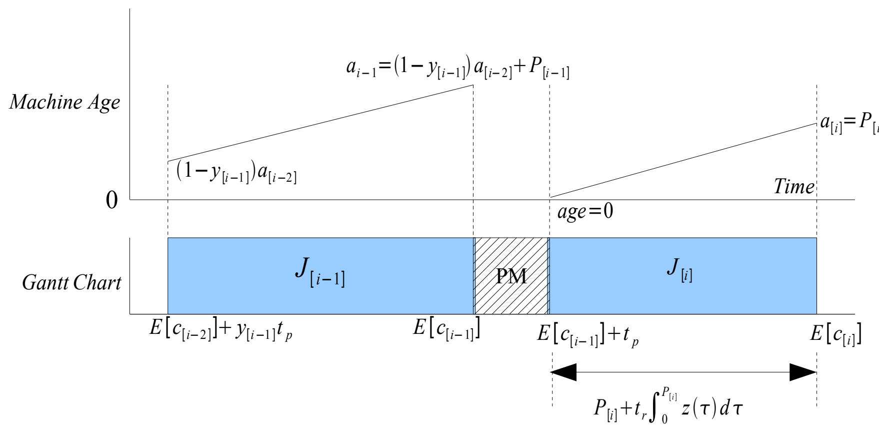

Figure 4.4: Gantt chart and the corresponding machine age with preventive maintenance

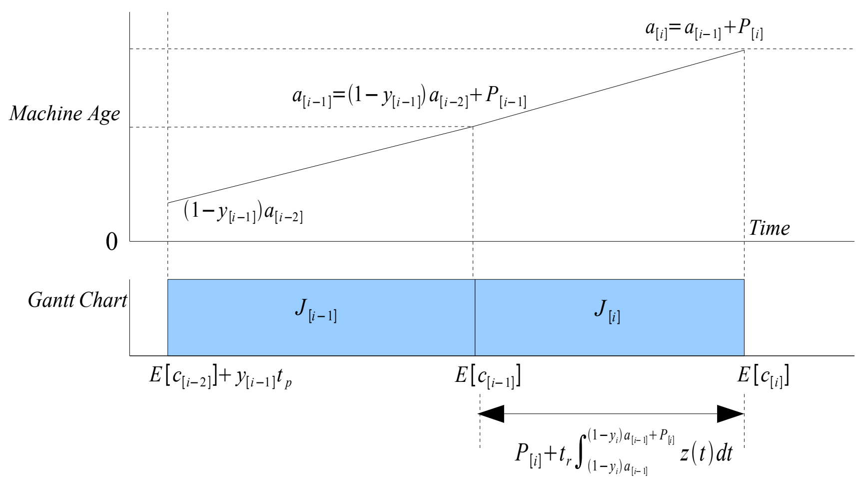

Figure 4.5: Gantt chart and the corresponding machine age without preventive maintenance

The expected cycle cost includes expected holding cost (HC), expected minimal repair cost (MRC), and PM cost (PMC). Each job order will represent processing one batch of size Q_i. Raw materials for all job orders are assumed to be released to the shop floor at time 0. Figure 4.6 shows the inventory level for job order i. The average inventory for a job order i is a sequence dependent. Hence

$$Q_{[i]} = \sum_{j=1}^{n} (Q_j x_{ij}) \quad \forall \quad i = 1, \cdots, n \tag{4.7}$$

The average holding quantity is equal to the sum of areas I and II (in Figure 4.6) over the $E(C_{[i]})$. i.e. $\bar{Q}_{[i]} = \frac{I+II}{E(c_{[i]})}$

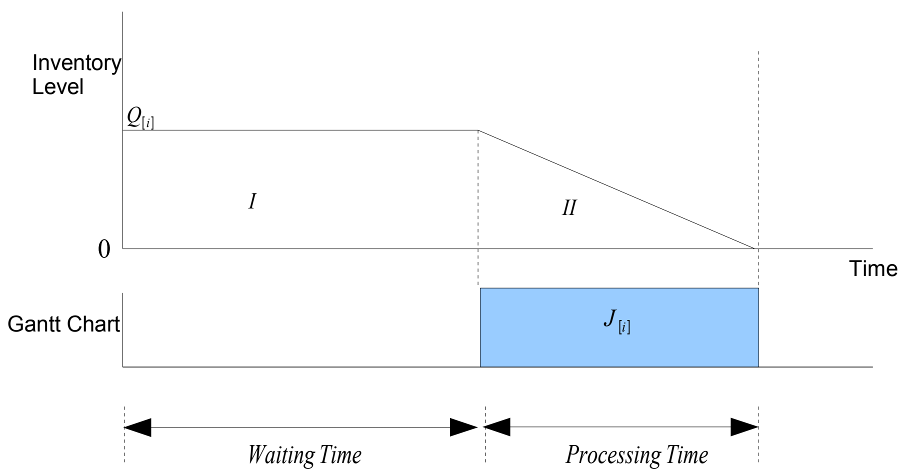

Figure 4.6: Gantt chart and the corresponding inventory level

$$\begin{aligned}
\bar{Q}_{[i]} &= \frac{Q_{[i]}\left(E(c_{[i]})-\frac{[P_{[i]}+t_r[m(a_{[i]})-m((1-y_k)a_{[i-1]})]]}{2}\right)}{E(c_{[i]})} \\
&= Q_{[i]}\left(1-\frac{[P_{[i]}+t_r[m(a_{[i]})-m((1-y_i)a_{[i-1]})]]}{2E(c_{[i]})}\right) \qquad (4.8)
\end{aligned}$$

Figure 4.7 shows the expected completion times for job $1, 2, \cdots, n$.

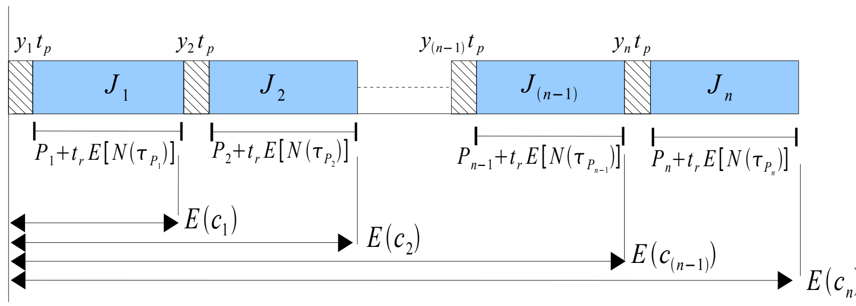

Figure 4.7: Gantt chart showing the expected completion times for job order i

The expected completion times for $(Job\ i = 1, 2, \cdots, n)$ can be found by substituting in a recursive manner as follows

$$\begin{aligned}
E[c_{[1]}] &= t_p y_1 + P_{[1]} + t_r\left[m(a_{[1]}) - m((1-y_1)a_{[0]})\right] \\
E[c_{[2]}] &= E[c_2] + t_p y_2 + P_{[2]} + t_r\left[m(a_{[2]}) - m((1-y_2)a_{[1]})\right] \\
&\vdots \\
E[c_{[n]}] &= E[c_{[n-1]}] + t_p y_n + P_{[n]} + t_r\left[m(a_{[n]}) - m((1-y_n)a_{[n-1]})\right] \qquad (4.9)
\end{aligned}$$

A general formula for $E[c_{[i]}]$ can be found as follows

$$\begin{aligned} E[c_{[i]}] &= \sum_{k=1}^{i} \left\{ t_p y_k + P_{[k]} + t_r E[N(\tau_{P_{[k]}})] \right\} \qquad i = 1, 2, \cdots, n \\ &= \sum_{k=1}^{i} \left\{ t_p y_k + P_k + t_r \left[m(a_{[k]}) - m((1 - y_k)a_{[k-1]}) \right] \right\} \\ & \qquad i = 1, 2, \cdots, n \end{aligned} \tag{4.10}$$

Hence,

$$\begin{aligned} \bar{Q}_{[i]} &= \frac{Q_{[i]} \left(E(c_{[i]}) - \frac{[P_{[i]} + t_r [m(a_{[i]}) - m((1-y_i)a_{[i-1]})]]}{2} \right)}{E(c_{[i]})} \\ &= Q_{[i]} \left\{ 1 - \frac{[P_{[i]} + t_r [m(a_{[i]}) - m((1-y_i)a_{[i-1]})]]}{2 \sum_{k=1}^{i} (t_p y_k + P_{[k]} + t_r (m(a_{[k]}) - m((1-y_k)a_{[k-1]}))} \right\} \end{aligned} \tag{4.11}$$

The holding cost is usually estimated by holding cost unit h, which is expressed in monetary unit per workpiece unit per time unit. Let $E(c_{[n]})$ be the expected time to complete all n jobs. Then the expected holding cost will be

$$HC = h \times E(c_{[n]}) \times \sum_{i=1}^{n} \bar{Q}_{[i]} \tag{4.12}$$

Given that c_m is the expected minimal repair cost per failure, then expected minimal repair will be

$$MRC = c_m \sum_{i=1}^{n} [m(a_{[i]}) - m((1 - y_i)a_{[i-1]})] \tag{4.13}$$

Given that c_p is the cost for each PM then expected PM cost

$$PMC = c_p \sum_{i=1}^{n} y_i \tag{4.14}$$

The expected total cost will be

$$\begin{aligned} E(Cost) = & \quad HC + MRC + PMC \\ = & \quad hE(c_{[n]}) \sum_{i=1}^{n} \bar{Q}_{[i]} + c_m \sum_{i=1}^{n} [m(a_{[i]}) - m((1-y_i)a_{[i-1]})] \\ & \quad + c_p \sum_{i=1}^{n} y_i \end{aligned} \tag{4.15}$$

Finally, figure 4.8 shows the resulting mathematical program for the integrated problem

$$Min\left\{hE(c_{[n]})\sum_{i=1}^{n}\bar{Q}_{[i]}+c_m\sum_{i=1}^{n}[m(a_{[i]})-m((1-y_i)a_{[i-1]})]+c_p\sum_{i=1}^{n}y_i\right\}$$

Subject to

$$P_{[i]}=\sum_{j=1}^{n}(P_j x_{ij})\quad i=1,2,\cdots,n$$

$$Q_{[i]}=\sum_{j=1}^{n}(Q_j x_{ij})\quad i=1,\cdots,n$$

$$a_{[0]}=\text{Initial machine age}$$

$$a_{[i]}=(1-y_i)a_{[i-1]}+P_{[i]}\quad i=1,2,\cdots,n$$

$$E(c_{[n]})=\sum_{k=1}^{n}\left\{t_p y_k+P_{[k]}+t_r\left[m(a_{[k]})-m((1-y_k)a_{[k-1]})\right]\right\}$$

$$\bar{Q}_{[i]}=Q_{[i]}\left\{1-\frac{[P_{[i]}+t_r[m(a_{[i]})-m((1-y_i)a_{[i-1]})]]}{2\sum_{k=1}^{i}(t_p y_k+P_{[k]}+t_r(m(a_{[k]})-m((1-y_k)a_{[k-1]}))}\right\}\quad i=1,2,\cdots,n$$

$$\sum_{j=1}^{n}x_{ij}=1\quad i=1,2,\cdots,n$$

$$\sum_{i=1}^{n}x_{ij}=1\quad i=1,2,\cdots,n$$

$$x_{ij}\,\text{binary}\quad i=1,2,\cdots,n\ j=1,2,\cdots,n$$

$$y_i\,\text{binary}\quad i=1,2,\cdots,n$$

Figure 4.8: Integrated cost model

4.4 SOLVING THE INTEGRATED PROBLEM

The formulation shown in Section 4.3 can be solved through one of the mathematical programming languages. In the following example GAMS language was used to input the model and the BARON solver was used to reach the optimal solution. The BARON solver is a computational system designed for solving non-convex NLP optimization problems to global optimality. When $\beta > 1$, it may be practical to perform preventive maintenance on the machine in order to reduce the increasing risk of machine failure.

Table 4.1 considers processing three job orders consisting of $Q_1 = Q_2 = Q_3 = 500$ work piece. Job order 1 needs six minutes for each work piece. Job order 2 needs three minutes for each work piece. Job order 3 needs two minutes for each work piece. The machine age is $a_{[0]} = 88$ hours. The preventive maintenance time is $t_p = 5$ hours. The machine failure rate follows a Weibull distribution with the following parameters $\beta = 2, \eta = 100$. Upon failure, a minimal repair is conducted with a repair time $t_r = 15$ hours. For the Weibull distribution $m(t) = \int_0^{t_1} \frac{\beta}{\eta^\beta} t^{(\beta-1)}\, dt = \left(\frac{t_1}{\eta}\right)^\beta$. $h = 1.50$ monetary unit/work piece/hour, $c_m = 500$ and $c_p = 500$.

