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RESEARCH PAPER

Model of Flow Shop Scheduling Problems Considering Multi-Item Testing Operations, Multiple Due Dates, And Sequence Dependent Setup Times

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ABSTRACT

Technological advancements have fueled heightened competition in manufacturing, compelling companies to adopt strategies prioritizing swift, timely, and high-quality customer service. This necessitates seamless integration of supportive systems such as resources, equipment, facilities, and workforce, underscoring the criticality of scheduling in aligning activities and resources for on-time task completion. Scheduling, inseparable from sequencing, is pivotal in optimizing manufacturing and service industries' operations. However, challenges arise when tasks converge with limited facility capacities, necessitating effective resource allocation. By leveraging mathematical techniques and heuristic methods, scheduling optimizes resource utilization, minimizes production costs, and enhances service quality. Despite its significance, existing models often overlook critical aspects like identical job consideration and sequence-dependent setup times, limiting real-world applicability. This research addresses these gaps by proposing robust mathematical models for intricate scheduling requirements. The proposed approach seeks to optimize manufacturing operations by effectively handling complex scheduling needs, thereby minimizing production costs and enhancing operational efficiency. This research endeavors to develop and implement a robust mathematical model and an efficient problem-solving algorithm for optimizing flow shop scheduling considering Multi-Item Testing Operations, Multiple Due Dates, And Sequence Dependent Setup Times on the complex requirements in real-world scenarios.

KEYWORDS: Scheduling; Flowshop; Due dates; Setup time.

1. Introduction

Technological advancements have made manufacturing companies increasingly competitive. To surpass their competitors, companies must have a strategy that prioritizes meeting customer needs quickly, on time, and with quality [1]. This plan can work well if supporting systems such as resources, equipment, facilities, and workforce are well integrated. Scheduling, which involves adjusting activities and resources to complete work on time, is crucial in the manufacturing and service industries. Scheduling cannot be separated from sequencing, which determines the order in which work must be done [2]. Scheduling can be problematic if tasks come together at a particular time and the company's facilities are limited.

Scheduling is a good measuring tool for aggregate planning. Actual orders at this stage will be first assigned to specific resources such as facilities, labour, and equipment. Then, work sequencing is carried out at each processing centre to optimize the existing capacity utility. The scheduling process includes allocating facilities, equipment, and labour for operational activity [3]. It is always related to allocating existing resources over a certain period and is a decision-making process that aims for optimization. Decision-making to improve service quality must consider various points of view, both from outside and within the company environment. In scheduling, the goal is to achieve maximum profitability. It is a decision-making process that plays a vital role in manufacturing. After all schedules have been prepared, all sources of raw materials and

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necessary resources must be available at the time determined jointly by production planning [4].

The manufacturing industry uses scheduling in procurement and production, transportation and distribution, and information processing and communications. The scheduling process uses mathematical techniques or heuristic methods to allocate limited resources to existing tasks [5],[6],[7]. Proper resource allocation enables the manufacturing industry to optimize and achieve its goals, such as minimizing the time to complete all work, minimizing the number of late tasks, and so on [8].

Other goals are to minimize processing times, subscription lead times, inventory levels, and efficient use of facilities, labour, and equipment. Scheduling takes into account various existing limitations. Good scheduling will have a positive impact, specifically lower operating costs and delivery times [9]. Some scheduling objectives, which are also adopted by the manufacturing industry, are increasing resource use or reducing waiting time so that total process time can be reduced and productivity increases—reducing the inventory of half-finished goods or reducing the number of jobs waiting in queues while resources are still working on other tasks [10], [11]. Reduce some delays on work that has a completion time limit so that it will minimize delay costs. It helps make decisions regarding factory capacity planning and the type of capacity needed so that expensive additional fees can be avoided.

Production scheduling is the process of allocating existing resources or machines to carry out a set of tasks within a certain period [12]. Production scheduling is critical in companies that use a make-to-order system, where new products will be produced according to consumer demand [13]. On average, manufacturing companies with an Make to Order production system have dynamic demand. This makes it difficult for production parties to make production plans. This difficulty causes frequent delays, and the available resources cannot be used optimally [14]. Companies need good planning to avoid these delays. Scheduling is ordering product manufacturing or processing on several machines [15]. The goal of scheduling is to increase resource use, reduce the inventory of semi-finished goods or the number of jobs waiting in queues, and reduce delays in work with a completion time limit [16].

