

**Joint Multi-Objective Production Scheduling and
Maintenance Planning Model for Green Environment**

BY

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Dedicated to my family, a special feeling of gratitude to my loving parents, Obaidallah and Fakhryia, whose words of love and push for tenacity ring in my ears. My sisters Ameera and Muneera have never left my side and are very special.

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LIST OF ABBREVIATIONS

CCS:	Carbon Capturing and Sequestration
CBM:	Condition-Based Maintenance
CM:	Corrective Maintenance
GAMS:	General Algebraic Modeling Language
GA:	Genetic Algorithm
GHG:	Greenhouse Gases
MIP:	Mixed-Integer Programming
MILP:	Mixed-Integer Linear Programming
MINLP:	Mixed-Integer Nonlinear Programming
MOO:	Multi-Objective Optimization
MOPSO:	Multi-Objective Particle Swarm Optimization
RCM:	Reliability-Centered Maintenance
TOU:	Time-of-Use
TPM:	Total Productive Maintenance

ABSTRACT

Full Name : Ahmad Obaidallah Alatwi
Thesis Title : Joint Multi-Objective Production Scheduling and Maintenance
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In industry, production and maintenance are intertwined. There has recently been a spike in interest in models investigating both production and maintenance together. On the other hand, green production scheduling, which takes environmental considerations seriously, has also witnessed remarkable interest from researchers. In this thesis, our objective is to integrate production scheduling and maintenance planning for a green environment. We aim to formulate a model that minimizes the maximum completion time while also reducing harmful gases emission to the environment, e.g., CO₂. We develop a mixed-integer nonlinear multi-objective optimization (MINLP-MOO) model to address the trade-off between energy consumption as a measure of sustainability and makespan as a measure of service level. The speed scaling technique is used to control energy consumption. Minimization of carbon footprint and minimization of makespan are conflicting objectives. The weighted-sum method is used to generate the Pareto frontier, and GAMS software with the LINDO solver is used to solve the model and analyze the results. A case study from the literature is used to demonstrate the applicability of the integrated model, and a sensitivity analysis is performed to gain additional managerial insights.

ملخص الرسالة

الاسم الكامل: أحمد عبيد الله العطوي

عنوان الرسالة: نظام متكامل متعدد الأهداف لجدولة الإنتاج وتخطيط الصيانة من أجل بيئة خضراء

التخصص: الهندسة الصناعية و النظم

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في الصناعة، تتداخل عمليات جدولة الإنتاج والصيانة كثيرا، حيث يؤثر كل منهما في الآخر. ولقد شهدت الآونة الأخيرة ازديادا في الاهتمام بالنماذج التي تدرس كل من الإنتاج والصيانة. ومن ناحية أخرى، فإن الجدولة الخضراء للإنتاج، التي تأخذ الاعتبارات البيئية على محمل الجد، شهدت هي الأخرى اهتمام ملحوظا من الباحثين. في هذه الأطروحة، هدفنا هو دمج جدولة الإنتاج وتخطيط الصيانة من أجل بيئة خضراء، حيث نهدف الى إيجاد نموذج متكامل يقلل من الحد الأقصى لوقت الإنجاز وفي ذات الوقت يقلل من الانبعاثات الغازية الضارة للبيئة، مثل ثاني أكسيد الكربون. ولقد طورنا نموذج تحسين مختلطا غير خطي متعدد الأهداف (MINLP-MOO) للمفاضلة بين استهلاك الطاقة كمقياس للاستدامة والوقت الأقصى للإنجاز كمقياس لمستوى الخدمة. كما تم استخدام تقنية تعديل السرعة للتحكم في استهلاك الطاقة.

إن التقليل من البصمة الكربونية وتقليل الوقت الأقصى للإنجاز معا يشكلان هدفين متضاربين. لذلك تم استخدام طريقة المجموع الموزون لتوليد حدود باريتو. كما استخدمنا برنامج GAMS بواسطة أداة حل LINDO لحل النموذج وتحليل النتائج. وحللنا النتائج في نهاية البحث وقدمنا أفكارا ومقترحات لتطوير العمل في هذا المجال.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Maintenance and production are inextricably linked because both impact the machine's capacity (Cui et al., 2019). Machines are prone to failure and degradation; this necessitates repair and maintenance activities, during which machines are unavailable, resulting in disrupted production scheduling. Therefore, establishing a maintenance plan to keep machines in healthy working condition while also making production scheduling is an urgent need. As a result, maintenance-production planning integration has become a significant concern for intelligent manufacturing (Liao et al., 2017). This integration has been studied for three decades; however, it ignores the energy factor (Ma et al., 2010).

The machine consumes power when it processes jobs, but it does not require any power when maintenance is performed because it is turned off at the time (Cui et al., 2019). As a result, in today's environmental production environment, maintenance-production planning is an interrelated element with sustainability considerations.

Several energy-saving techniques are considered in sustainable energy-efficient scheduling problems to reduce energy consumption and meet this integration. These techniques include the machine speed scaling mechanism that allows the machine's speed to be

adjusted to control the processing energy consumption. The Time-of-use (TOU) tariff technique in which energy prices are higher in-peak periods than off-peak periods. The On/Off mechanism that switching off machines reduces nonprocessing energy consumption. The technique used in this work is machine speed scaling.

The majority of production scheduling work is focused on economic aspects while ignoring environmental aspects, i.e., a green environment. However, a review of the literature on sustainable production scheduling reveals that the role of maintenance is rarely considered. This thesis investigates the role of maintenance in a production schedule that considers both economic and environmental aspects.