Table 4.1: Example parameters for the integrated cost model

Job order	Job order size (work piece)	Processing time per work piece (minute)	Processing time per job order (hour)
1	500	6	50
2	500	3	25
3	500	2	16.66

$$Min\left\{hE(c_{[3]})\sum_{i=1}^{3}\bar{Q}_{[i]}+c_m\sum_{i=1}^{3}\left[m(a_{[i]})-m((1-y_i)a_{[i-1]})\right]+c_p\sum_{i=1}^{3}y_i\right\}$$

Subject to

$$\begin{aligned}
P_{[1]} &= 53x_{11} + 26x_{12} + 18.67x_{13} \\
P_{[2]} &= 53x_{21} + 26x_{22} + 18.67x_{23} \\
P_{[3]} &= 53x_{31} + 26x_{32} + 18.67x_{33} \\
Q_{[1]} &= 500x_{11} + 500x_{12} + 500x_{13} \\
Q_{[2]} &= 500x_{21} + 500x_{22} + 500x_{23} \\
Q_{[3]} &= 500x_{31} + 500x_{32} + 500x_{33} \\
a_{[0]} &= 88 \\
a_{[1]} &= P_{[1]} + (1 - y_1)88 \\
a_{[2]} &= P_{[2]} + (1 - y_2)\left[P_{[1]} + (1 - y_1)88\right] \\
a_{[3]} &= P_{[3]} + (1 - y_3)\left[P_{[2]} + (1 - y_2)P_{[1]} + (1 - y_1)88\right] \\
E(c_{[3]}) &= \textstyle\sum_{k=1}^{3} \left\{t_p y_k + P_{[k]} + t_r \left[m(a_{[k]}) - m((1 - y_i)a_{[k-1]})\right]\right\}
\end{aligned}$$

$$\begin{aligned}
\bar{Q}_{[1]} = &\quad Q_{[1]}\left\{1-\frac{[P_{[1]}+t_r[m(P_{[1]}+(1-y_1)88)-m((1-y_1)88)]]}{2(t_p y_1+P_{[1]}+t_r(m(P_{[1]}+(1-y_1)88)-m((1-y_1)88)))}\right\}\\
\bar{Q}_{[2]} = &\quad Q_{[2]}\left\{1-\frac{[P_{[2]}+t_r[m(a_{[2]})-m((1-y_2)a_{[1]})]]}{2\sum_{k=1}^{2}(t_p y_k+P_{[k]}+t_r(m(a_{[k]})-m((1-y_k)a_{[k-1]}))}\right\}\\
\bar{Q}_{[3]} = &\quad Q_{[3]}\left\{1-\frac{[P_{[3]}+t_r[m(a_{[3]})-m((1-y_3)a_{[2]})]]}{2\sum_{k=1}^{3}(t_p y_k+P_{[k]}+t_r(m(a_{[k]})-m((1-y_k)a_{[k-1]}))}\right\}
\end{aligned}$$

$$x_{11}+x_{12}+x_{13}=1$$

$$x_{21}+x_{22}+x_{23}=1$$

$$x_{31}+x_{32}+x_{33}=1$$

$$x_{11}+x_{21}+x_{31}=1$$

$$x_{12}+x_{22}+x_{32}=1$$

$$x_{13}+x_{23}+x_{33}=1$$

binary variables $\quad x_{11}, x_{12}, x_{13}, x_{21}, x_{22}, x_{23}, x_{31}, x_{32}, x_{33}, y_1, y_2, y_3$

Solution: $x_{13}=x_{22}=x_{31}=1$ and $x_{11}=x_{12}=x_{21}=x_{23}=x_{32}=x_{33}=0$ and $y_1=y_3=1$ and $y_2=0$ with a total expected cost that is equal to $\$178,030$. Hence, the optimal job and PM sequences result in Job order sequence $J_3-J_2-J_1$ and PM decisions $y_1=0, y_2=1, y_3=0$ will give the minimal cost. This means that to achieve the minimum expected cost, production should start with Job 3, PM, Job 2 then Job 1.

The effect of six parameters (β, t_p, t_r, c_m, c_p, h) over the expected cost is shown in the two tables 4.2 and 4.3. A $2^6=64$ factorial design was used to generate 64 trials (32 trials for $\beta=2$ and another 32 trials for $\beta=3$). Table 4.2 shows that the cost will increase with c_p, c_m and h increase. The need for more PM can be seen with $t_r = 30\ hours$ compared to $t_r = 15\ hours$. The machine will have more failures with the increase of β, hence, PM is more economically justified with higher machine failures. This can be shown by comparing the costs with $\beta = 3$ and $\beta = 2$ where costs are less in Table 4.3.

The use of mathematical modeling for the purpose of production scheduling or preventive maintenance planning is well established in the literature. Typically, preventive maintenance planning models are stochastic models designed to either maximize equipment availability or minimize equipment maintenance costs. The next section will show how the integrated solution compares to the independent solution. The PM problem will be treated independently of the production sequence. The optimal PM interval is derived such that the machine availability will be maximized. The PM interval will be then superimposed on the production schedule that was found in example 1. The resulting cost will be compared to the integrated scheduling cost.

Table 4.2: Parameters effect on expected cost ($\beta = 2$)

Trial	*Parameters* β	t_p	t_r	c_m	c_p	h	*Optimal Sequence* *PM*	*Production Jobs*	*Cost*
1	2	5	15	1500	500	1.5	010	321	178,030
2	2	5	15	1500	500	3	010	321	354,080
3	2	5	15	1500	1000	1.5	010	321	178,530
4	2	5	15	1500	1000	3	010	321	354,580
5	2	5	15	3000	500	1.5	010	321	179,510
6	2	5	15	3000	500	3	010	321	355,560
7	2	5	15	3000	1000	1.5	010	321	180,010
8	2	5	15	3000	1000	3	010	321	356,060
9	2	5	30	1500	500	1.5	101	321	191,380
10	2	5	30	1500	500	3	101	321	381,040
11	2	5	30	1500	1000	1.5	101	321	192,380
12	2	5	30	1500	1000	3	101	321	382,040
13	2	5	30	3000	500	1.5	101	321	192,100
14	2	5	30	3000	500	3	101	321	381,760
15	2	5	30	3000	1000	1.5	101	321	193,100
16	2	5	30	3000	1000	3	101	321	382,760
17	2	10	15	1500	500	1.5	010	321	188,310
18	2	10	15	1500	500	3	010	321	374,640
19	2	10	15	1500	1000	1.5	010	321	188,810
20	2	10	15	1500	1000	3	010	321	375,140
21	2	10	15	3000	500	1.5	010	321	189,790
22	2	10	15	3000	500	3	010	321	376,120
23	2	10	15	3000	1000	1.5	010	321	190,290
24	2	10	15	3000	1000	3	010	321	376,620
25	2	10	30	1500	500	1.5	010	321	211,900
26	2	10	30	1500	500	3	010	321	421,810
27	2	10	30	1500	1000	1.5	010	321	212,400
28	2	10	30	1500	1000	3	010	321	422,310
29	2	10	30	3000	500	1.5	010	321	213,380
30	2	10	30	3000	500	3	010	321	423,290
31	2	10	30	3000	1000	1.5	010	321	213,880
32	2	10	30	3000	1000	3	010	321	423,790

Table 4.3: Parameters effect on expected cost($\beta = 3$)

	Parameters						*Optimal Sequence*		
Trial	β	t_p	t_r	c_m	c_p	h	*PM*	*Production Jobs*	*Cost*
33	3	5	15	1500	500	1.5	101	321	175,700
34	3	5	15	1500	500	3	101	321	350,040
35	3	5	15	1500	1000	1.5	101	321	176,700
36	3	5	15	1500	1000	3	101	321	351,040
37	3	5	15	3000	500	1.5	101	321	176,060
38	3	5	15	3000	500	3	101	321	350,400
39	3	5	15	3000	1000	1.5	101	321	177,060
40	3	5	15	3000	1000	3	101	321	351,400
41	3	5	30	1500	500	1.5	101	321	180,650
42	3	5	30	1500	500	3	101	321	359,950
43	3	5	30	1500	1000	1.5	101	321	181,650
44	3	5	30	1500	1000	3	101	321	360,950
45	3	5	30	3000	500	1.5	101	321	181,010
46	3	5	30	3000	500	3	101	321	360,300
47	3	5	30	3000	1000	1.5	101	321	182,010
48	3	5	30	3000	1000	3	101	321	361,300
49	3	10	15	1500	500	1.5	010	321	190,910
50	3	10	15	1500	500	3	010	321	379,790
51	3	10	15	1500	1000	1.5	010	321	191,410
52	3	10	15	1500	1000	3	010	321	380,290
53	3	10	15	3000	500	1.5	010	321	192,450
54	3	10	15	3000	500	3	010	321	381,330
55	3	10	15	3000	1000	1.5	010	321	192,950
56	3	10	15	3000	1000	3	010	321	381,830
57	3	10	30	1500	500	1.5	101	321	206,780
58	3	10	30	1500	500	3	101	321	412,200
59	3	10	30	1500	1000	1.5	101	321	207,780
60	3	10	30	1500	1000	3	101	321	413,200
61	3	10	30	3000	500	1.5	101	321	207,130
62	3	10	30	3000	500	3	101	321	412,560
63	3	10	30	3000	1000	1.5	101	321	208,130
64	3	10	30	3000	1000	3	101	321	413,560

4.5 SOLUTION ANALYSIS

In Section 4.3, it was shown how maintenance decision y_i can affect the $E[cost]$. This section will investigate the benefits of integrating the job scheduling and PM decisions by solving independently for the optimal PM, such that the availability of the machine is maximized. This is will show how do it compares to the optimal integrated job sequence.

Machine availability $A(\tau)$ is defined as the ratio of machine uptime $[0, \tau]$ to the total time that includes uptime, repair time and PM time.

$$\begin{aligned} A(\tau) = & \frac{uptime}{\text{uptime+maintenance time+repair time}} \\ = & \frac{\tau}{\tau + t_p + t_r N(\tau)} \\ = & \frac{\tau}{\tau + t_p + t_r \left[(\frac{\tau}{\eta})^{\beta} - 0 \right]} \end{aligned} \tag{4.16}$$

Hence, to find τ^*, $A(\tau)$ is differentiated with respect to τ and equal it to zero.

$$\begin{aligned} \frac{dA(\tau)}{d\tau} = & \frac{\left(\tau + t_p + t_r (\frac{\tau}{\eta})^{\beta}\right) - \tau \left(1 + \frac{\beta t_r}{\eta^{\beta}} \tau^{(\beta-1)}\right)}{\left(\tau + t_p + t_r (\frac{\tau}{\eta})^{\beta}\right)^2} \\ = & 0 \end{aligned}$$

$$\tau + t_p + t_r \left(\frac{\tau}{\eta}\right)^{\beta} - \left(\tau + \beta t_r \left(\frac{\tau}{\eta}\right)^{\beta}\right) = 0$$
$$\tau = \eta \left[\frac{t_p}{t_r(\beta-1)}\right]^{\left(\frac{1}{\beta}\right)}$$

For Example 1, $\tau^* = 100\left[\frac{5}{15}\right]^{\left(\frac{1}{2}\right)} = 57.7$ hours. This indicates that the machine should be maintained at the age of 57.7 hours. Since the initial machine age of 88 is higher than τ^*, then PM is scheduled at time 0 then it will start processing job 3 at age 0. The machine will finish job 3 at age 16.66 and job 2 at age 41.66. Now, if the machine reaches the age of 57.7 hours during job 1. There are two options:

- Schedule PM after job 1. The machine will finish job 1 at age 91.66 hours (see Figure 4.9).
- Schedule another PM before job 1. The machine will finish job 1 at age 53.75 hours (see Figure 4.10).

For the given sequence $(J_3 - J_2 - J_1)$ there are $2^3 = 8$ PM decisions that are shown in the following table.

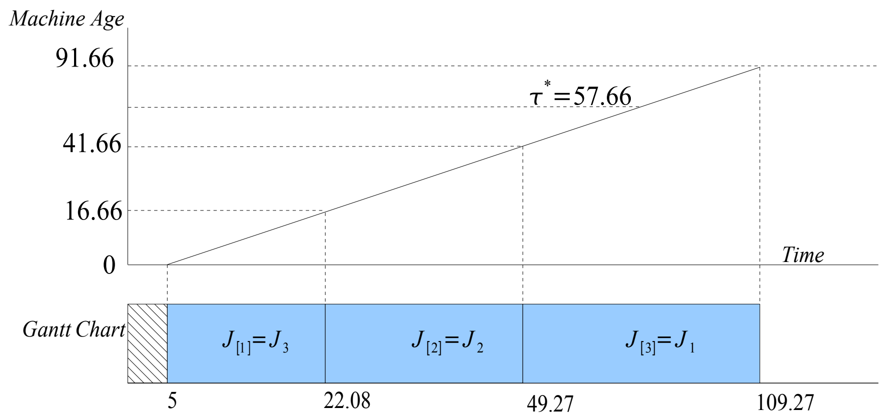

Figure 4.9: Gantt chart and the corresponding machine age for scheduling preventive maintenance before J_3 only

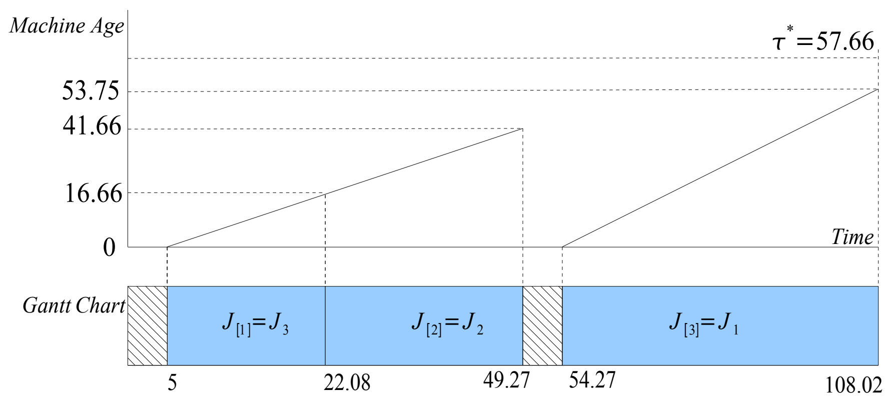

Figure 4.10: Gantt chart and the corresponding machine age for scheduling preventive maintenance before J_1 and before J_3

Table 4.4: PM effect job order sequence $J_3 - J_2 - J_1$

	y_1	y_2	y_3	$Cost$
1	0	0	1	181,930
2	0	1	0	178,030
3	0	1	1	181,130
4	1	0	0	182,480
5	1	0	1	181,250
6	1	1	0	187,300
7	1	1	1	190,470
8	0	0	0	202,220

In table 4.4, the cost for the schedule in Figure 4.9 is $182,480$ which is $\left(\frac{|182{,}480-178{,}030|}{178{,}030} = 2.50\%\right)$ higher than the optimal integrated solution found. The cost for the schedule in Figure 4.10 is $181,250$, which is $\left(\frac{|181{,}250-178{,}030|}{178{,}030} = 1.8\%\right)$ higher than the optimal integrated solution found.