Forward scheduling is a sequence of jobs starting from time zero and then moving forward to the due date [17]. This scheduling will be feasible but will not meet the due date. Meanwhile, backward scheduling can meet due dates. Scheduling operations on the production floor is one of the critical problems in planning and managing manufacturing processes [18]. The problem of operations scheduling (job scheduling) focuses on how to allocate limited production resources (machines) to carry out processes on a series of operational activities (jobs) in one time period to optimize certain objective functions [19]. According to Pinedo, "Finding the best operations schedule can be a relatively easy or difficult task, depending on the type of production floor, technical limitations of the manufacturing process, and performance criteria."

The scheduling optimization that will be carried out to support time to market for the industrial world (manufacturers and importers) of products, which, based on the product's characteristics, is included in the job fellowship. Fellowship is one of the most frequently studied job scheduling problems. In fellowship job scheduling, several jobs are processed in a series of operational stages [20], [21]. All jobs are processed in a one-way process flow, starting from a series of stages and continuing to a series of m stages. In the fellowship model, each operational stage only has one machine unit. However, practical conditions in production lines do not use one machine unit at each stage of operation. So, the fellowship model is often modified by placing several parallel identical machines at each stage of operation [22], [23].

Based on several studies, a development model for fellowship machines is needed to consider sequence-dependent setup times, identical jobs, multi-due dates, multi-item, and priority jobs to solve problems. Through this research, we can develop research models such as those intended to solve problems in natural systems.

2. Literature Review

2.1. Research position

According to the Dessouky research model for flow shop scheduling problems with uniform parallel machines and identical jobs, this research model aims to minimize the time span for similar jobs. The limitation of this model is that it needs to consider the existence of multiple due dates for each scheduled job. The expected due date is used [24].

According to the Arabameri research model regarding flow shop scheduling problems without waiting time, the primary constraint is sequence-dependent setup times [25]. This research uses a solving method, Tabu Search, and particle swarm optimization. A limitation of this research in describing a natural system is that identical jobs are not considered in job scheduling. This model explicitly assumes that the jobs in the scheduling process are non-identical. However, in a natural system, identical jobs may exist in the existing scheduling.

Another model that needs to consider the possibility of similar employment in scheduling is the research model of Nogueira [26], regarding the problem of scheduling parallel machines with unequal functions and capabilities to minimize the total earliness and tardiness penalties. Solving this model uses Hybrid Greedy Randomized Adaptive Search Procedure (GRASP) Heuristics.

Research model Kyparisis priority index sequence rules for scheduling with time-dependent job processing times. This model explains that scheduling is processed earlier for jobs with a high priority than for jobs that are not prioritized [27]. The aim of this research is twofold. The first objective is to investigate the possibility of identifying a priority index rule to minimize makespan. The second objective is to determine the objective function of job family time completion in general, which can be minimized using priority index rules.

According to Zhao, flow shop scheduling is characterized by a unidirectional process flow for each job type [28]. The methods usually assume that the operation setup is independent of the work order and is included in the processing time. Meanwhile, the conditions found in several industries are a different machine setup time for each job change, affecting the scheduling sequence.

Hsu stated scheduling problems in sequence-dependent setups occur in several production systems [29]. When a machine is used to process various types of products, setup time and costs can arise due to changing product types. If machine setup is carried out frequently and the time is long enough, then, of course, it will affect scheduling. Consequently, we have to consider the influence of machine setup on scheduling.

Tab. 1. Research gap

Author	Gap
Dessouky (1998)	The model doesn't consider multiple due dates for each scheduled job, which is crucial in real-world scenarios where different jobs may have different deadlines.
Arabameri (2018)	This model limitation lies in its assumption that jobs are non-identical, overlooking the presence of identical jobs that are common in natural systems.
Nogueira (2014)	This model needs to better account for the presence of similar jobs in the scheduling process.
Kyparisis (2013)	The model needs to address the practical aspect of sequence-dependent setup times in the context of identical or similar jobs.
Zhao (2018)	This model doesn't consider that machine setup times can vary with each job change, which significantly impacts scheduling efficiency.
Hsu (2019)	The model does not provide a comprehensive solution for minimizing these impacts in a scheduling context.
This Research (2024)	1. Build a robust mathematical model for flow shop scheduling that can effectively handle the complex scheduling requirements in the field, particularly those related to scheduling testing operations for multiple items, multiple due dates, sequence-dependent setup times, and priority jobs. 2. Develop an efficient problem-solving algorithm in the form of a testing operation scheduling optimization system that focuses on minimizing production costs. 3. Implement the flow shop scheduling optimization algorithm in real-world scenarios, where its effectiveness can be evaluated and improved.