This chapter introduces the thesis objectives and discusses environmental sustainability, production scheduling, and maintenance. Section 1.2 discusses sustainability issues. Then, production scheduling and machine speed scaling mechanism are outlined in section 1.3. Maintenance planning techniques are defined in section 1.4. Multi-objective optimization and the weighted-sum method are introduced in section 1.5. The thesis objectives are provided in section 1.6. Section 1.7 outlines thesis organization

1.2 Environmental sustainability considerations

The need to consider sustainability and energy saving has become fundamental to manufacturing, and the firms are becoming more environmentally conscious. As a result, there is a greater emphasis on reducing energy consumption and pollutant production

(Chen et al., 2013). (Gahm et al., 2016) noted that the sustainability requirement is important towards providing solutions to current needs without creating any compromise in the ability of future generations to meet their supply and manufacturing needs. Efforts towards creating a sustainable production process have been observed growing in production industries (Gong et al., 2015; Chiong et al., 2016).

Production companies have been designated as frontrunners in the sustainability course (van der Veen and Venugopal, 2014; Glock et al., 2012). Over time, firms in various industrial and manufacturing sectors have devised methodologies, policies, and plans to support sustainability. Management of sustainability involves interventions in supply chains because about 50 to 70% of the value of an item is associated with suppliers (Reefke et al., 2010). There has been persistent debate about the extent to which a firm's sustainability and economic status are directly related. Conventional literature points to an inevitable trade-off between environmental sustainability and a firm's profitability. In essence, when an organization commits to investing more in the sustainability course, the consequential result will be increased cost and reduced profits. Counteracting this hypothesis is the idea that sustainability interventions such as the "lean is green" concept encourages reductions in total energy consumption (van der Veen and Venugopal, 2014). Along with such platforms of argument, it is then concluded that trade-off is divided efficiently so that sustainability and profitmaking are simultaneously improved.

1.2.1 Carbon policies

The most common environmental effect caused by industrial production processes is the emission of greenhouse gases (GHG), which serves as the foundation for the majority of environmental considerations during the assessment of environmentally sustainable supply chain operations (Can and Turkay, 2014). The amount of GHG released from a single industrial entity is termed a carbon footprint. (Tang et al., 2016) cited two ways through which carbon emissions can be realized: through obligatory emission reduction regulations, including carbon cap guidelines and carbon taxing, and by promoting voluntary emission reduction measures. The second alternative is especially effective because of its ability to endorse market potential through a good corporate image and improvement in product demand and the price structure. There are different environmental management approaches for modeling the sustainable economic order quantity, such as Carbon tax, Direct cap, and Direct accounting.

1.2.1.1 Direct accounting

Direct accounting treats carbon footprints, among other aspects of sustainability, as an additional cost input (Bouchery et al., 2012). (Can and Turkay, 2014) asserted that the direct method of accounting is optional in most business jurisdictions and is used solely at the discretion of the organization's management. A firm may choose to compute total cost incursions considering environmental aspects to keep track of real organizational value by investigating emissions and other associated costs.

1.2.1.2 Carbon tax

Regulatory agencies may impose a carbon tax to encourage organizations to take account of environmental costs. There are various tax rates such as fixed carbon tax rate and progressive carbon tax rate, i.e., the tax rate will be lower when emissions below a threshold or higher if emissions are above the threshold, nonlinear, piecewise linear, staircase, ..., etc.

1.2.1.3 Direct Cap

Regulatory agencies may impose an upper limit on GHG emissions. It is undesirable to adhere to excessively high or excessively low emission caps under a strict carbon cap policy. Carbon emissions increase linearly within a certain cap range while costs decrease non-linearly, reducing emissions without significantly increasing costs.

1.2.1.4 Cap & Trade

Companies emitting less than the allowed cap are rewarded, whereas those over-emitters are penalized. This penalty and reward mechanism is achieved via a carbon trading market. Companies emitting lower than the cap sell their allowances, i.e., the number of emissions under the cap, whereas those emitting more than the cap buy such allowances. As a result, in a cap-and-trade system, the caps are not strict but rather encouraging. Such markets have

already emerged in the EU and the USA, and company participation in the system is required.

1.2.1.5 Carbon Offsets

Carbon offsets involve emission-reducing investments. These investments may be in the form of energy-efficient equipment and facilities, renewable energy resources, energy-saving programs, carbon capturing and sequestration (CCS) systems, to name a few. The organization pays the price for the offset in return for a reduced carbon footprint due to the increased technology and environmentally friendly resources.

1.3 Green production scheduling

Production planning and scheduling are essential in green manufacturing (Haapala et al., 2013). A review of the literature by (Gahm et al., 2016) analyzed multiple applications of green scheduling. It showed that green scheduling contributes to improving energy efficiency in manufacturing companies and can substantially contribute to the more sustainable production of goods. Research conducted by (Chiong et al., 2016) investigated selected papers on the topic of sustainable scheduling of manufacturing and transportation systems.

1.3.1 Machine Speed Scaling

In literature, different techniques are considered to reduce energy consumption during production scheduling. These techniques include the machine speed scaling mechanism, where machines can process jobs at different speeds to control the processing energy consumption. Besides, the TOU tariff technique where energy prices are higher in peak periods than off-peak periods, and the on/off mechanism reduces the non-processing energy consumption.

In the speed scaling mechanism, machines are allowed to process jobs at different speeds. The higher the speed, the more deterioration of the machine, which means more power consumption and more gases emitted. Since machines consume different amounts of energy at different speed levels, choosing reasonable processing speeds for jobs can reduce energy consumption (Che et al., 2016).

1.4 Maintenance

Maintenance is a very important function in the manufacturing field. Maintenance has a significant impact not only on production volume, production cost, and product quality but also on individuals' well-being and the natural environment. Environmental risks and GHG emissions can be reduced by applying a successful maintenance plan (Yan and Hua, 2010). Energy consumption increases as a machine deteriorate during its lifetime (Yan and Hua, 2010). Unexpected failures and downtimes necessitate unnecessary setups, resulting in significantly increasing energy consumption each time the machine turns on (Heilala et al.,

2008). A significant amount of energy can be saved by executing an optimal maintenance plan (Takata et al., 2004). Therefore, the effect of maintenance planning on green scheduling should be considered.