Independent planning may provide optimal performance at the level of a specific function. Usually there is a global optimal that includes all major functions in the production system. This global optimal can only be achieved by integrating models for all different functions. Integrated production models are expected to deal with multiple objectives with a conflicting nature. Hence, planning these elements independently will cause conflicts between functions. This disturbance can be avoided through integrated modeling.

4.6 CONCLUSIONS

In this Chapter, production scheduling and maintenance operations for a single machine were integrated at the shop floor level. The objective was to find the job order sequence and maintenance decisions that would minimize the expected cost. The contribution of this work was to study the effect of production and maintenance scheduling on WIP inventory. The problem was formulated as a mixed integer program. The integrated solution simultaneously provided the production and maintenance schedule.

Integrated modeling is expected to provide better savings over independent models; hence, integrated modeling has recently gained momentum. However, integrated models are sophisticated and are not easy to solve. Research in integrated modeling still has great potential to contribute, justified by the expected savings provided by integrated modeling.

Chapter 5

INTEGRATING PRODUCTION, MAINTENANCE AND QUALITY: A PRELIMINARY INVESTIGATION

In this chapter, we provide an overview for some of the recent work that combines costs of maintenance, scheduling and quality. Section 5.1 briefly discusses the work of Pandey et al. (2010*c*, 2011*b*) that integrates maintenance and quality. Then, Section 5.2 discusses the work of Pandey et al. (2010*a*,*b*, 2011*a*) which investigates the effect of integrating maintenance and quality over scheduling.

5.1 MAINTENANCE AND QUALITY INTEGRATION

Pandey et al. (2010*c*) included rejection cost for nonconforming items into corrective maintenance cost. In their model, a machine has a single component that is subject to two random failure modes, namely FC_1 and

FC_2. Machine ceases production immediately after FC_1 while it keeps producing nonconforming items when FC_2 occurs. For example, in case of a computer numerical controlled (CNC) grinding machine, if work head belt is broken, then it will stop the machine completely, while if loosening of ball screw chuck nut occurs, then it will continue producing undesired oval-shaped components. After the occurrence of FC_2, a shift in the process mean will continue increasing until it is detected and maintenance conducted for restoring the process back to normal. Amount of defective products are estimated based on the deviation (δ) from a standard mean μ_0 for a certain quality characteristic. The quality of the machine is defined by its ability to produce products with minimum deviation from the standard mean which is a function of its age. A control chart mechanism is used to detect the process shift due to machine aging. For the quality characteristic, the upper specification limit, lower specification limit and target value are known. $\bar{X}$-chart is used to detect the production process which operates with a known and constant standard deviation σ. After a PM, production starts in a in-control state and with time the process mean $\bar{x}$ starts to deviate away from μ_0. The deviation (process shift) is expressed by the amount $\delta\sigma$ and it affects the proportion of nonconforming items.

Preventive maintenance is introduced to the machine to minimize the cost per unit time (CPUT). The planner should define time between PM's (TBM) which minimize (CPUT). Total cost includes preventive maintenance costs in addition to corrective maintenance cost.

$$CPUT = \frac{N_{CM} \times C_{CM} + N_{PM} \times C_{PM}}{T}$$

Where T is the evaluation period, (C_{PM}) is the cost of PM and (C_{CM}) is the cost of corrective maintenance. N_{PM} is the number of PM's and N_{CM} is the number of corrective maintenance.

Pandey et al. (2010c) studied two models M_1 and M_2:

1. Model M1: Expected total cost model based on independent models for calculating maintenance and rejection costs.

2. Model M2: Expected total cost model based on integrating rejection cost in the optimal maintenance model.

They assumed the maintenance to be imperfect. In this section we relaxed this assumption and reproduced the results with the assumption that PM restores the machine to "as good as new" condition. The machine age will be zero after PM and increase till the age of TBM, which occurs before the next PM.

In M1, CPUT is calculated based on cost of repair/replacement and downtime cost, as follows:

$$E[C_{CM}]_{M_1} = MTTR_{CM}.[PR.C_{lp} + LC] + C_{Rep} \tag{5.1}$$

$$E[C_{PM}]_{M_1} = MTTR_{PM}.[PR.C_{lp} + LC] + C_{Res} \tag{5.2}$$

Where $MTTR_{CM}$ and $MTTR_{PM}$ are the mean time to repair for corrective and for preventive maintenance. PR is production rate, C_{lp} is cost of lost production, LC is labor cost, C_{Rep} is repair cost, and C_{Res} is restoration cost.

Let TBM^* be the time between maintenance that maximize machine availability.

$$TBM^* = \eta \left[\frac{MTTR_{PM}}{MTTR_{CM}\,(\beta - 1)} \right]^{\left(\frac{1}{\beta}\right)} \tag{5.3}$$

$$\begin{aligned} E[N_{PM}] &= \quad \tfrac{T}{TBM^*} \\ E[N_{CM}] &= \quad T\tfrac{TBM^{(\beta-1)}}{\eta^{\beta}} \end{aligned} \tag{5.4}$$

The expected annual total cost of maintenance action during planning period will be

$$\begin{aligned} E[C_f]_{M1} = &\quad E[N_{CM}] \times E[C_{CM}]_{M1} + E[N_{PM}] \times E[C_{PM}]_{M1} \\ = &\quad E[N_{CM}] \times [MTTR_{CM}.[PR.C_{lp} + LC] + C_{Rep}] + \\ &\quad E[N_{PM}] \times [MTTR_{PM}.[PR.C_{lp} + LC] + C_{Res}] \end{aligned} \tag{5.5}$$

Thus the expected total cost of model M_1

$$[ETC_{M+Q}]_{M_1} = CPUT_{TBM^*} \times T + C_{Rejection}.E[N_{defect}].E[N_{CM}].P_{FM_2} \quad (5.6)$$

Where P_{FM_2} is the probability to experience failure mode that causes quality drift and $C_{Rejection}$ is the cost of rejection.

In M_1, rejection cost was added independently to $CPUT_{TBM}$. In M_2, $CPUT$ will be calculated through integrating directly the rejection cost to corrective maintenance cost $E[C_{CM}]_{M_2}$ as follows:

$$\begin{aligned} E[C_{CM}]_{FM1} &= MTTR_{CM}\,(PR.C_{lp} + LC) + C_{Rep} \\ E[C_{CM}]_{FM2} &= E[C_{Rej}] + MTTR_{CM}\,(PR.C_{lp} + LC) + C_{Rep} \\ E[C_{CM}]_{M_2} &= E[C_{CM}]_{FM1} \times P_{FM_1} + E[C_{CM}]_{FM2} \times P_{FM_2} \end{aligned} \quad (5.7)$$

Hence,

$$\begin{aligned} CPUT_{M_2} &= \frac{E[N_{CM}] \times E[C_{CM}] + E[N_{PM}] \times E[C_{PM}]}{T} \\ &= \frac{E[N_{CM}] \times E[C_{CM}] + E[N_{PM}] \times [MTTR_{PM}.[PR.C_{lp} + LC] + C_{Res}]}{T} \end{aligned} \quad (5.8)$$

$$[ETC_{M+Q}]_{M_2} = CPUT_{M_2}.T \quad (5.9)$$

Let $P_{FM_2} = 0.4$, $\beta = 2$, $\eta = 1000$, $MTTR_{CM} = 12h$ and $MTTR_{PM} = 7h$. The machine is supposed to operate three 7-hour-shifts a day and 6 days a week.

$$TBM = \eta \left(\frac{MTTR_{PM}}{MTTR_{CM}(1 - \beta_\delta)} \right)^{(1/\beta_\delta)} = 764$$

$$E[N_{PM}] = \frac{3 \times 7 \times 6 \times 52}{764} = 8.6$$

$$E[N_{CM}] = E[N_{PM}] \left(\frac{TBM}{\eta} \right)^{\beta} = 5$$

Table 5.2 shows $[ETC_{M+Q}]_{M_1}$ and $[ETC_{M+Q}]_{M_2}$ for different quality policies shown in Table 5.1.

Table 5.1: Control chart parameters

Policy	δ	LCL	UCL	n	TBS	β	$E[N_{Out-of-control}]$		
							PR=45	PR=60	PR=90
P1	0.6	-2	2	4	8	78.75%	14	18	28
P2	0.6	-2	2	6	8	70.18%	10	13	20
P3	0.6	-2	2	4	16	78.75%	28	37	56
P4	0.6	-2	2	6	16	70.18%	20	26	40
P5	0.6	-3	3	4	8	96.41%	83	111	167
P6	0.6	-3	3	6	8	93.70%	47	63	95
P7	0.6	-3	3	4	16	96.41%	167	223	334
P8	0.6	-3	3	6	16	93.70%	95	127	191

Table 5.2: Total cost for model 1 and 2 under different quality policies

	$[ETC_{M+Q}]_{M_1}$			$[ETC_{M+Q}]_{M_2}$		
$PR =$	45	60	90	45	60	90
	$C_{rej} = 20,000$ and $C_{lp} = 2,000$					
P1	11,369,480	15,132,618	22,738,961	10,504,759	13,979,657	21,009,518
P2	11,209,347	14,932,451	22,418,694	10,344,626	13,779,490	20,689,251
P3	11,929,948	15,893,252	23,859,895	11,065,227	14,740,291	22,130,453
P4	11,609,681	15,452,885	23,219,361	10,744,960	14,299,924	21,489,919
P5	14,131,784	18,855,723	28,303,601	13,267,063	17,702,761	26,574,158
P6	12,690,582	16,934,120	25,421,197	11,825,861	15,781,159	23,691,755
P7	17,494,588	23,339,461	34,989,175	16,629,867	22,186,500	33,259,733
P8	14,612,184	19,496,257	29,264,402	13,747,463	18,343,295	27,534,960
	$C_{rej} = 25,000$ and $C_{lp} = 1,000$					
P1	6,105,091	8,106,760	12,210,181	5,672,730	7,530,279	11,345,460
P2	5,904,924	7,856,551	11,809,847	5,472,563	7,280,070	10,945,126
P3	6,805,675	9,057,553	13,611,350	6,373,314	8,481,072	12,746,629
P4	6,405,341	8,507,094	12,810,682	5,972,980	7,930,613	11,945,961
P5	9,557,970	12,760,640	19,165,981	9,125,609	12,184,160	18,301,260
P6	7,756,468	10,358,637	15,562,977	7,324,107	9,782,157	14,698,256
P7	13,761,475	18,365,314	27,522,950	13,329,114	17,788,833	26,658,229
P8	10,158,470	13,561,308	20,366,983	9,726,110	12,984,827	19,502,262
	$C_{rej} = 20,000$ and $C_{lp} = 1,000$					
P1	5,964,974	7,926,609	11,929,948	5,532,613	7,350,129	11,065,227
P2	5,804,840	7,726,443	11,609,681	5,372,480	7,149,962	10,744,960
P3	6,525,441	8,687,244	13,050,882	6,093,081	8,110,763	12,186,161
P4	6,205,174	8,246,877	12,410,348	5,772,814	7,670,396	11,545,627
P5	8,727,277	11,649,714	17,494,588	8,294,917	11,073,233	16,629,867
P6	7,286,075	9,728,112	14,612,184	6,853,715	9,151,631	13,747,463
P7	12,090,081	16,133,453	24,180,162	11,657,721	15,556,972	23,315,441
P8	9,207,678	12,290,248	18,455,389	8,775,317	11,713,767	17,590,668
	$C_{rej} = 25,000$ and $C_{lp} = 700$					
P1	4,483,739	5,944,957	8,967,477	4,181,086	5,541,421	8,362,173
P2	4,283,572	5,694,748	8,567,144	3,980,919	5,291,212	7,961,839
P3	5,184,323	6,895,750	10,368,646	4,881,671	6,492,213	9,763,341
P4	4,783,989	6,345,291	9,567,978	4,481,337	5,941,754	8,962,673
P5	7,936,618	10,598,838	15,923,277	7,633,965	10,195,301	15,317,973
P6	6,135,116	8,196,835	12,320,273	5,832,463	7,793,298	11,714,968
P7	12,140,123	16,203,511	24,280,246	11,837,471	15,799,975	23,674,941
P8	8,537,119	11,399,505	17,124,279	8,234,466	10,995,969	16,518,974
	$C_{rej} = 20,000$ and $C_{lp} = 700$					
P1	4,343,622	5,764,807	8,687,244	4,040,970	5,361,270	8,081,939
P2	4,183,488	5,564,640	8,366,977	3,880,836	5,161,104	7,761,672
P3	4,904,089	6,525,441	9,808,178	4,601,437	6,121,905	9,202,874
P4	4,583,822	6,085,074	9,167,644	4,281,170	5,681,537	8,562,340
P5	7,105,925	9,487,911	14,251,884	6,803,273	9,084,375	13,646,579
P6	5,664,723	7,566,309	11,369,480	5,362,071	7,162,773	10,764,176
P7	10,468,729	13,971,650	20,937,458	10,166,077	13,568,114	20,332,154
P8	7,586,326	10,128,445	15,212,685	7,283,673	9,724,909	14,607,380

By comparing results in table 5.2, $[ETC_{M+Q}]_{M_2}$ shows savings over $[ETC_{M+Q}]_{M_1}$. Same as Pandey et al. (2010c), it is observed that the proposed approach by them still gives better results compared to the conventional approaches that do not consider the cost of rejection and when the maintenance is perfect as we assumed.