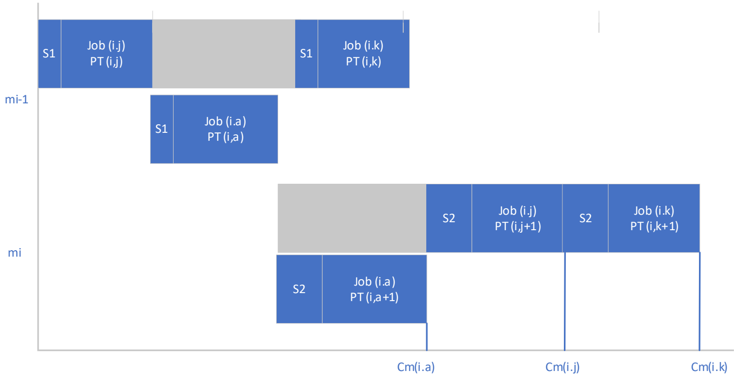

Fig. 1. Conceptual model

2.2. Basic concepts of scheduling

Baker states that in production planning, two functions are known to be interrelated: the planning function and the scheduling function [12]. The planning function has attention to the following problems:

1. What products or services must be provided?
2. How many of these products or services must be provided?
3. What resources must be provided to deliver these products and services?

Scheduling function can be applied when the required tasks are available. In practice, the planning and scheduling functions must be distinct.

According to Baker, scheduling allocates resources for tasks based on time [12]. Meanwhile, Fogarty defines scheduling as the activity of making schedules, both Master Production Schedules, factory floor schedules, maintenance schedules and so on [30]. Meanwhile, Morton and Pentico state that scheduling is organizing, selecting, and determining the time to use resources to produce a certain amount of output at a particular time by meeting the constraints of time and resource availability [17].

According to Schroeder, scheduling is a guide or indication of what to do, with whom, and with what equipment to use to complete a job at a particular time [30].

Pinedo states that scheduling is always related to allocating existing resources at a certain period; it is a decision-making process whose goal is optimality [19].

Scheduling can be a source of problems if orders come simultaneously at a particular time while the facilities owned by the company are limited. If this happens, the priority rule will be applied [32]. To make scheduling, data is needed, including the type and number of jobs to be processed, the order of dependence between production processes, the operating time for each operation, and the facilities required by each operation. From these inputs, the resulting scheduling is a sequence of jobs to be scheduled.

To schedule well, companies need production planning and control to use production facilities efficiently. Thus, the required production planning and control include the following:

1. Create a list of incoming orders, considering production capacity.
2. Before the order is produced, check the availability of raw materials.
3. Set a time limit for the work and supervise when production is in progress.
4. From the ongoing production activities, make a report as feedback.
5. Supervise the efficiency of the production process.

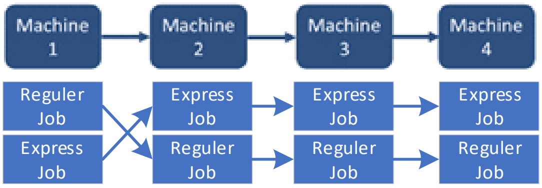

Fig. 2. Flow shop scheduling with express job

Figure 2, a series of machines is arranged sequentially to test a product with variations. In manufacturing sectors, including automobile production, pharmaceuticals, printing, and chemical manufacturing, setup times for tasks such as cleaning, testing and equipment

replacement are significantly influenced by the sequence of machine operations [33].
Each machine has different production capabilities in processing the tested product, and the processing time and setup time required for each machine are not necessarily the same. The setup time is zero if two products with the exact dimensions are tested on the same machine. The orders arrive randomly, and it is impossible to predict the day of arrival or the number of products to be tested.
When a product is tested, it is considered a regular job. The consumer who carries out the test receives the results according to the due date determined by the order arrival time. The costs incurred are the standard testing costs, which are included in the production costs and are based on the testing time required to process the product. If there is a delay in processing the product, the additional costs incurred due to the delay are added to the production costs.
A consumer requesting a new product not included in the previous testing schedule is considered an "express job." This job is prioritized and included in the ongoing scheduling, and an express fee is charged to the consumer. The express fee is based on the order completion time before the specified due date, and the standard testing costs are based on the testing time required to process the product. This express fee is a deduction from the production costs and is considered additional profit. If an express job comes after a regular job is done, then the express job needs to be done immediately.