There are multiple maintenance strategies in manufacturing companies, including:

- Corrective maintenance (CM): no maintenance is performed unless a failure occurs. This strategy can be implemented in companies with large marginal profits.
- Condition-based maintenance (CBM): sensor data such as vibration, lubricant level, and ultrasonic sound level are collected and analyzed to determine the likelihood of a potential failure. This strategy might not be affordable for all companies due to the significant investment in installing necessary sensors and monitoring technology.
- Total productive maintenance (TPM) strategy: this alternative integrates the concepts of maintenance and quality via performing daily inspections by trained operators to eliminate major losses in downtimes, setups, and yield in production. Successful implementation of this strategy requires a high level of employee involvement.
- Reliability-centered maintenance (RCM): the primary goal is to increase machine uptime and maintain the machine reliability level rather than restoring it to an ideal situation.

1.5 Multi-objective optimization

Multi-objective optimization (MOO) implies simultaneous optimization of all objective functions together. MOO seeks to determine a vector of decision variables within a feasible region to minimize a vector of objective functions that usually conflict with each other. The optimal solution is replaced with the preferred solution, and optimality is replaced with Pareto-optimality. A vector $x^* \in S$ is said to be Pareto optimal for a multi-objective problem if all other vectors $x \in S$ have a higher value for at least one of the objective functions $f(i)$, with $i = 1, \dots, n$, or have the same value for all the objective functions

Among the most common approaches to solve multi-objective problems are the weighted method, ε -constraint method, goal programming, and multi-level programming. In this research, we use the weighted method to solve the model.

1.5.1 The weighted-sum method

The weighted-sum method, sometimes referred to as the scalarization technique, integrates multiple objectives into a single objective scalar function. Each objective is multiplied by a decision-maker -specified weight, w . The weight of an objective is chosen in proportion to the relative importance of the objective. It can be represented mathematically as follows:

$$\left. \begin{array}{l} \text{minimize} \quad f_1(x) \\ \text{maximize} \quad \vdots \\ \text{minimize} \quad f_m(x) \end{array} \right\} \quad \text{minimize} \quad w_1 f_1(x) + w_2 f_2(x) + \cdots + w_m f_m(x); \quad \sum_{i=1}^m w_i = 1$$

Where $w_i \in (0,1)$ is the weight of the i th objective function, and it is usual practice to choose

The weighted sum method is one of the most widely used due to its simplicity. Although the weighted sums method makes it hard to obtain the uniform Pareto optimal solutions and the Pareto front for nonconvex regions, it is still convenient and effective. It is the most commonly used multi-objective scalar method (Das and Dennis, 1997). This paper takes the weighted sums method to solve MOO problems to get satisfactory Pareto optimal solutions rapidly.

Despite its shortcomings in depicting the Pareto optimal set, the weighted sum method for MOO is still widely used to provide multiple solution points by consistently varying the weights and providing solutions that reflect the preference of each object.

Some of the characteristics of the weighted-sum method:

- Simple and easy to use.
- For convex problems, it guarantees to find solutions on the entire Pareto- optimal set.

- Cannot find specific Pareto-optimal solutions in the case of a nonconvex objective space.
- For mixed problems (min-max), we need to convert all the objectives into one type.
- Two different sets of weights do not necessarily lead to two different Pareto-optimal solutions.

1.6 Thesis Objectives

The overall objective of the thesis is to develop a joint multi-objective production scheduling and maintenance planning model for a green environment.

We are going to address the following sub-objectives:

- Conducting a literature review for the related integrated models.
- Developing a MINLP-MOO model.
- Applying a machine speed scaling mechanism to control the processing energy consumption.
- Identifying maintenance plans to minimize environmental effects.
- Studying the trade-off among conflicting objectives.
- Introducing numerical examples to verify the validity of the proposed model.
- Analyzing the computed results.

1.7 Thesis Organization

The rest of this thesis is organized according to the following description. In chapter 2 a literature review is conducted. Chapter 3 presents the development of the integrated model of green production scheduling and maintenance planning. Chapter 5 includes the conclusion of the thesis in addition to suggestions for future extensions.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This literature review considers sustainable production scheduling and maintenance planning in manufacturing. The integration of the two activities has recently received a lot of attention in the literature. Previously, these integrating activities were treated separately. This lack of coordination has the potential to result in significant production losses. As a result, the integration is justified by the avoidance of such losses.

2.2 Sustainable scheduling

The literature includes different machine environments.

2.2.1. Single Machine

(Che et al., 2015) considered a single-machine problem with speed scaling scheduling to minimize energy consumption by bounding the maximum tardiness. A mixed-integer linear programming (MILP) model is developed for solving the problem.

(Che et al., 2016) formulated a continuous-time MILP model to resolve the single machine scenario. A greedy insertion heuristic was used to insert time periods into real-time energy consumption rates and then placing each job in periods of minimum energy consumption cost. They considered a case study of a Chinese company and reported that about 30% of energy consumption was reducible using the proposed heuristic algorithm. Referencing a case of large-scale production, they reported that the MILP model and the greedy insertion heuristic algorithm were effective tools for providing accurate and well-informed solutions associated with low energy costs and short uptime for large-scale machines.

2.2.2. Parallel Machines

(Che et al., 2017) investigated an energy-conscious unrelated parallel machine scheduling problem under a TOU electricity pricing scheme in the parallel machine. The electricity price varies throughout the day. They developed an improved continuous-time MILP model for the problem.