5.2 MAINTENANCE, QUALITY CONTROL DECISIONS, AND SCHEDULING

In Pandey et al. (2010a,b), the decision of when to do maintenance t_{pm} was integrated with the decisions of SPC quality control chart design parameters (Duncan's mode) i.e. sample size n_s, time between samples h, and the number of standard deviations of the sampling distribution between the center line of the control chart and the control limits k. The objective is to simultaneously determine optimal values of n_s, h, k, and t_{pm} that minimizes the cost of maintenance and quality control. The total expected cost is associated with poor quality, inspection/ sampling, corrective/preventive maintenance and process downtime. Pandey et al. (2010a,b) superimposed the optimal preventive maintenance interval obtained onto the production-schedule to determine optimal job sequences that will minimize penalty cost incurred due to schedule delay.

In Pandey et al. (2010a,b), PM was assumed to be imperfect. We relaxed this assumption and reproduced the results. The details of the relaxed model are described in the following.

The expected process quality control cost for the evaluation period is given as

$$E[TCQ]_{Process_failure} \quad = E[C_{process}] \times \tfrac{T_{eval}}{E[T_{cycle}]} \tag{5.10}$$

We need to calculate the $E[C_{process}]$ and $E[T_{cycle}]$ for the quality control chart. The cycle length consists of the in-control $E[T_1]$ and the out-of-control time and process resetting or machine restoration time.

$$E[T_1] = \frac{1}{\lambda} + T_0 \alpha \sum_{i=0}^{\infty} i[e^{-\lambda h_i} - e^{-\lambda h_{(i+1)}}] \tag{5.11}$$

Where α is type I error and β_δ is type II error for δ shift in mean. T_0 is the time spend to search for false alarm.

The out of control time $E[T_2]$ consists of the expected time of the following events:

- the time between occurrence of an assignable cause and the next sample
- the expected time to trigger an out-of-control signal
- the expected time to plot and chart a sample nT_s where T_s is time

needed to sample and chart one item

- the expected time to validate the assignable cause T_1
- the expected time to reset the process if failure is due to external reasons T_{reset} or the expected time to restore the machine MT_{CM} if failure is due to FM_2

The out-of-control time $E[T_2]$ can be expressed as follows

$$\begin{aligned} E[T_2] = \quad & h \times (ARL2_{mc}\tfrac{\lambda_2}{\lambda} + ARL2_E\tfrac{\lambda_1}{\lambda}) - \tau \\ & + n_sT_s + T_1 + (T_{reset}\tfrac{\lambda_1}{\lambda} + MT_{CM}\tfrac{\lambda_2}{\lambda}) \end{aligned} \tag{5.12}$$

$$\begin{aligned} E[T_{cycle}] = & \quad E[T_1] + E[T_2] \\ = & \quad \tfrac{1}{\lambda} + T_0 \times \tfrac{S}{ARL1} + h \times (ARL2_{mc}\tfrac{\lambda_2}{\lambda} + ARL2_E\tfrac{\lambda_1}{\lambda}) - \tau + \\ & \quad n_sT_s + T_1 + (T_{reset}\tfrac{\lambda_1}{\lambda} + MT_{CM}\tfrac{\lambda_2}{\lambda}) \end{aligned} \tag{5.13}$$

For the evaluation period T_{eval}, the expected process quality control cost will be

$$E[TCQ] = E[C_{cycle}] \times \frac{T_{eval}}{E[T_{cycle}]} \tag{5.14}$$

The process quality cost $E[TCQ]$ consists of the following components: the cost of rejection incurred while operating process in-control C_I and out of control C_o, the cost of sampling, and the cost of evaluating the false alarm and true alarm and cost of resetting or restoring (through corrective maintenance) the process.

The expected total cost per unit time of preventive maintenance and process quality control chart policy $ECPUT_{M*Q}$ is the ratio of the sum of the expected total cost of the process quality control $E[TCQ]$, expected total cost of preventive maintenance $E[C_{pm}]$ and expected total cost of machine failure $E[C_{CM}]_{FM_1}$ to the evaluation time.

$$ECPUT_{M*Q} = \frac{E[C_{CM}]_{FM_1} + E[C_{pm}] + E[TCQ]}{T_{eval}} \tag{5.15}$$

Example:

A case of camshaft from an industrial context is presented. Most automotive manufactures want to have a camshaft that optimizes the performance level they need at a given revolution per minute. This requires proper machining of the camshaft as per the specifications. Cam shaft diameter is an important quality characteristic. Hence, an $\bar{x}$ control chart is used to monitor the manufacturing process. The initial values of relevant parameters are presented in table 5.3

Table 5.3: Example parameters

Parameter	value	parameter	value
δ_E	1.5	δ_{mc}	0.6
T_s	1/3	C_F	100
C_v	50	C_f	1200
C_{rej}	3000	C_{FCPCM}	10000
C_{reset}	5000	T_0	1
T_1	1	T_{reset}	2
PR	10	C_{lp}	400
LC	500	C_{FCPPM}	1000

The global optimization tool box of Maple 12 has been used to solve the optimization problem. The optimal values of decision variables that minimize the expected total cost of system per unit time $ECPUT_{M*Q}$ are as follows $h^* = 22.47$, $k^* = 5.63$, $n_s^* = 8.78$, $t_{PM}^* = 285.35$ and $ECPUT_{M*Q}^* = 108.74$. The main decision parameters are to determine inspection timing h and preventive maintenance timing t_{PM}.

After finding the optimal time between maintenance, it will be super imposed on the batch sequence. A full enumeration will be performed before finding the optimal sequence. Consider a single machine that processes three batches using the presented (in table 5.3) processing time, setup time, penalty cost, due date (DD), and other production parameters

Table 5.4: Parameters for batches

Batch	P (min)	size	setup time	total time	Release	DD	P_i	holding cost
1	6	500	3	53	0	100	75	1.71
2	3	500	1	26	0	50	50	1.71
3	2	500	2	18.66	0	40	45	1.71

The following costs are occurring and results in $CPUT_S$ as follows:

Tardiness $= \sum P_i \left[max(0, C_i - d_i)\right]$

Inventory cost $= \sum h_i \bar{Q}_i C_i$

$$CPUT_S = \frac{Tardinesscost + Inventorycost}{C_{max}}$$

Table 5.5 shows the cost of the different six sequences where sequence $3-2-1$ gives the least cost.

Table 5.5: Possible batches sequences

sequence	C_1	C_2	C_3	T_1	T_2	T_3	Penalty	Inventory	$CPUT_S$
1-2-3	53	79	98	0	29	58	4060	333450	3443.98
1-3-2	53	98	72	0	48	32	3840	324472	3350.13
2-1-3	79	26	98	0	0	58	2610	321907	3311.40
2-3-1	98	26	45	0	0	5	225	278302	2842.12
3-1-2	72	98	19	0	48	0	2400	309937	3187.11
3-2-1	98	45	19	0	0	0	0	275310	2809.29

This section reproduced the work of Pandey et al. (2010b,c) with the assumption of a perfect maintenance. The optimal PM interval that resulted from the integrated model of maintenance and quality is superimposed on the production schedule. A full enumeration for all possible combinations was conducted to find where to place the PM job. The results with perfect PM, same as Pandey et al. (2010b,c), still advocates for the three way integration between scheduling, maintenance and quality control.

5.3 CONCLUSIONS

In this chapter, we tested the integration between maintenance and quality control. In the first model, we tested the inclusion of maintenance into the rejection cost due to quality deviation. The model studies the effect of rejection cost on optimal maintenance planning decision. In the second model, we tested the integration between economic design of control chart with determining optimal timing for PM. The timing was superimposed on a three jobs schedule and a full enumeration for the six sequences has been explored to determine the minimal cost. In the two sections, the integration is highly justified between scheduling, maintenance and quality control.

Chapter 6

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

6.1 SUMMARY

This dissertation considered the integration of scheduling of production, maintenance and quality control functions. Chapter 2 of this dissertation presented a comprehensive review for the state-of-the art framework of the literature and identified gaps for further investigation. A framework for classifying integrated models into interrelated and integrated models is presented. Models that consider one function with the effect of other function as a constraint is classified as "interrelated". Models that jointly considers the decisions of two functions or more are classified as "integrated" models.

Chapter 3 of the dissertation studied integrating job scheduling and preventive maintenance (PM) on a single machine so that the expected total job completion times is minimized. The machine is subjected to random breakdowns that follow an increasing failure hazard rate. If the machine fails while processing a job, it is subjected to a minimal repair action that brings the machine back to operation without altering its age. The problem was formulated as a mixed integer program that once solved provides a schedule that combines job processing and PM.

The same problem is considered in the Chapter 4 of the dissertation with the objective of minimizing the total cost of PM, repair, and work in process inventory. Maintenance cost is affected by the frequency of performing preventive maintenance, where in each time a fixed cost occurs. The repair cost and inventory cost were considered. The problem was formulated as a mixed integer program that once solved provides a schedule that combines PM and job processing.

6.2 DISSERTATION CONTRIBUTION

The main contributions of this dissertation are the following:

1. A comprehensive review for integrated modeling literature is provided. The review differentiates between the models depending on the integration level. This review provides researchers with a well structured overview of the literature that helps in identifying gaps that are still open for research and their relation to other well studied areas.

2. A mixed integer program was proposed to solve the integrated schedul-

ing of job processing and preventive maintenance operations. The objective function was to minimize the expected total weighted completion times. An explicit formula was proposed to the objective function that include decision variables related to job scheduling as well as preventive maintenance. The results of this part of the dissertation advance research of integration of production and maintenance one step ahead.

3. A model that captures costs of preventive maintenance, minimal repair and work in process holding cost was proposed. The problem was formulated and solved as a mixed integer program. This model brings integration in the context of economic optimization which is a major concern in real life applications.

6.3 FUTURE RESEARCH DIRECTIONS

The area of integrated modeling is still wide open for further research in different dimensions. From a production scheduling point of view, it would be of great interest to consider multiple machines with different types of shops like jobshop, flowshop and parallel machines. From a maintenance point of view, different polices or different maintenance actions can be explored. Such an enhancement to the current models would help well with the advanced problems faced by todays manufacturers. The following suggestions are also worth exploring:

1. With the rise of globalization and the concept of open markets, most plants are producing different types of products for different markets. As such, many issues can be considered such as:
   (a) The pricing of these products becomes an issue and should be connected to the production, maintenance and quality costs.
   (b) Logistics can be included and the maintenance of the fleet can be part of the model.
   (c) Integrated models can be studied with the trends of outsourcing policies for maintenance and productions of subcomponents.
2. Integrated models can also be extended to other job related performance measures, such as meeting due dates or multi performance criteria.

3. The assumption of constant maintenance and repair times can be generalized to be random variables following a certain distribution. The model can be studied under the effect of different repair and preventive maintenance time random distributions.

4. In many cases, the machine is drastically affected by the type of job it performs. This effect can be investigated in future work.

5. The inventory consumption was assumed to be linearly affected by processing times. The model should perhaps be tested with non linear inventory consumption, as well.