3. Method

The stages of the research are described as follows:

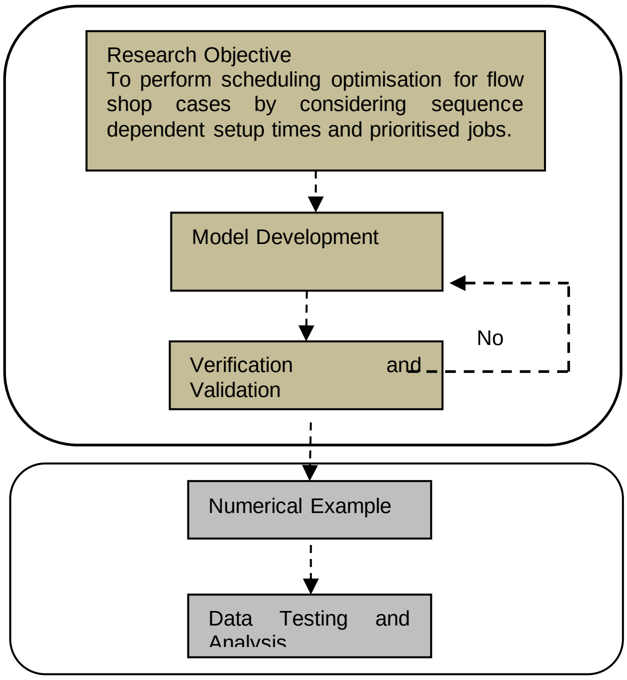

Fig. 3. Methodology Research

a. Basic Research Model

The model used in this research consists of several fellowship studies, including Dessouky, which considers identical jobs and uniform parallel machines, and Arabameri, which considers sequence-dependent setup times. Meanwhile, the Kyparisis model considers the job priority index a scheduling sequence.

b. Proposed Model

This stage prepares a general problem-solving framework to form the proposed model. The proposed model formulation regarding the flow shop scheduling problem is expressed as Integer Non-Linear Programming (INLP), and these models aim to present exact solutions. [34]. This formulation is compiled into the Lingo 18.0 software format for searching for solutions. In finding a solution, it is necessary to determine scheduling in order of index priority jobs to process priority jobs first by minimizing sequencing, which results in significant delays. The formation of the proposed model is carried out by considering the reference models used.

c. Numerical Testing

Numerical testing is carried out to test the algorithm developed using actual data.

d. Analysis

The analysis is carried out to interpret the results of the numerical tests that have been carried out. The solution comes from processing Gant chart data showing machine work scheduling. In this section, we will also examine further the results of the data processing that has been carried out. At this stage, a comparison of the algorithms developed is carried out on factors such as blocking machines, sequence-dependent setup time, and online scheduling, which influence late work.

4. Results

4.1. Assumptions model used

This model is a job scheduling model with Multi-Item Testing Operations, Multiple Due Dates, with Sequence-Dependent Setup Times. This model has several assumptions as follows:

1. The machine is always available, and there is no damage or maintenance to the machine.
2. All jobs can be processed without defects (errors).
3. There are no interruptions to the job being processed
4. There is a priority for each job so that there are express and regular jobs.
5. Job transfer time between machines is 0 (zero).
6. Machines arranged in series are not identical, both in terms of capability and production speed.No two or more jobs are carried out on the same machine simultaneously.
7. Sequence-dependent setup occurs between jobs. Setup starts when the job exists.
8. The priority job in this model is one job.

4.2. Notation used

The notation used in the development of the mathematical model is :

Indices and Sets

a, j,k job index (a, j, k $\in$ J)

i machine set

A regular job subset

B job express subset

Parameter

n actual number of jobs

m number of machines (unit)

$P_{i(a,j,k)}$ processing time of job a, j, k on machine i (hr)

$ST_{i(a,j,k)}$ setup time of job a,j, k on machine i (hrs)

$d_{a,j,k}$ due date job a, j ,k

w_j' job j earliness penalty for each unit of earliness time

w_j'' job j tardiness penalty for each unit of tardiness time

Decision Variable

TC Total Cost

C_{ij} completion time of job j on machine i (hr)

E_j earliness job j

E_a earliness job a (hr)

T_j tardiness job j

$C_{i(a,j,k)}$ completion time for job a, j, k at machine i (hrs)

$C_{m(a,j,k)}$ completion time job k at machine i (hrs)