2.2.3. Flow Shop

(Bruzzone et al., 2012) considered energy saving in an advanced planning and scheduling system for a flexible flow shop. A mixed-integer programming (MIP) model is built to minimize energy consumption with no change in the sequence of tasks.

(Mansouri et al., 2016) developed a model in the flow shop to optimize energy consumption and makespan using a heuristic model that considered process setup and running times.

2.2.4. Job Shop

(Zhang and Chiong, 2016) introduced the objective of minimizing energy consumption into a typical production scheduling model based on a machine speed scaling framework. They proposed a multi-objective genetic algorithm incorporated with two problem-specific local improvement strategies to solve this bi-objective optimization problem.

2.2.5. Applications of Energy Efficient Sustainable Scheduling

(Wang et al., 2016) conducted a case study of a glass manufacturing company. They investigated a single machine batch scheduling problem with non-identical job sizes in manufacturing for scheduling glass decoration and caramelization. The key resource of the manufacturing process is a furnace, i.e., a batch machine, which is used to accommodate and ceramic glasses. The problem is formulated as an integer programming model. Then, an exact ϵ -constraint method is adapted to obtain the Pareto front. Two heuristic methods are developed to obtain approximate Pareto fronts. Computational experiments on randomly generated instances showed the effectiveness of the methods.

(Zhang, 2018) conducted a study on environment-aware production scheduling for the painting process in the automobile industry. The research employed a multi-objective particle swarm optimization (MOPSO) approach to find a solution to the particulate matter scattering scenario. The idea of the MOPSO is that each particle can be described entirely within its own particulate space using what is called a velocity vector which considers the direction and speed of a particle of paint. Then, the optimization process becomes a trade-off between the current scattering direction of the particle and the best position that it can occupy. The researcher reported that this technique outperformed two other renowned multi-objective approaches from a statistical sense, thus enhancing the utility of green scheduling in reducing environmental effects associated with automobile manufacturing and finishing processes.

(Che et al., 2016) considered a case study of a Chinese company and reported that about 30% of energy consumption was reducible using the proposed heuristic algorithm. Referencing a case of largescale production, reported that the MILP model and the greedy insertion heuristic algorithm were effective tools for providing accurate and well-informed solutions associated with low energy costs and short uptime for large-scale machines.

2.3 Production Scheduling and Maintenance

(Jasiulewicz-Kaczmarek, 2013) addressed the role of maintenance in realizing a company's sustainable production practices. Maintenance has been perceived as a "necessary evil".

However, changes in the manufacturing paradigm toward sustainable development have changed this look at maintenance.

(Zhao and Tang, 2010) considered a single machine with an aging effect and investigated the deterioration scheduling. The processing of jobs and the maintenance activities of the machine are scheduled simultaneously. The objective is to schedule the jobs and the maintenance activities to minimize the makespan. They proposed a polynomial-time algorithm to solve the problem.

(Huang and Yu, 2016) proposed a flow shop scheduling environment that allows multiple identical parallel machines. Appropriately scheduling maintenance activity on parallel machines is necessary to prevent excessive energy consumption and minimize the required makespan for clean production. Saving energy can prevent excessive waste. This study showed that the scheduling problem on parallel machines with deteriorating maintenance activity could be solved efficiently in an environment-friendly and economical way.

2.4 Sustainable Scheduling and Maintenance

(Mirahmadi and Taghipour, 2019) proposed a stochastic mathematical model for a joint production and maintenance operations scheduling problem in a flexible job shop environment in which both traditional and energy-efficient aspects are modeled. The research aimed to minimize the expected makespan in the scheduling problem focusing on

CO2 emissions reduction in an actual workshop where breakdowns can happen at any moment and make machines unavailable for processing operations. The Genetic Algorithm (GA) is applied for the proposed stochastic model to minimize the expected makespan.

(Cui et al., 2019) proposed an integrated production scheduling, maintenance planning, and energy controlling under TOU electricity tariff for a single machine. They aimed to optimize a bi-objective model. The first objective in the study is makespan, to measure the service level, and the second objective is the total energy cost that measures energy sustainability. They solved the model using a heuristic framework. The Pareto frontier can serve as a tool for managers to consider energy cost explicitly in making decisions. It is observed in some scenarios that reducing energy costs will not increase the makespan.

2.5 Speed Scaling Technique

(Fang et al., 2011) introduced the speed scaling technique in a flow shop scheduling problem that considers peak power load, energy consumption, and associated carbon footprint in addition to cycle time.

(Che et al., 2015) developed a MILP model for a single-machine problem with speed scaling scheduling to minimize energy consumption with bounded maximum tardiness.

(Zhang and Chiong, 2016) explicitly introduced the objective of minimizing energy consumption into a typical production scheduling model based on a machine speed scaling framework. A multi-objective GA is proposed with two problem-specific local improvement strategies to solve this bi-objective optimization problem.

CHAPTER 3

INTEGRATED MODEL DEVELOPMENT

3.1 Introduction

This chapter aims to develop a hybrid multi-objective sustainable production scheduling and maintenance planning model in a single machine. This model addresses two objectives: the first is to minimize the production makespan, and the second is to reduce the machine's pollution effects, i.e., gas emissions. Section 3.2 describes the problem, section 3.3 goes over the model's development, and a numerical example of the model is provided in Section 3.4.

3.2 Problem description

This work studies a single-machine scheduling problem in which the machine is not continuously available due to machine degradation, i.e., The machine is subject to breakdown. The time to failure for this machine is subjected to Weibull distribution with scale parameter, θ , and shape parameter, $\beta > 1$. There is a set of jobs $J = \{1, 2, \dots, n\}$, and each job needs to be processed on the machine with the order $I = \{1, 2, \dots, n\}$. There is also a finite and discrete set of speeds $S = \{1, \dots, d\}$ that affect the power consumption,

which will affect the amount of gas emissions. Moreover, every job runs at a particular speed on the machine.