Appendix A

GAMS code for minimizing $EWCT$

```
sets
    i positions  / 1*3/
    j jobs       /1*3/  ;
alias(i,f);
Parameters
  p(j) process time j
      /
1         8
2        48
3        41
   /
  w(j) weight j
      /
1        2
2        10
```

```
3       10
/;
Scalar beta shape factor in failure distribution  /2/;
Scalar theta scale factor in failure distribution  /100/;
Scalar age starting machine age  /88/;
Scalar tp preventive maintenance time  /5/;
Scalar tr repair time  /15/;
Variables
        x(i,j)     sequence decision
        y(i)       maintenance decision
        a(i)       machine ages
        a_bar_0    machine starting effective age
        a_bar(i)   machine effective ages
        m_a(i)     integrated hazard for machine ages
        m_a_bar_0  integrated hazard for machine starting effective ages
        m_a_bar(i) integrated hazard for machine effective ages
        ex_p(i)    expected processing time
        pos_p(i)   process time in position i
        pos_w(i)   weight in position i
        z          total expected completion time;

Binary Variable x;
Binary Variable y;
```

```
Positive Variable a;

Positive Variable a_bar;

Positive Variable a_bar_0;

Positive Variable m_a;

Positive Variable m_a_bar;

Positive Variable m_a_bar_0;

Positive Variable ex_p;

Positive Variable pos_p;

Positive Variable pos_w;


Equations

         cost   define objective function

         c1(i)  position process

         c2(i)  position weight

         c3     age after first job

         c4(i)  age after each job after i=1

         c5     effective age before job 1

         c6(i)  age after each job

         c7     integrate hazard for effective initial machine age

         c8(i)  integrate hazard for effective age before each job

         c9(i)  integrate hazard for effective age after each job

         c10    expected processing time for first job

         c11(i) expected processing time for jobs after first job
```

```
        c12(j) one job only will occupy each position
        c13(i) one position only for one job ;

cost ..  z =e= sum(i, sum( f$(ord(f)>=ord(i)), pos_w(f)) *(y(i)*tp+ex_p(i)) );

c1(i)    .. pos_p(i)       =e=     sum(j,x(i,j)*p(j));
c2(i)    .. pos_w(i)       =e=     sum(j,x(i,j)*w(j));
c3       .. a('1')         =e=     pos_p('1')+(1-y('1'))*age;
c4(i-1)  .. a(i)           =e=     pos_p(i)+a_bar(i-1);
c5       .. a_bar_0        =e=     (1-y('1'))*age;
c6(i-1)  .. a_bar(i-1)     =e=     (1-y(i))* a(i-1);
c7       .. m_a_bar_0      =e=     (a_bar_0/theta)**beta;
c8(i-1)  .. m_a_bar(i-1)   =e=     (a_bar(i-1)/theta)**beta;
c9(i)    .. m_a(i)         =e=     (a(i)/theta)**beta;
c10      .. ex_p('1')      =e=     pos_p('1')+tr*(m_a('1')-m_a_bar_0);
c11(i-1) .. ex_p(i)        =e=     pos_p(i)+tr*(m_a(i)-m_a_bar(i-1));
c12(j)   .. sum(i,x(i,j))  =e=     1;
c13(i)   .. sum(j,x(i,j))  =e=     1;

model transport /all/;
Solve transport using minlp minimizing z;
Display x.l,y.l, z.l;
```

Appendix B

Full enumeration code

```
clear all

l=1;f=0;

%for nn=1:l

N=3; %Number of jobs

% %for i=1:2^N*factorial(N)

sequence=perms(1:1:N);

% PP =randint(1,N,[1,50]);

% WW = randint(1,N,[1,10]);

% age=randint(1,1,[1,100]);

age=88;

PP=[8 48 41];

PP_j=PP;

WW=[2 10 10];

WW_j=WW;

eta=100;
```

```
beta=2;
t_r=15;
t_p=5;
age_th=eta^2*t_p./(2*t_r*PP);

%end
%for i=1:size(sequence,2)
%     perms(0:1:1)
%      nchoosek(0:1:3,4)
%     dec2bin(1)
%     dec2bin(7,N)
y=zeros(2^N,N);%maintenance decisions
for i=1:2^N
    y(i,:)=bitget(uint8(i), N:-1:1);
end

for i=1:size(sequence,1)% filling the sequence
    for j=1:size(sequence,2)
        for m=1:N
            if sequence(i,j)==m
                P(i,j)=PP(m);
                W(i,j)=WW(m);
                WSPT(i,j)=W(i,j)/P(i,j);
```

```
                %age_th(i,j)=eta^2*t_p/(2*t_r*P(i,j));
            end
        end

    end
end



a={}; %age after job completion
for i=1:size(sequence,1)
    a{i}=zeros(2^N,N);
    for h=1:2^N
        a{i}(h,1)=age;
    end
end
af={}; %effective age
for i=1:size(sequence,1)
    af{i}=zeros(2^N,N);
end
for k=1:size(sequence,1)
    for i=1:2^N
        for j=1:N
            if j==1
```

```
                %             af(i,j)=age
                %a{k}(i,j)= age*(1-y(i,j))
                af{k}(i,j)= (1-y(i,j))*a{k}(i,j);
            else
                a{k}(i,j)=af{k}(i,j-1)+P(k,j-1);

                af{k}(i,j)= (1-y(i,j))*a{k}(i,j);
            end
        end
    end
end
Cj={}; % completion time
for k=1:size(sequence,1)
    Cj{k}={};
    for i=1:2^N
        Cj{k}{i}=0;
    end
end

for k=1:size(sequence,1)
    for i=1:2^N
        for j=1:N
            if j==1
```

```
                Cj{k}{i}(j)=y(i,j)*t_p+P(k,j)+ ...
                t_r*((a{k}(i,j+1)/eta)^beta-(af{k}(i,j)/eta)^beta );
            elseif j==N
                Cj{k}{i}(j)=Cj{k}{i}(j-1)+y(i,j)*t_p+P(k,j)+...
                t_r*(((af{k}(i,j)+P(k,j))/eta)^beta-(af{k}(i,j)/eta)^beta );

            else
                Cj{k}{i}(j)=Cj{k}{i}(j-1)+y(i,j)*t_p+P(k,j)+...
                t_r*((a{k}(i,j+1)/eta)^beta-(af{k}(i,j)/eta)^beta );
            end
        end
    end
end
cc=1; %c_count
C=0;
for k=1:size(sequence,1)
    for i=1:2^N
        C(cc)=sum(W(k,:).*Cj{k}{i});
        cc=cc+1;
    end
end
[as,bs]=min(C);
bs1=ceil(bs/2^N);
```

```
bs2=mod(bs,2^N);
sequenceo=sequence(bs1,:);
yo=bitget(str2num(dec2bin(bs2,N)), N:-1:1);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%TWEC
WSPT_min=sort(WSPT(1,:),'descend');
for i=1:size(sequence,1)
    if WSPT(i,:)==WSPT_min
        sequence_TWEC=sequence(i,:);
        s1=(i-1)*2^N+1;
        s2=i*2^N;
        TWEC=zeros(1,2^N);
        r=0;
        for s=s1:s2
            r=r+1;
            TWEC(r)=C(s);
        end
        COST_WSPT=min(TWEC);
        for d=1:2^N
            if TWEC(d)==COST_WSPT
                y_WSPT=bitget(str2num(dec2bin(d,N)), N:-1:1);
            end
        end
```

```
    end
end

a_2=age;
Ni=N;
y_2={};
indexes=1:size(PP,2);
indexes_j=0;%indexes;
WSPT_remain={};
af_2c={};
for j=1:N
    for i=1:N
%           if sum(i==indexes_j)==1
%               y_2{j}(i)=[];
%           else
        if a_2(j)<age_th(i)
            y_2{j}(i)=0;
        else
            y_2{j}(i)=1
        end

%           end
        af_2(i)=(1-y_2{j}(i))*a_2(j);
```

```
        if j==1
            WSPT_remain{j}(i)=WW_j(i)/(y_2{j}(i)*t_p+PP_j(i)+...
            t_r*(((af_2(i)+PP_j(i))/eta)^beta-(af_2(i)/eta)^beta ));
        else
        if sum(i==indexes_j)==1
            %for t=1:length(indexes_j)
           WSPT_remain{j}(i)=0; %
            %end
        else
        WSPT_remain{j}(i)=WW_j(i)/(y_2{j}(i)*t_p+PP_j(i)+...
        t_r*(((af_2(i)+PP_j(i))/eta)^beta-(af_2(i)/eta)^beta ));
        end
        end
    end
    [J_value,J_max(j)]=max(WSPT_remain{j});
    indexes_j(j)=J_max(j);
%     Ni=Ni-1;


    a_2(j+1)=af_2(J_max(j))+PP(J_max(j));
    %PP_j(J_max(j))
%     PP_j = PP(indexes_j);
%     WW_j = WW(indexes_j);
af_2c{j}=af_2;
```

```
y_2c(j)=y_2{j}(J_max(j));
    clear af_2;
end
y_2c
indexes_j



%%%%%%%%%%%%%%%%%%%%%
COST_WSPT_remain=min(C);
sequence_TWEC_remain=indexes_j;
y_WSPT_remain=y_2c;
output={min(C),COST_WSPT,COST_WSPT_remain;...
    sequenceo,sequence_TWEC,sequence_TWEC_remain;...
    yo,y_WSPT,y_WSPT_remain};
% m={};
if COST_WSPT > min(C)
%     f=f+1;
    COST_WSPT;
    sequence_TWEC;
    y_WSPT;
    min(C);
    sequenceo;
```

```
    yo;
end
% end
% f_percent=(1-f/l)*100
```

Nomenclature

PM	Preventive maintenance
n	Number of job to be scheduled
P_j	Processing time of job j
w_j	Weight of job j
$P_{[j]}$	Processing time of the i^{th} job in the sequence
$w_{[j]}$	Weight of i^{th} job in the sequence
$c_{[i]}$	Expected completion time of i^{th} job
T	Time to failure
β	Weibull shape parameter for probability distribution of T
η	Weibull scale parameter for probability distribution of T
$a_{[0]}$	Age of the machine prior to job sequencing-PM planning
$a_{[i]}$	Age of the machine after the i^{th} job in the sequence
t_r	Time required to repair the machine
t_p	Time required to perform PM on the machine
τ	Time elapsed since last PM
$N(\tau)$	Number of machine failures in τ time units of machine operation
$m(\tau)$	Expected number of failures in period of τ
$z(\tau)$	Hazard function of τ
y_i	PM binary decision variable

c_p	PM cost
c_m	Minimal repair cost
Q_i	Job order size
h_i	Holding cost for one working piece of job order
FC_1	Failure mode 1
FC_2	Failure mode 2
δ_E	Shift in the mean due to external factor
δ_{mc}	Shift in the mean due to FM_2
β_δ	type II error
α	Type I error
LCL	Lower control limit
UCL	Upper control limit
LSL	Lower specifications limit
USL	Upper specifications limit
n_s	sample size
C_{CM}	cost of corrective maintenance
$CPUT$	Cost per unit time
N_{CM}	Number of corrective maintenance
$MTTR_{CM}$	Mean time to repair
$MTTR_{PM}$	Mean time to PM
PR	Production rate
C_{lp}	Cost of lost production
LC	Labor cost

C_{Rep}	Cost of repair
C_{Res}	Cost of restoration
TBM	Time between maintenance
C_{Rej}	Cost of rejection
R_{δ}	Percentage of nonconforming items
$E[N_{defect}]$	Expected number of defectives
T_s	Time to sample and chart one item
T_0	Time spent to search for false alarm
T_1	Time to validate the assignable cause
c_f	False alarm cost
c_F	Fixed cost per sample
c_v	variable cost per sample
ARL_1	Average run length when process in control
ARL_2	Average run length when process out control
C_{FCPCM}	Fixed cost per CM
C_{FCPPM}	Fixed cost per PM
P_{FM_2}	is the probability to have failure mode
h	Time between samples
k	Control chart width

Bibliography

Abboud, N., Jaber, M. and Noueihed, N. (2000) 'Economic lot sizing with the consideration of random machine unavailability time', *Computers and Operations Research*, Vol. 27, No. 4, pp.335–351.

Adiri, I., Bruno, J., Frostig, E. and Kan, A. R. (1989) 'Single machine flow time scheduling with a single breakdown', *ACTA Informatica*, Vol. 26, No. 7, pp.679–696.

Aggoune, R. (2003) 'Minimizing the makespan for the flow shop scheduling problem with availability constraints', *European Journal of Operational Research*, Vol. 153, No. 3, pp.534–543.

Aggoune, R. and Portmann, M.-C. (2006) 'Flow shop scheduling problem with limited machine availability: a heuristic approach', *International Journal of Production Economics*, Vol. 99, No. 1–2, pp.4–15.

Aghezzaf, E., Jamali, M. and Ait-Kadi, D. (2007) 'An integrated production and preventive maintenance planning model', *European Journal of Operational Research*, Vol. 181, No. 2, pp.679–685.

Aksoy, A. and Ozturk, N. (2010) 'Simulated annealing approach in scheduling of virtual cellular manufacturing in the automotive industry', *International Journal of Vehicle Design*, Vol. 52, No. 1–4, pp.82–95.

Allaoui, H. and Artiba, A. (2004) 'Integrating simulation and optimization to schedule a hybrid flow shop with maintenance constraints', *Computers and Industrial Engineering*, Vol. 47, No. 4, pp.431–450.

Allaoui, H. and Artiba, A. (2006) 'Scheduling two-stage hybrid flow shop with availability constraints', *Computers and Operations Research*, Vol. 33, No. 5, pp.1399–1419.

Allaoui, H., Lamouri, S., Artiba, A. and Aghezzaf, E. (2008) 'Simultaneously scheduling n jobs and the preventive maintenance on the two-machine flow shop to minimize the makespan', *International Journal of Production Economics*, Vol. 112, No. 1, pp.161–167.

Anily, S., Glass, C. A. and Hassin, R. (1998) 'The scheduling of maintenance service', *Discrete Applied Mathematics*, Vol. 82, No. 1–3, pp.27–42.

Asano, M. and Ohta, H. (1999*a*) 'Scheduling with shutdowns and sequence dependent set-up times', *International Journal of Production Research*, Vol. 37, No. 7, pp.1661–1676.

Asano, M. and Ohta, H. (1999*b*) 'Single machine scheduling to meet due times under shutdown constraints', *International Journal of Production Economics*, Vol. 60-61, April 20, pp.537–547.

Banerjee, A. and Burton, J. (1990) 'Equipment utilization based maintenance task scheduling in a job shop', *European Journal of Operational Research*, Vol. 45, No. 2–3, pp.191–202.

Ben-Daya, M. (1999) 'Integrated production maintenance and quality model for imperfect processes', *IIE Transactions*, Vol. 31, No. 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*, Vol. 76, No. 3, pp.257–264.

Ben-Daya, M. and Duffuaa, S. (1995) 'Maintenance and quality: the missing link', *Journal of Quality in Maintenance Engineering*, Vol. 1, No. 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*, Vol. 51, No. 7, pp.875–881.

Ben-Daya, M. and Makhdoum, M. (1998) 'Integrated production maintenance and quality model for imperfect under various maintenance policies', *Journal of the Operational Research Society*, Vol. 49, No. 8, 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*, Vol. 12, No. 1, pp.68–80.

Ben-Daya, M. and Rahim, M. (2001) Integrated production, quality and maintenance models: an overview *in* M. Rahim and M. Ben-Daya, eds, 'Integrated models in production planning, inventory, quality and maintenance' Kluwer Academic Publishers, Boston Massachusetts, New York pp. 3–28.

Ben-Daya, M. and Rahim, M. A. (2000) 'Effect of maintenance on the economic design of $\bar{x} - control$ chart', *European Journal of Operational Research*, Vol. 120, No. 1, pp.131–143.

Berrichi, A., Amodeo, L., Yalaoui, F., Chtelet, E. and Mezghiche, M. (2009) 'Bi-objective optimization algorithms for joint production and maintenance scheduling: application to the parallel machine problem', *Journal of Intelligent Manufacturing*, Vol. 20, No. 4, pp.389–400.

Berrichi, A., Yalaoui, F., Amodeo, L. and Mezghiche, M. (2010) 'Bi-objective ant colony optimization approach to optimize production and maintenance scheduling', *Computers and Operations Research*, Vol. 37, No. 9, pp.1584–1596.

Berrittoni, J. (1964) 'Practical applications of the Weibull distribution', *Industrial Quality Control*, Vol. 21, pp.61–79.

Blazewicz, J. and Formanowicz, P. (2002) 'Scheduling jobs in open shops with limited machine availability', *RAIRO - Operations Research*, Vol. 36, No. 2, pp.149–156.

Blazewicz, J., Breit, J., Formanowicz, P., Kubiak, W. and Schmidt, G. (2001) 'Heuristic algorithms for the two-machine flowshop with limited machine availability', *Omega*, Vol. 29, No. 6, pp.599–608.

Brandolese, M., Franci, M. and Pozzetti, A. (1996) 'Production and maintenance integrated planning', *International Journal of Production Research*, Vol. 34, No. 7, pp.2059–2075.

Breit, J., Schmidt, G. and Strusevich, V. (2003) ‘Non-preemptive two-machine open shop scheduling with non-availability constraints’, *Mathematical Methods of Operations Research*, Vol. 57, No. 2, pp.217–234.

Budai, G., Dekker, R. and Nicolai, R. P. (2008) Maintenance and production: a review of planning models *in* D. Murty and K. Kobbacy, eds, ‘Complex System Maintenance Handbook’ Springer Series in Reliability Engineering, Springer-Verlag Limited, London pp. 321–344.

Burton, J., Banerjee, A. and Sylla, C. (1989) ‘A simulation study of sequencing and maintenance decisions in a dynamic job shop’, *Computers and Industrial Engineering*, Vol. 17, No. 1–4, pp.447–452.

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*, Vol. 51, No. 6, pp.800–817.

Cassady, C. and Kutanoglu, E. (2003) ‘Minimizing job tardiness using integrated preventive maintenance planning and production scheduling’, *IIE Transactions*, Vol. 35, No. 2, pp.503–513.

Cassady, C. and Kutanoglu, E. (2005) ‘Integrating preventive maintenance planning and production scheduling for a single machine’, *IEEE Transactions On Reliability*, Vol. 54, No. 2, pp.304–309.

Cassady, C., Bowden, R., Liew, L. and Pohl, E. A. (2000) ‘Combining preventive maintenance and statistical process control: a preliminary investigation’, *IIE Transactions*, Vol. 32, No. 6, pp.471–478.

Cassady, C., Pohl, E. and Murdock, W. (2001) ‘Selective maintenance modeling for industrial systems’, *Journal of Quality in Maintenance Engineering*, Vol. 7, No. 2, pp.104–114.

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*, Vol. 74, No. 1–3, pp.135–146.

Chakravarty, A. and Balakrishnan, N. (1995) ‘Impact of job-sequence on the down-time of a deteriorating flexible machine’, *European Journal of Operational Research*, Vol. 87, No. 2, pp.299–315.

Chan, F. (2001) 'Simulation analysis of maintenance policies in a flow line production system', *International Journal of Computer Applications in Technology*, Vol. 14, No. 1–3, pp.78–86.

Chan, F., Chung, S., Chan, L., Finke, G. and Tiwari, M. (2006) 'Solving distributed FMS scheduling problems subject to maintenance: genetic algorithms approach', *Robotics and Computer-Integrated Manufacturing*, Vol. 22, No. 5–6, pp.493–504.

Chand, S. (1989) 'Lot size and setup frequency with learning in setups and process quality', *European Journal of Operational Research*, Vol. 42, No. 2, pp.190–202.

Charles-Owaba, O., Oluleye, A., Oyawale, F. and Oke, S. (2008*a*) 'A facility maintenance scheduling model incorporating opportunity and inflationary costs', *International Journal of Industrial and Systems Engineering*, Vol. 3, No. 4, pp.423–466.

Charles-Owaba, O., Oluleye, A., Oyawale, F. and Oke, S. (2008*b*) 'Sensitivity analysis of a preventive maintenance scheduling model', *International Journal of Industrial and Systems Engineering*, Vol. 3, No. 3, pp.298–323.

Chelbi, A. and Ait-Kadi, D. (2004) 'Analysis of a production/inventory system with randomly failing production unit submitted to a regular preventive maintenance', *European Journal of Operational Research*, Vol. 156, No. 3, pp.712–718.

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*, Vol. 14, No. 2, pp.161–176.

Chen, J. (2006*a*) 'Optimization models for the machine scheduling problem with a single flexible maintenance activity', *Engineering Optimization*, Vol. 38, No. 1, pp.53–71.

Chen, J. (2006*b*) 'Single-machine scheduling with flexible and periodic maintenance', *Journal of the Operational Research Society*, Vol. 57, No. 6, pp.703–710.

Chen, J. (2010) 'Economic optimisation for an imperfect production system with rework and scrap rate', *International Journal of Industrial and Systems Engineering*, Vol. 6, No. 1, pp.92–109.

Chen, J. S. (2008) 'Scheduling of nonresumable jobs and flexible maintenance activities on a single machine to minimize makespan', *European Journal of Operational Research*, Vol. 190, No. 1, pp.90–102.

Chen, W. (2006*c*) 'Minimizing total flow time in the single-machine scheduling problem with periodic maintenance', *Journal of the Operational Research Society*, Vol. 57, No. 4, pp.410–415.

Chen, W. (2007*a*) 'An efficient algorithm for scheduling jobs on a machine with periodic maintenance', *International Journal of Advanced Manufacturing Technology*, Vol. 34, No. 11-12, pp.1173–1182.

Chen, W. (2007*b*) 'Minimizing total flow time and maximum tardiness with periodic maintenance', *Journal of Quality in Maintenance Engineering*, Vol. 13, No. 3, pp.293–303.

Chen, W. (2007*c*) 'Scheduling of jobs and maintenance in a textile company', *International Journal of Advanced Manufacturing Technology*, Vol. 31, No. 7–8, pp.737–742.

Chen, W. and Liao, C. (2005) 'Scheduling with different maintenance policies in a textile company', *Journal of Quality in Maintenance Engineering*, Vol. 11, No. 1, pp.43–52.

Chen, W. and Tsou, J. (2008) 'Sequencing heuristic for scheduling jobs with periodic maintenance', *International Journal of Information and Management Sciences*, Vol. 19, No. 4, pp.635–649.

Chen, W.-J. (2009) 'Minimizing number of tardy jobs on a single machine subject to periodic maintenance', *Omega*, Vol. 37, No. 3, pp.591–599.

Cheng, T. (1989) 'An economic production quantity model with flexibility and reliability considerations', *European Journal of Operational Research*, Vol. 39, No. 2, pp.174–179.

Cheng, T. (1991) 'An economic order quantity model with demand dependent unit production cost and imperfect production processes', *IIE Transactions*, Vol. 23, No. 1, pp.23–28.

Cheng, X. W. T. (2007) 'Machine scheduling with an availability constraint and job delivery coordination', *Naval Research Logistics*, Vol. 54, No. 1, pp.11–20.

Cheung, K.-Y., Hui, C.-W., Sakamoto, H., Hirata, K. and O'Young, L. (2004) 'Short-term site-wide maintenance scheduling', *Computers and Chemical Engineering*, Vol. 28, No. 1–2, pp.91–102.

Chiu, H.-N. and Huang, B.-S. (1995) 'The economic design of $\bar{x}$-chart and s^2 control charts with preventive maintenance and increasing hazard rate', *Journal of Quality in Maintenance Engineering*, Vol. 1, No. 4, pp.17–40.

Chiu, H.-N. and Huang, B.-S. (1996) 'The economic design of $\bar{x}$ control charts with repair cost depending on detection delay', *Computers and Industrial Engineering*, Vol. 30, No. 4, pp.707–718.

Chiu, S., Ting, C.-K. and Chiu, Y.-S. (2007) 'Optimal production lot sizing with rework, scrap rate, and service level constraint', *Mathematical and Computer Modelling*, Vol. 46, No. 3–4, pp.535–549.

Chung, K.-J. (2003) 'Approximations to production lot sizing with machine breakdowns', *Computers and Operations Research*, Vol. 30, No. 10, pp.1499–1507.

Collani, E. (1999) 'Control of production process subject to random shocks', *Annals of Operations Research*, Vol. 91, No. 1, pp.289–304.

Coudert, T., Grabot, B. and Archimede, B. (2002) 'Production/maintenance cooperative scheduling using multi-agents and fuzzy logic', *International Journal of Production Research*, Vol. 40, No. 18, pp.4611–4632.

Das, T. K. and Sarkar, S. (1999) 'Optimal preventive maintenance in a production inventory', *IIE Transactions*, Vol. 31, No. 6, pp.537–551.

Dedopoulos, I. T. and Shah, N. (1995) 'Preventive maintenance policy optimization for multipurpose plant equipment', *Computers and Chemical Engineering*, Vol. 19, No. 1, pp.693–698.

Diaby, M. (2010*a*) 'Linear programming formulation of the set partitioning problem', *International Journal of Operational Research*, Vol. 8, No. 4, pp.399–427.

Diaby, M. (2010*b*) 'Linear programming formulation of the vertex colouring problem', *International Journal of Mathematics in Operational Research*, Vol. 2, No. 3, pp.259–289.

Dieulle, L., Bérenguer, C., Grall, A. and Roussignol, M. (2003) 'Sequential condition-based maintenance scheduling for a deteriorating system', *European Journal of Operational Research*, Vol. 150, No. 2, pp.451–461.

Dijkhuizen, G. V. (2001) Maintenance grouping in multi-setup multi-component production systems *in* M. Rahim and M. Ben-Daya, eds, 'Integrated models in production planning, inventory, quality and maintenance' Kluwer Academic Publishers, Boston pp. 283–306.

Duffuaa, S. O. and Al-Sultan, K. (1997) 'Mathematical programming approaches for the management of maintenance planning and scheduling', *Journal of Quality in Maintenance Engineering*, Vol. 3, No. 3, pp.163–176.

Duffuaa, S. O. and Al-Sultan, K. (1999) 'A stochastic programming model for scheduling maintenance personnel', *Applied Mathematical Modelling*, Vol. 23, No. 5, pp.385–397.

El-Ferik, S. (2008) 'Economic production lot-sizing for an unreliable machine under imperfect age-based maintenance policy', *European Journal of Operational Research*, Vol. 186, No. 1, pp.150–163.

Espinouse, M., 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*, Vol. 37, No. 1, pp.497–500.

Espinouse, M. L., 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*, Vol. 52, No. 1, pp.116–121.

Faria, J., Nunes, E. and Matos, M. (2010) 'Cost and quality of service analysis of production systems based on the cumulative downtime', *International Journal of Production Research*, Vol. 48, No. 6, pp.1653–1684.

Finch, B. and Gilbert, J. (1986) 'Developing maintenance craft labor efficiency through an integrated planning and control system: a prescriptive model', *Journal of Operations Management*, Vol. 6, No. 3–4, pp.449–459.