The proposed mathematical model has the following assumptions:

1. A single machine is considered, where only one job can be processed at one time.
2. The machine is subject to breakdown.
3. Preventive maintenance is assumed to be perfect and restores the machine to an as-good-as-new condition. PM is planned to be usage-based maintenance.
4. Corrective minimal repair the machine failure rate to as-bad-as-it-was before the failure.
5. Setup time is not considered.
6. Preemption is not allowed except in breakdowns.
7. Cancellation is not allowed.
8. Jobs are ready at time zero with no precedence constraints.
9. Every job runs at a particular speed on the machine.
10. The machine can't be interrupted for PM unless the job is completely finished. So, a PM action can be scheduled only before the beginning of a new job.
11. Idle time is ignored.

3.2.1. Maintenance Plan

The maintenance plan for this model involves two actions: minimal corrective repair and perfect preventive maintenance. According to (Liao et al., 2017), the machine may fail while processing a job. If the machine fails, it is repaired minimally, and it takes t_r time units. The minimal repair means the machine failure rate after the repair is equal to as bad as it was, i.e., the age of the machine will remain the same as before the failure.

A preventive maintenance action can be performed, and it takes t_{pm} time units only before starting any job to reduce the chance of machine failure, i.e., a job cannot be interrupted for PM. After preventive maintenance, the machine failure is at the minimum level, and the machine is in an as-good-as-new state, i.e., the machine age becomes zero.

The expected number of minimal repairs, $E(O_{[i]})$, during the job i processing time is equal to:

$$E(O_{[i]}) = \int_{a_i}^{b_i} \lambda(t) dt = \left(\frac{b_i}{\theta}\right)^\beta - \left(\frac{a_i}{\theta}\right)^\beta \quad (3.1)$$

Where $\lambda(t)$ denote the failure rate as a function of the machine age, t , of the machine that has Weibull distribution with scale parameter, θ , and shape parameter, β , and a_i denote the

machine age at the beginning of job i processing and b_i is the machine age at end of job i processing.

3.2.2. Speed Scaling

According to (Sharma et al., 2015) "Changing the operating speeds of the machines is perhaps the most straightforward method to change the peak load and energy consumption".

Machine age at the beginning of job i processing is equal to:

$$a_i = b_{i-1}(1 - w_i) \quad (3.2)$$

where w_i is a binary variable equals 1 if maintenance is done before job i , 0 otherwise.

Adjusting the speed of the machine affects both processing time and energy consumption. At a higher speed, the processing time will be shortened; however, energy consumption will increase. The increase in energy consumption is because that machine deteriorates faster when it works at a higher speed.

With nominal speed, v_{nom} , the machine age at the end of job i is:

$$b_i = a_i + \sum_{j \in J} \sum_{s \in S} X_{jis} \frac{p_j}{v_{snom}} v_s \quad (3.3)$$

Where X_{jis} is a binary variable equals 1 if job j is the i th job processed with speed s , and 0 otherwise.

In the latter equation, Eq. (3.3), the higher the speed, the older the machine is, the higher the failure rate.

3.3 Development of the model

Now, we can develop the integrated model of production scheduling and maintenance planning along with sustainability considerations. The objective is to minimize makespan and carbon emissions by simultaneous scheduling of jobs sequence and PM assignments.

3.3.1. Model notations

The following table shows the notations of this model.

Table 3.1 Notations of the model

Sets/Indices
j : job number; $j \in 1, 2, \dots, n$.
i : job order; $i \in 1, 2, \dots, n$.
s : machine speed index; $s \in S$.
Parameters
P_j : processing time of a job at nominal speed.
$v(s)$: speed factor of the machine.
q_s : power consumption during processing time in Kw at speed s .
P_{js} : processing time of job j at speed s .
ϵ : carbon footprint per unit of electricity consumed (kg CO ₂ equivalent to kWh).
G_{max} : the carbon footprint of the schedule.
t_r : minimal repair time when machine fails
t_{pm} : preventive maintenance time
β : Weibull shape parameter = 2
θ : Weibull scale parameter = 50
Decision variables
X_{jis} : equal to 1 if job j is the i th job processed with speed s , and 0 otherwise.
w_i : equal to 1 if maintenance is done before job i , 0 otherwise
$E(C_i)$: the expected completion time of the i th job processed
C_{max} : the maximum completion time of jobs (Makespan)
$E(O_{[i]})$: the expected number of minimal repairs during job i processing time

3.3.2. Production scheduling model

Considering the production scheduling model for a single machine where the machine is always available with no breakdown. The objective related to production in our model is the makespan, i.e., the maximum completion time of all jobs in the schedule:

$$C_{max} = \max(C_{[i]}) \quad (3.4)$$

With no preemption, the basic mathematical model can be expressed mathematically as follows:

$$\text{Minimize } C_{max}$$

Subject to

$$\sum_{i=1}^n X_{j,i} = 1, \quad j = 1, 2, \dots, n \quad (3.5)$$

$$\sum_{j=1}^n X_{j,i} = 1, \quad i = 1, 2, \dots, n \quad (3.6)$$

$$X_{ji}: \text{ binary variables} \quad (3.7)$$

Eq. (3.5) ensures that each position in the scheduling sequence can only receive one job, while Eq. (3.6) indicates that each job can be assigned to one position in the scheduling sequence.

3.3.3. Joint Model

The joint model integrates production scheduling, maintenance planning, and sustainability considerations. The objective is to minimize makespan and carbon emissions by simultaneously scheduling the jobs and deciding on when to do PM.

The completion time for each job is affected by:

1. The completion time of the previous job.
2. The processing time of the current job.
3. The expected time for repairing a potential failure.
4. Time for performing preventive maintenance.