Gao, J., Gen, M. and Sun, L. (2006) 'Scheduling jobs and maintenances in flexible job shop with a hybrid genetic algorithm', *Journal of Intelligent Manufacturing*, Vol. 17, No. 4, pp.493–507.

Gharbi, A. and Kenné, J.-P. (2000) 'Production and preventive maintenance rates control for a manufacturing system: an experimental design approach', *International Journal of Production Economics*, Vol. 65, No. 3, pp.275–287.

Gharbi, A. and Kenné, J.-P. (2005) 'Maintenance scheduling and production control of multiple-machine manufacturing systems', *Computers and Industrial Engineering*, Vol. 48, No. 4, pp.693–707.

Gholami, M., Zandieh, M. and Alem-Tabriz, A. (2009) 'Scheduling hybrid flow shop with sequence-dependent setup times and machines with random breakdowns', *The International Journal of Advanced Manufacturing Technology*, Vol. 42, No. 1-2, pp.189–201.

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*, Vol. 27, No. 11, pp.1543–1555.

Goswami, A., Mahata, G. and Prakash, O. (2010) 'Optimal retailer replenishment decisions in the EPQ model for deteriorating items with two level of trade credit financing', *International Journal of Mathematics in Operational Research*, Vol. 2, No. 1, pp.17–39.

Goyal, S., Gunasekaran, A., Martikainen, T. and Yli-Olli, P. (1993) 'Integrating production and quality control policies: a survey', *European Journal of Operational Research*, Vol. 69, No. 1, pp.1–13.

Graves, G. H. and Lee, C.-Y. (1999) 'Scheduling maintenance and semiresumable jobs on a single machine', *Naval Research Logistics*, Vol. 46, No. 7, pp.845–863.

Gribkovskaia, I., Kovalev, S. and Werner, F. (2010) 'Batching for work and rework processes on dedicated facilities to minimize the makespan', *Omega*, Vol. 38, No. 6, pp.522–527.

Groenevelt, H., Pintelon, L. and Seidmann, A. (1992*a*) 'Production batching with machine breakdowns and safety stocks', *Operations Research*, Vol. 40, No. 5, pp.959–971.

Groenevelt, H., Pintelon, L. and Seidmann, A. (1992*b*) 'Production lot sizing with machine breakdowns', *Management Science*, Vol. 38, No. 1, pp.104–123.

Gunasekaran, A., Korukonda, A., Virtanen, I. and Yli-Olli, P. (1995) 'Optimal investment and lot sizing policies for improved productivity and quality', *International Journal of Production Research*, Vol. 33, No. 1, pp.261–278.

Guo, Y., Lim, A., Rodrigues, B. and Yu, S. (2007) 'Machine scheduling performance with maintenance and failure', *Mathematical and Computer Modelling*, Vol. 45, No. 9-10, pp.1067–1080.

Gurela, S. and Akturk, M. S. (2008) 'Scheduling preventive maintenance on a single CNC machine', *International Journal of Production Research*, Vol. 46, No. 24, pp.6797–6821.

Hariga, M. and Ben-Daya, M. (1998) 'The economic manufacturing lot sizing problem with imperfect manufacturing process: bounds and optimal solutions', *Naval Research Logistics*, Vol. 45, No. 4, pp.423–433.

Ho, J. C. and Wong, J. S. (1995) 'Makespan minimization for m parallel identical processors', *Naval Research Logistics*, Vol. 42, No. 6, pp.935–948.

Holthaus, O. (1999) 'Scheduling in job shops with machine breakdowns: an experimental study', *Computers and Industrial Engineering*, Vol. 36, No. 1, pp.137–162.

Hong, J.-D. (1995) 'The effects of manufacturing lead time and process quality in multi-process production system', *Production Planning and Control*, Vol. 6, No. 4, pp.311–319.

Huang, B.-S. and Chiu, H.-N. (1995) 'The quality management of the imperfect production process under two monitoring policies', *International Journal of Quality and Reliability Management*, Vol. 12, No. 3, pp.19–31.

Iravani, S. M. and Duenyas, I. (2002) 'Integrated maintenance and production control of a deteriorating production system', *IIE Transactions*, Vol. 34, No. 5, pp.423–435.

Ji, M., He, Y. and Cheng, T. (2007) 'Single-machine scheduling with periodic maintenance to minimize makespan', *Computers and Operations Research*, Vol. 34, No. 6, pp.1764–1770.

Karamatsoukis, C. and Kyriakidis, E. (2010) 'Optimal maintenance of two stochastically deteriorating machines with an intermediate buffer', *European Journal of Operational Research*, Vol. 207, No. 1, pp.297–308.

Keller, G. and Noori, H. (1988) 'Impact of investing in the quality improvement on the lot size model', *OMEGA International Journal of Management Science*, Vol. 16, No. 6, pp.595–601.

Kellerer, H. (1998) 'Algorithms for multiprocessor scheduling with machine release times', *IIE Transactions*, Vol. 30, No. 11, pp.991–999.

Kenne, J., Gharbi, A. and Najid, N. (2009) 'On the integrated production, inventory and preventive maintenance problem in manufacturing systems with back-order', *International Journal of Simulation and Process Modelling*, Vol. 5, No. 4, pp.300–312.

Kenné, J.-P. and Boukas, E. (2003) 'Hierarchical control of production and maintenance rates in manufacturing systems', *Journal of Quality in Maintenance Engineering*, Vol. 9, No. 1, pp.66–82.

Kenné, J.-P., Boukas, E. and Gharbi, A. (2003) 'Control of production and corrective maintenance rates in multiple-machine, multiple-product manufacturing system', *Mathematical and Computer Modelling*, Vol. 38, No. 3–4, pp.351–365.

Kenné, J.-P., Gharbi, A. and Beit, M. (2006) 'Age dependent production planning and maintenance strategies in unreliable manufacturing systems with lost sale', *European Journal of Operational Research*, Vol. 178, No. 2, pp.408–420.

Khanra, S., Sana, S. S. and Chaudhuri, K. (2010) 'An EOQ model for perishable item with stock and price dependent demand rate', *International Journal of Mathematics in Operational Research*, Vol. 2, No. 3, pp.320–335.

Khouja, M. and Mehraz, A. (1994) 'Economic production lot size model with variable production rate and imperfect quality', *Journal of the Operational Research Society*, Vol. 45, No. 12, pp.1405–1417.

Kim, C. and Hong, Y. (1999) 'An optimal production run length in deteriorating production processes', *International Journal of Production Economics*, Vol. 58, No. 2, pp.183–189.

Kubiak, W., Blazewicz, J. B., Formanowicz, P., Breit, J. and Schmidt, G. (2002) 'Two machine flowshops with limited machine availability', *European Journal of Operational Research*, Vol. 136, No. 3, pp.528–540.

Kubzin, M. A. and Strusevich, V. A. (2005) 'Two-machine flow shop no-wait scheduling with machine maintenance', *4OR: A Quarterly Journal of Operations Research*, Vol. 3, No. 4, pp.303–313.

Kuo, Y. and Chang, Z.-A. (2007) 'Integrated production scheduling and preventive maintenance planning for a single machine under a cumulative damage failure process', *Naval Research Logistics*, Vol. 54, No. 6, pp.602–614.

Kyriakidis, E. and Dimitrakos, T. (2006) 'Optimal preventive maintenance of a production system with an intermediate buffer', *European Journal of Operational Research*, Vol. 168, No. 1, pp.86–99.

Lee, C.-Y. (1991) 'Parallel machines scheduling with non-simultaneous machine available time', *Discrete Applied Mathematics*, Vol. 30, No. 1, pp.53–61.

Lee, C.-Y. (1996) 'Machine scheduling with an availability constraint', *Journal of Global Optimization*, Vol. 9, No. 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*, Vol. 20, No. 3, pp.129–139.

Lee, C.-Y. (1999) ‘Two-machine flowshop scheduling with availability constraints’, *European Journal of Operational Research*, Vol. 114, No. 2, pp.420–429.

Lee, C.-Y. and Chen, Z.-L. (2000) ‘Scheduling jobs and maintenance activities on parallel machines’, *Naval Research Logistics*, Vol. 47, No. 2, pp.145–165.

Lee, C.-Y. and Liman, S. (1992) ‘Single machine flow-time scheduling with scheduled maintenance’, *Acta Informatica*, Vol. 29, No. 4, pp.375–382.

Lee, C.-Y. and Liman, S. (1993) ‘Capacitated two parallel machines scheduling to minimize sum of job completion times’, *Discrete Applied Mathematics*, Vol. 41, No. 3, pp.211–222.

Lee, C.-Y. and Lin, C.-S. (2001) ‘Single-machine scheduling with maintenance and repair rate-modifying activities’, *European Journal of Operational Research*, Vol. 135, No. 3, pp.493–513.

Lee, H. (2005) ‘A cost/benefit model for investments in inventory and preventive maintenance in an imperfect production system’, *Computers and Industrial Engineering*, Vol. 48, No. 1, pp.55–68.

Lee, H. and Rosenblatt, M. (1987) ‘Simultaneous determination of production cycle and inspection schedules in a production systems’, *Management Science*, Vol. 33, No. 9, pp.1125–1137.

Lee, H. and Rosenblatt, M. (1989) ‘A production and maintenance planning model with restoration cost dependent on detection delay’, *IIE Transactions*, Vol. 21, No. 4, pp.368–375.

Lee, W.-C. and Wu, C.-C. (2008) ‘Multi-machine scheduling with deteriorating jobs and scheduled maintenance’, *Applied Mathematical Modelling*, Vol. 32, No. 3, pp.362–372.

Lee, Y. and Zipkin, P. (1992) ‘Production control in a Kanban-Like system with defective outputs’, *International Journal of Production Economics*, Vol. 28, No. 2, pp.143–155.

Leung, J.-T. and Pinedo, M. (2004) ‘A note on scheduling parallel machines subject to breakdown and repair’, *Naval Research Logistics*, Vol. 51, No. 1, pp.60–71.

Liao, C. and Chen, W. (2003) 'Single-machine scheduling with periodic maintenance and nonresumable jobs', *Computers and Operations Research*, Vol. 30, No. 9, pp.1335–1347.

Liao, C.-J., Chen, C.-M. and Lin, C.-H. (2007) 'Minimizing makespan for two parallel machines with job limit on each availability interval', *Journal of the Operational Research Society*, Vol. 58, No. 7, pp.938–947.

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*, Vol. 160, No. 2, pp.445–456.

Liao, L.-M. and Tsai, C.-H. (2009) 'Heuristic algorithms for two-machine flowshop with availability constraints', *Computers and Industrial Engineering*, Vol. 56, No. 1, pp.306–311.

Lin, C.-H. and Liao, C.-J. (2007) 'Makespan minimization for two parallel machines with an unavailable period on each machine', *International Journal of Advanced Manufacturing Technology*, Vol. 33, No. 9–10, pp.1024–1030.

Lin, G. and Gong, D. (2006) 'On a production-inventory system of deteriorating items subject to random machine breakdowns with a fixed repair time', *Mathematics and Computer Modelling*, Vol. 43, No. 7–8, pp.920–932.

Lin, Y., Tseng, S. and Liou, M. (1991) 'Optimal inspection schedule in the imperfect production system under general shift distribution', *Journal of the Chinese Institute of Industrial Engineers*, Vol. 8, No. 2, pp.73–81.

Linderman, K., McKone-Sweet, K. and Anderson, J. (2005) 'An integrated systems approach to process control and maintenance', *European Journal of Operational Research*, Vol. 164, No. 2, pp.324–340.

Liou, M.-J., Tseng, S.-T. and Lin, T.-M. (1994) 'Effects of inspection errors to the imperfect EMQ model', *IIE Transactions*, Vol. 26, No. 2, pp.42–51.

Lodree, J. and Geiger, C. (2010) 'A note on the optimal sequence position for a rate-modifying activity under simple linear deterioration', *European Journal of Operational Research*, Vol. 201, No. 2, pp.644–648.

Lou, S., Sethi, S. and Sorger, G. (1992) 'Stability of real time lot scheduling policies for an unreliable machine', *IEEE Transactions on Automatic Control*, Vol. 37, No. 12, pp.1966–1970.

Low, C., Hsu, C.-J. and Su, C.-T. (2008) 'Minimizing the makespan with an availability constraint on a single machine under simple linear deterioration', *Computers and Mathematics with Applications*, Vol. 56, No. 1, pp.257–265.

Low, C., Ji, M., Hsu, C.-J. and Su, C.-T. (2010) 'Minimizing the makespan in a single machine scheduling problems with flexible and periodic maintenance', *Applied Mathematical Modelling*, Vol. 34, No. 2, pp.334–342.

Makis, V. and Fung, J. (1995) 'Optimal preventive replacement, lot sizing and inspection policy for a deteriorating production system', *Journal of Quality in Maintenance Engineering*, Vol. 1, No. 4, pp.41–55.

Makis, V. and Fung, J. (1998) 'An EMQ model with inspections and random machine failures', *Journal of the Operational Research Society*, Vol. 49, No. 1, pp.66–76.

Mehraz, A., Myers, B. and Khouja, M. (1991) 'Quality and inventory issues within the newsboy problem', *Computers and Operations Research*, Vol. 18, No. 5, pp.397–410.