Thus, considering these influences, the expected value of completion time of job i can be constructed as:

$$E(C_{[i]}) = E(C_{[i-1]}) + \sum_{j=1}^n \sum_{s \in S} X_{jis} * P_{js} + t_r E(O_{[i]}) + t_{pm} w_i \quad (3.8)$$

Model Formulation

Two types of objective functions are considered: technical objective and environmental objective. The technical objective is to minimize the makespan, while the environmental objective is to minimize the carbon footprint of the schedule. The mathematical formulation of the integrated model is as follows:

$$\text{Minimize } C_{max}$$

$$\text{Minimize } G_{max}$$

Subject to:

$$C_{max} \geq E(C_{[n]}) \quad (3.9)$$

$$E(C_{[1]}) = \sum_{j=1}^n \sum_{s \in S} X_{j1s} * P_{js} + t_r E(O_1) + t_{pm} w_1 \quad (3.10)$$

$$E(C_{[i]}) = E(C_{[i-1]}) + \sum_{j=1}^n \sum_{s \in S} X_{jis} * P_{js} + t_r E(O_{[i]}) + t_{pm} w_i \quad (3.11)$$

$$\sum_{i=1}^n \sum_{s=1}^d X_{j,i,s} = 1, \quad j = 1, 2, \dots, n \quad (3.12)$$

$$\sum_{i=1}^n \sum_{s=1}^d X_{j,i,s} = 1, \quad i = 1, 2, \dots, n \quad (3.13)$$

Eq. (3.12) ensures that each position in the scheduling sequence can only receive one job at one specific speed. Eq. (3.13) indicates that each job can be assigned to one position at a particular speed in the scheduling sequence. Eqs. (3.12) and (3.13) together ensure that each job is processed with only one speed.

$$\sum_{j=1}^n \sum_{i=1}^n \sum_{s \in S} \epsilon \cdot q_{js} \cdot P_{js} \cdot X_{jis} \leq G_{max} \quad (3.14)$$

Eq. (3.14) ensures that the carbon footprint of the schedule is less than the allowable limit, G_{max} .

$$s_{nom} = s_2 \quad (3.15)$$

$$X_{jis}, w_i \text{ are binary variables} \quad (3.16)$$

3.4 A Numerical Example and Results

A numerical example is provided to illustrate the integrated model application. GAMS software was used to solve the model.

Table 3.2 Parameters of the model

ϵ :	carbon footprint per unit of electricity consumed = 0.218 kg CO2 equivalent to kWh
t_r :	minimal repair time when the machine fails = 4 hours
t_{pm} :	preventive maintenance time = 15 hours
β :	Weibull shape parameter = 2
θ :	Weibull scale parameter = 50

There are three jobs with the following processing times (hours):

Table 3.3 Processing time of jobs

Jobs	J1	J2	J3
processing time	15	20	15

These jobs can be processed at three different speeds on the machine as shown in the following table:

Table 3.4 Inputs of the numerical example (Wang, 2019)

Speed Factor	Power (KW)
$V(s1) = 57$	43
$V(s2) = 127$	95
$V(s3) = 422$	315

3.4.1 Multi-objective scenario

Multi-objective approaches are necessary for models that have conflicting objectives. They can help decision-makers in complex decision-making situations and trade-off analysis. Minimizing carbon footprint and makespan are conflicting objectives. (Mansouri et al., 2016) showed the conflict between energy consumption and makespan in a flow shop scheduling problem as demonstrated below.

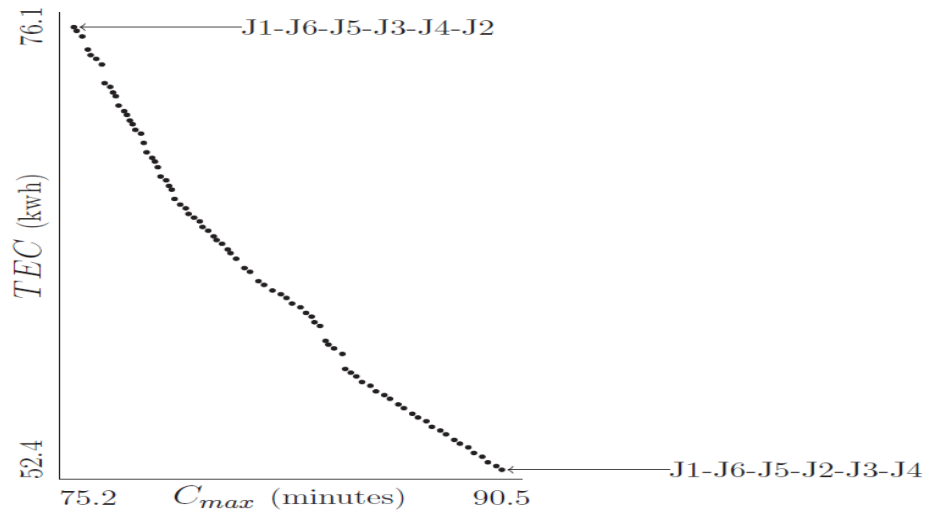


Figure 3.1 Conflict between energy consumption and makespan (Mansouri et al., 2016)

- **The multi-objective weighted sum technique**

In this scenario, we aim to minimize makespan and gas emissions simultaneously. The weighted sum technique is applied for different weights of the objectives. Results are shown in the following table:

Table 3.5 Results of The Weighted Sum Method

Makespan Weight	Carbon Weight	Makespan	Carbon
0.01	0.99	79.36	1033.3
0.02	0.98	79.36	1033.3
0.03	0.97	79.36	1033.3
0.04	0.96	79.36	1033.3
0.05	0.95	79.36	1033.3
0.06	0.94	79.36	1033.3
0.07	0.93	79.36	1033.3
0.08	0.92	79.36	1033.3
0.09	0.91	79.36	1033.3
0.1	0.9	79.36	1033.3
0.11	0.89	79.36	1033.3
0.12	0.88	79.36	1033.3
0.13	0.87	79.36	1033.3
0.14	0.86	79.36	1033.3
0.15	0.85	79.36	1033.3
0.16	0.84	79.36	1033.3
0.17	0.83	79.36	1033.3
0.18	0.82	79.36	1033.3
0.19	0.81	79.36	1033.3
0.2	0.8	79.36	1033.3
0.21	0.79	79.36	1033.3
0.22	0.78	79.36	1033.3
0.23	0.77	79.36	1033.3
0.24	0.76	79.36	1033.3
0.25	0.75	79.36	1033.3
0.26	0.74	79.36	1033.3
0.27	0.73	79.36	1033.3

0.28	0.72	79.36	1033.3
0.29	0.71	79.36	1033.3
0.3	0.7	79.36	1033.3
0.31	0.69	79.36	1033.3
0.32	0.68	79.36	1033.3
0.33	0.67	79.36	1033.3
0.34	0.66	79.36	1033.3
0.35	0.65	79.36	1033.3
0.36	0.64	79.36	1033.3
0.37	0.63	79.36	1033.3
0.38	0.62	79.36	1033.3
0.39	0.61	79.36	1033.3
0.4	0.6	79.36	1033.3
0.41	0.59	79.36	1033.3
0.42	0.58	79.36	1033.3
0.43	0.57	79.36	1033.3
0.44	0.56	79.36	1033.3
0.45	0.55	79.36	1033.3
0.46	0.54	79.36	1033.3
0.47	0.53	79.36	1033.3
0.48	0.52	79.36	1033.3
0.49	0.51	79.36	1033.3
0.5	0.5	79.36	1033.3
0.51	0.49	79.36	1033.3
0.52	0.48	79.36	1033.3
0.53	0.47	79.36	1033.3
0.54	0.46	79.36	1033.3
0.55	0.45	79.36	1033.3
0.56	0.44	79.36	1033.3

0.57	0.43	79.36	1033.3
0.58	0.42	79.36	1033.3
0.59	0.41	79.36	1033.3
0.6	0.4	79.36	1033.3
0.61	0.39	79.36	1033.3
0.62	0.38	79.36	1033.3
0.63	0.37	79.36	1033.3
0.64	0.36	79.36	1033.3
0.65	0.35	79.36	1033.3
0.66	0.34	79.36	1033.3
0.67	0.33	79.36	1033.3
0.68	0.32	79.36	1033.3
0.69	0.31	79.36	1033.3
0.7	0.3	79.36	1033.3
0.71	0.29	79.36	1033.3
0.72	0.28	79.36	1033.3
0.73	0.27	79.36	1033.3
0.74	0.26	79.36	1033.3
0.75	0.25	79.36	1033.3
0.76	0.24	79.36	1033.3
0.77	0.23	79.36	1033.3
0.78	0.22	79.36	1033.3
0.79	0.21	79.36	1033.3
0.8	0.2	79.36	1033.3
0.81	0.19	79.36	1033.3
0.82	0.18	79.36	1033.3
0.83	0.17	79.36	1033.3
0.84	0.16	79.36	1033.3
0.85	0.15	79.36	1033.3

0.86	0.14	79.36	1033.3
0.87	0.13	79.36	1033.3
0.88	0.12	79.36	1033.3
0.89	0.11	79.36	1033.3
0.9	0.1	79.36	1033.3
0.91	0.09	79.36	1033.3
0.92	0.08	73.22	1034.62
0.93	0.07	73.22	1034.62
0.94	0.06	73.22	1034.62
0.95	0.05	73.22	1034.62
0.96	0.04	73.22	1034.62
0.97	0.03	61.8	1035.5
0.98	0.02	61.8	1035.5
0.99	0.01	61.8	1035.5

From the table, we can see that the minimum carbon footprint is 1,033.3 kg CO₂ when we have job 1 processed at position 3 at speed 3 and when we process job 2 at position 2 with speed 3 while job 3 is processed at position 1 at speed 3.

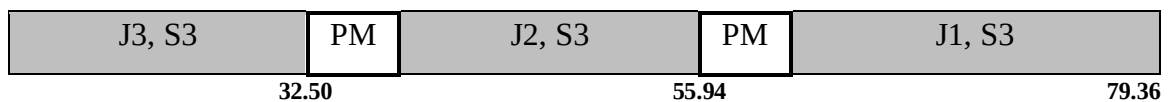


Figure 3.2 Job sequence for minimum gas emission = 1033.3

The minimum makespan (61.8 h) in the Pareto front is illustrated in the following Gantt chart:

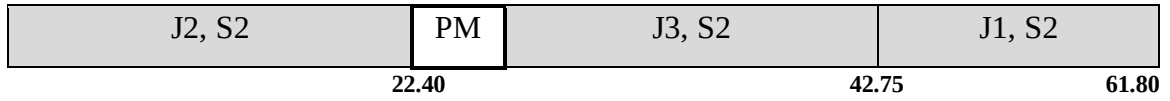


Figure 3.3 Job sequence for minimum makespan, gas emission = 1035.5

3.5 Sensitivity Analysis

We analyzed the single objective model compared to the multiple objective model. In addition, we investigated the example using a traditional production scheduling model without maintenance planning.