Mellouli, R., Sadfi, C., Chu, C. and Kacem, I. (2009) 'Identical parallel-machine scheduling under availability constraints to minimize the sum of completion times', *European Journal of Operational Research*, Vol. 197, No. 3, pp.1150–1165.

Mosheiov, G. (1994) 'Minimizing the sum of job completion times on capacitated parallel machines', *Mathematical and Computer Modelling*, Vol. 20, No. 6, pp.91–99.

Mosheiov, G. and Sarig, A. (2009) 'Scheduling a maintenance activity to minimize total weighted completion-time', *Computers and Mathematics with Applications*, Vol. 57, No. 4, pp.619–623.

Naderi, B., Zandieh, M. and Fatemi-Ghomi (2009*a*) 'A study on integrating sequence dependent setup time flexible flow lines and preventive maintenance scheduling', *Journal of Intelligent Manufacturing,*, Vol. 20, No. 6, pp.683–694.

Naderi, B., Zandieh, M. and Fatemi-Ghomi, S. M. T. (2009*b*) 'Scheduling sequence-dependent setup time job shops with preventive maintenance', *International Journal Advanced Manufacturing Technology*, Vol. 43, No. 1–2, pp.170–181.

O'Donovan, R., Uzsoy, R. and McKay, K. (1999) 'Predictable scheduling of a single machine with breakdowns and sensitive jobs', *International Journal of Production Research*, Vol. 37, No. 18, pp.4217–4233.

Ohta, H. and Ogawa, S. (1991) Joint determination of production cycle and inspection schedules under inspection errors *in* M. Pridhan and C. Brien, eds, 'Production Research: approaching the 21st Century' Tylor and Francis pp. 179–188.

Okamura, H., Dohi, T. and Osaki, S. (2001) Computations algorithms of cost-effective EMQ policies with PM *in* M. Rahim and M. Ben-Daya, eds, 'Integrated models in production planning, inventory, quality and maintenance' Kluwer Academic Publishers, Boston Massachusetts, New York pp. 31–65.

Pan, E., Liao, W. and Xi, L. (2010) 'Single-machine-based production scheduling model integrated preventive maintenance planning', *International Journal of Advanced Manufacturing Technology*, Vol. 50, No. 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*, Vol. 94, No. 3, pp.732–741.

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*, Vol. 180, No. 1, pp.329–353.

Panagiotidou, S. and Tagaras, G. (2008) 'Evaluation of maintenance policies for equipment subject to quality shifts and failures', *International Journal of Production Research*, Vol. 46, No. 20, pp.5761–5779.

Pandey, D., Kulkarni, M. and Vrat, P. (2010*a*) 'Consideration of production scheduling, maintenance and quality policies: a review and conceptual framework', *International Journal of Advanced Operations Management*, Vol. 2, No. 1/2, pp.1–24.

Pandey, D., Kulkarni, M. and Vrat, P. (2010*b*) 'An integrated model for maintenance planning, process quality control and production scheduling', *POMS 21 Annual conference. Vancouver, Canada, May 7–May 10.*

Pandey, D., Kulkarni, M. and Vrat, P. (2010*c*) 'A model for optimal maintenance interval incorporating the cost of rejections in manufacturing', *Journal of Advances in Management Research*, Vol. 7, No. 2, pp.219–232.

Pandey, D., Kulkarni, M. and Vrat, P. (2011*a*) 'A methodology for joint optimization for maintenance planning, process quality and production scheduling', *Computers and Industrial Engineering*, Vol. x, No. x, pp.xx–xx.

Pandey, D., Kulkarni, M. and Vrat, P. (2011*b*) 'A methodology for simultaneous optimisation of design parameters for the preventive maintenance and quality policy incorporating taguchi loss function', *International Journal of Production Research*, Vol. , No. iFirst, pp.1–16.

Pate-Cornell, M., Lee, H. and Tagaras, G. (1987) 'Warning of malfunction: the decision to inspect and maintain production processes on schedule or on demand', *Management Science*, Vol. 33, No. 10, pp.1277–1290.

Peters, M., Schneider, H. and Tang, K. (1988) 'Joint determination of optimal inventory and quality control policy', *Management Science*, Vol. 34, No. 8, pp.991–1004.

Pistikopoulos, E., Vassiliadis, C. and Papageorgiou, L. (2000) 'Process design for maintainability: an optimization approach', *Computers and Chemical Engineering*, Vol. 24, No. 2–7, pp.203–208.

Porteus, E. (1986) 'Optimal lot sizing, process quality improvement and setup cost reduction', *Operations Research*, Vol. 34, No. 1, pp.137–144.

Qi, X., Chen, T. and Tu, F. (1999) 'Scheduling the maintenance on a single machine', *Journal of the Operations Research Society*, Vol. 50, No. 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*, Vol. 127, No. 3, pp.546–564.

Radhoui, M., Rezg, N. and Chelbi, A. (2010) ‘Joint quality control and preventive maintenance strategy for imperfect production processes’, *Journal of Intelligent Manufacturing*, Vol. 21, No. 2, pp.205–212.

Rahim, M. (1994) ‘Joint determination of quantity, inspection, schedule and control chart design’, *IIE Transactions*, Vol. 26, No. 6, pp.2–11.

Rahim, M. and Banerjee, P. (1988) ‘Optimal production run for a process with random linear drift’, *OMEGA: International Journal of Management Science*, Vol. 16, No. 4, pp.347–351.

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*, Vol. 36, No. 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*, Vol. 52, No. 12, pp.1370–1378.

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 machine’, *International Journal of Operations Research*, Vol. 4, No. 1, pp.32–41.

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 Research*, Vol. 34, No. 2, pp.421–446.

Rosenblatt, M. J. and Lee, H. L. (1986*a*) ‘A comparative study of continuous and periodic inspection policies in deteriorating production systems’, *IIE Transactions*, Vol. 18, No. 1, pp.2–9.

Rosenblatt, M. J. and Lee, H. L. (1986*b*) 'Economic production cycles with imperfect production processes', *IIE Transactions*, Vol. 18, No. 1, pp.48–55.

Sadfi, C., Penz, B., Rapine, C., Blazewicz, J. and Formanowicz, P. (2005) 'An improved approximation algorithm for the single machine total completion time scheduling problem with availability constraints', *European Journal of Operational Research*, Vol. 161, No. 1, pp.3–10.

Salameh, K. and Jaber, M. (2000) 'Economic production quantity model for items with imperfect quality', *International Journal of Production Economics*, Vol. 64, No. 1, pp.59–64.

Sana, S. and Chaudhuri, K. (2010) 'An EMQ model in an imperfect production process', *International Journal of Systems Science*, Vol. 41, No. 6, pp.635–646.

Sanmarti, E., Espuna, A. and Puigjaner, L. (1995) 'Effects of equipment failure uncertainty in batch production scheduling', *Computers and Chemical Engineering*, Vol. 19, No. 1, pp.565–570.

Sarper, H. (1993) 'Scheduling for maintenance of completely processed low-demand large items', *Applied Mathematical Modelling*, Vol. 17, No. 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*, Vol. 55, No. 4, pp.830–840.

Schmidt, G. (1988) 'Scheduling independent tasks with deadlines on semi-identical processors', *Journal of the Operations Research Society*, Vol. 39, No. 3, pp.271–277.

Schmidt, G. (2000) 'Scheduling with limited machine availability', *European Journal of Operational Research*, Vol. 121, No. 1, pp.1–15.

Schneider, H., Tang, K. and O'Cinneide, C. (1990) 'Optimal control of a production process subject to random deterioration', *Operations Research*, Vol. 38, No. 6, pp.1116–1122.

Sloan, T. (2004) 'A periodic review production and maintenance model with random demand, deteriorating equipment, and binomial yield', *Journal of the Operational Research Society*, Vol. 55, No. 6, pp.647–656.

Sortrakul, N. and Cassady, C. (2007) 'Methodology and theory: genetic algorithms for total weighted expected tardiness integrated preventive maintenance planning and production scheduling for a single machine', *Journal of Quality in Maintenance Engineering*, Vol. 13, No. 1, pp.49–61.

Sortrakul, N., Nachtmann, H. and Cassady, C. (2005) 'Genetic algorithms for integrated preventive maintenance planning and production scheduling for a single machine', *Computers in Industry*, Vol. 56, No. 2, pp.161–168.

Srinivasan, M. and Lee, H. (1996) 'Production-inventory systems with preventive maintenance', *IIE Transactions*, Vol. 28, No. 11, pp.879–890.

Sudiarso, A. and Labib, A. (2002) 'A fuzzy logic approach to an integrated maintenance/production scheduling algorithm', *International Journal of Production Research*, Vol. 40, No. 13, pp.3121–3138.

Sun, J. and Xi, L. (2010) 'Optimal maintenance policy for degrading manufacturing systems using long-term average cost criterion', *Production Planning and Control, First published on: 22 October 2010 (iFirst).*

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*, Vol. 124, No. 1, pp.151–158.

Sun-Lee, I. and Yoon, S. (2010) 'Coordinated scheduling of production and delivery stages with stage-dependent inventory holding costs', *Omega*, Vol. 38, No. 6, pp.509–521.

Suresh, V. and Chaudhuri, D. (1996) 'Scheduling of unrelated parallel machines when machine availability is specified', *Production Planning and Control*, Vol. 7, No. 4, pp.393–400.

Tagaras, G. (1988) 'An integrated cost model for the joint optimization of process control and maintenance', *Journal of the Operational Research Society*, Vol. 39, No. 8, pp.757–766.

Taguchi, G. (1986) *Introduction to quality engineering* Asian Productivity Organization American Supplier Institute, Michigan, Ann Arbor.

Tseng, S. (1996) 'Optimal preventive maintenance policy for deteriorating production systems', *IIE Transactions*, Vol. 28, No. 8, pp.687–694.

Tseng, S., Yeh, R. and Ho, W. (1998) 'Imperfect maintenance policies for deteriorating production systems', *International Journal of Production Economics*, Vol. 55, No. 2, pp.191–201.

Vassiliadis, C. and Pistikopoulos, E. (2001) 'Maintenance scheduling and process optimization under uncertainty', *Computers and Chemical Engineering*, Vol. 25, No. 2–3, pp.217–236.

Vaurio, J. (1999) 'Availability and cost functions for periodically inspected preventively maintained units', *Reliability Engineering and System Safety*, Vol. 63, No. 2, pp.133–140.

Voros, J. (1999) 'Lot sizing with quality improvement and setup time reduction', *European Journal of Operational Research*, Vol. 113, No. 3, pp.568–574.

Wang, C. and Sheu, S. (2003) 'Determining the optimal production-maintenance policy with inspection errors: using a Markov chain', *Computers and Operations Research*, Vol. 30, No. 1, pp.1–17.

Weinstein, L. and Chung, C. (1999) 'Integrating maintenance and production decisions in a hierarchical production planning environment', *Computers and Operations Research*, Vol. 26, No. 10-11, 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*, Vol. 87, No. 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*, Vol. 188, No. 2, pp.516–529.

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*, Vol. 35, No. 4, pp.1344–1349.

Yang, D.-L., Hsu, C.-J. and Kuo, W. (2008) 'A two-machine flowshop scheduling problem with a separated maintenance constraint', *Operations Research*, Vol. 35, No. 3, pp.876–883.

Yang, D.-L., Hung, C.-L., Hsu, C.-J. and Chem, M.-S. (2002) 'Minimizing the makespan in a single machine scheduling problem with a flexible maintenance', *Journal of the Chinese Institute of Industrial Engineers*, Vol. 19, No. 1, pp.63–66.

Yao, X., Xie, X., Fu, M. and Marcus, S. (2005) 'Optimal joint preventive maintenance and production policies', *Naval Research Logistics*, Vol. 52, No. 7, pp.668–681.

Yeh, R., Ho, W. and Tseng, S. (2000) 'Optimal production run length for products sold with warranty', *European Journal of Operational Research*, Vol. 120, No. 3, pp.575–582.

Yeung, T. G., Cassady, C. and Schneider, K. (2008) 'Simultaneous optimization of $\bar{X}$ control chart and age-based preventive maintenance policies under an economic objective', *IIE Transactions*, Vol. 40, No. 2, pp.147–159.

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*, Vol. 39, No. 9-10, pp.954–964.

Zhou, W.-H. and Zhu, G.-L. (2008) 'Economic design of integrated model of control chart and maintenance management', *Mathematical and Computer Modelling*, Vol. 47, No. 11-12, pp.1389–1395.

Vita

Laith A. Hadidi received his B.Sc. in Mechanical Engineering and M.Sc. in Industrial Engineering from the University of Jordan, Amman, Jordan, in 2002 and 2005, respectively. Then he joined, as a Ph.D. candidate and lecturer-B, the Systems Engineering Department at King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia. Laith completed his Ph.D. in Industrial and Systems Engineering in June, 2011. His areas of research interests include preventive maintenance planning, operations sequencing and scheduling, production systems design and simulation.

Laith is originally from the Hashemite Kingdom of Jordan. He lives in Amman, Jordan and can be reached by Email: laith.alhadidi@gmail.com and Mobile: 00962796507017. Laith stayed within KFUPM campus during his doctoral studies. His contact details for KFUPM are: Email: lhadidi@kfupm.edu.sa and Mobile: 00966501277088.