3.5.1 Single Objective scenario

In this scenario we mainly aim to minimize makespan while considering gas emission as a constraint Eq. (3.14). Trying different bounds for gas emissions, we derived the following results:

Table 3.6 Results of Single Objective Scenario

Carbon Footprint	Makespan
1,033.0	0.00
1,033.1	0.00
1,033.2	0.00
1,033.3	0.00
1,033.4	79.36

1,033.5	79.36
1,033.6	79.36
1,033.7	79.36
1,033.8	79.36
1,033.9	79.36
1,034.0	76.29
1,034.1	76.29
1,034.2	69.24
1,034.3	69.24
1,034.4	69.24
1,034.5	69.24
1,034.6	69.24
1,034.7	69.24
1,034.8	69.24
1,034.9	69.24
1,035.0	69.24
1,035.1	69.24
1,035.2	69.24
1,035.3	69.24
1,035.4	69.24
1,035.5	65.77
1,035.6	61.8
1,035.7	61.8
1,035.8	61.8
1,035.9	61.8
1,036.0	61.8
1,036.1	61.8
1,036.2	61.8
1,036.3	61.8
1,036.4	61.8
1,036.5	61.8
1,036.6	61.8
1,036.7	61.8
1,036.8	61.8
1,036.9	61.8
1,037.0	61.8
1,037.1	61.8
1,037.2	61.8
1,037.3	61.8

The table shows that the minimum makespan is 61.8 hours, which is the same value found by the weighted sum method. The minimum carbon footprint is 1,033.4 kg CO₂. This scenario provides a wider Pareto front, including:

Table 3.7 Pareto Front for the single objective scenario

Carbon Footprint	Makespan
1,033.4	79.36
1,034.0	76.29
1,034.2	69.24
1,035.5	65.77
1,035.6	61.8

3.5.2 Production Scheduling Model Without Maintenance Planning

Assume the machine is always available for processing jobs during the planning time horizon), there are no machine breakdowns and maintenance time and no change in gas emissions rate during processing time.

However, in reality, the machine will degrade with increased usage and age. As the machine reaches the maintenance threshold after 32.8 hours (Liao et al., 2017), at least one machine failure occurs. The time for replacement is 15.

Let us compare this scenario with the joint model case in figure 3.3. Figure 3.4 demonstrates a traditional production scheduling model without maintenance planning.

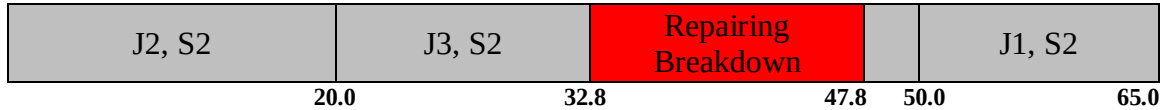


Figure 3.4 Production scheduling model without maintenance planning

Makespan resulting = 65.0, while carbon footprint will equal to 1,035.5 Kg CO₂.

The comparison between this scenario without maintenance and our joint model is depicted in the following table:

Table 3.8 comparison between No maintenance model and joint model

Benchmark	NO maintenance	Joint Model	Save of Joint model
Cmax	65	61.8	4.9 %
Gmax	1035.5	1035.5	

Hence, it is obvious that this scenario performs much worse than the one obtained by our proposed scheduling model. Our proposed scheduling model should be much more effective than the one without maintenance planning. As maintenance is a much more

comprehensive operation than repair, perhaps corresponding to replacing several machine's key components, maintenance planning must be considered into production scheduling models.

CHAPTER 4

CONCLUSION

4.1 Introduction

In this chapter, we discuss the summary of the thesis. Section 4.2 provides a conclusion of the proposed model developed. Section 4.3 presents the suggested extensions for future research.

4.2 Summary

An integrated multi-objective sustainable production scheduling and maintenance planning model is developed. This model addresses two objectives: the first objective is to minimize the makespan, and the second objective is to minimize the gas emissions. The weighted-sum method is used to generate the Pareto frontier, and GAMS software with the LINDO solver is used to solve the model and analyze the results. A case study from the literature is utilized to demonstrate the applicability and effectiveness of the integrated model. A sensitivity analysis is performed by changing the values of some parameters of the model to gain additional managerial insights.

There is a conflict between makespan and carbon footprint, where minimization of one objective is only achieved by increasing the value of the other objective. The lowest carbon footprint is found when jobs are processed at the highest speed. Table 3.9 shows that the least total energy consumption for each job happens at the highest speed since it has the least power to speed ratio. This results in lowest carbon footprint since it is proportional to the energy consumption.

While the least makespan is found when jobs are processed at the nominal speed, the expected time for repairing a potential failure at the highest speed is relatively long compared to the nominal speed. In addition to that, more PM assignments are needed at the highest speed making the makespan even longer.

Table 3.9 Processing time and energy consumption for jobs

			processing time			Energy consumption (KWh)		
Speed Factor	Power (KW)	Power/Speed	J1	J2	J3	J1	J2	J3
57	43	0.754386	33.42	44.56	33.42	1437.11	1916.14	1437.11
127	95	0.748031	15	20	15	1425	1900	1425
422	315	0.746445	4.514218	6.018957	4.514218	1421.979	1895.972	1421.979

This model emphasizes the interrelationship between the three aspects of production scheduling, maintenance planning, and environmental sustainability. The lack of coordination among these aspects would result in significant production losses. The absence of maintenance resulted in a higher cost compared to our joint model, as the sensitivity analysis shows in table 3.8. In comparison, neglecting environmental aspects conflicts with today's environmental production awareness, resulting in energy-related costs and taxes imposed by regulatory agencies.

4.3 Future Extensions

This work has several potential extensions; one clear extension of this single machine model is to consider other machine environments, for instance, parallel machines and job shops. The model can be extended to other maintenance plans, such as predictive maintenance. The literature can be enriched by measuring other objective functions such as minimizing lateness or flow time in the production part and minimizing noise in the environmental aspect. Other saving energy techniques can be tried, such as time of use tariff and turn on and off mechanism. Idle time can be considered in an extended work for real practice operations. The analogous Preempted schedule of our work can be investigated.

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