Binary Variable

X_{ia} 1, if job a is job priority. 0, otherwise.

y_{jk} 1, if job k process after job j. 0, otherwise

4.3. Problem definition

a. Scheduling in this study is a type of flow shop scheduling where a set of n jobs are ready to be processed on a set of i machines, where m machines are fellowships that process on all jobs must pass through machine 1, machine 2, machine k in order completion.

b. In this flow shop scheduling, each job has its own setup time S_{ijk}, processing time P_{jk}, and due date d_j. For each machine, the processing time between machine 1, machine 2, and machine m has an unequal processing time P_{jk} for each job based on the product and the setup time S_{ijk}. When the process of a job starts on the first machine, it cannot be interrupted until the process is on the next machine. The processing time P_{jk} for each product is different because the more significant the product, the longer the processing time on the same machine.

c. The problem in flow shop scheduling is related to scheduling a job j assignment on machine i, which aims to minimise production costs.

d. Production cost is the sum of regular cost plus tardiness cost minus express cost.

e. Regular cost is the total amount of process time for each job multiplied by the process cost charged for each unit of time.

f. Tardiness cost is the time difference between completion time minus due date multiplied by the tardiness fee charged for each unit of time.

g. Job j on machine i must have been completed to be able to work on job k on machine i.
h. If a job has been released, it must be done to completion (non-preemptive).
i. Setup time exists if the products being worked on are different from the products. This can be determined if the value of product processing time between one product and another is different; then, there is no setup time between these products.
j. Job delay (tardy) occurs if the job being done exceeds the due date
k. Earliness job (acceleration) if the job is done faster than each job's due date.

4.4. Model component

Objective Function

$$\mathrm{MIN} = \mathrm{TC} \tag{1}$$

Model 1 is the objective function for minimizing the total production cost.

$$\mathrm{TC} = \left(\sum \text{regular cost} + \sum \text{penalty cost}\right) - \sum \text{ekspress cost} \tag{2}$$

Model 2 is the summation of the total regular costs incurred for each job, added to the total penalty costs for each job experiencing tardiness, minus the total express costs for each job prioritized for processing.

$$\text{Regular cost} = \sum \text{Pij} \times \text{operational cost} \tag{3}$$

Model 3 is the cost function charged to each job based on the processing time multiplied by the cost required to process the job per unit of time.

$$\text{Penalty cost} = \sum \mathrm{T(j)} \times \text{tardiness cost} \tag{4}$$

Model 4 is the cost charged to jobs that experience tardiness based on the duration of the delay multiplied by the cost required to process the job per unit of time.

$$\text{Ekspress cost} = \sum \mathrm{E(a)} \text{ x earliness cost} \tag{5}$$

Model 5 is the cost charged to jobs that experience acceleration based on the duration of earliness multiplied by the cost required to process the job per unit of time.

Constraints

$$C_{ia} \geq (ST_{ia} + p_{ia}) \times X_{ia} \tag{6}$$

Model 6 is a constraint that ensures that the completion time of job a on machine i is greater than or equal to the processing time of job a on machine i plus the setup time of job a multiplied by the binary function of assigning priority jobs.

$$C_{(i-1)a} + ST_{ia} + P_{ia} = C_{ia} \quad i = 1,2,3,\ldots,m \tag{7}$$

Model 7 ensures that the completion time of job a on machine i is equal to the completion time of job a on the previous machine (i-1) plus the processing time of job a on machine i and the setup time of job a on machine i.

$$d_a - C_{ma} \leq E_a \quad a = 1 \tag{8}$$

Model 8 indicates that the difference between the due date of job a and the completion time of job a on machine m is less than or equal to earliness.

$$C_{ik} + M(1 - y_{jk}) \geq C_{ia} + C_{ij} + S_{ik} + ST_{ijk} + p_{ik} \tag{9}$$

$i = 1,2,\ldots,m;\ j,$
$k = 1,2,\ldots,n;$
$j \neq k$

Model 9 ensures that the completion time of job k on machine i, added with the binary assignment function ensuring that job k is processed after job j, is greater than or equal to the completion time of job a. This completion time includes the completion time of job j on machine i plus the processing time of job j on machine i and the setup time of job k, minus the existing setup time if the job being processed is a similar product on machine i, and if job j is the preceding job.

$$C_{(i-1)j} + ST_{ij} + P_{ij} = C_{ij} \tag{10}$$

$i = 1,2,3,\ldots,m;$
$j = 1,\ldots,n$

Model 10 ensures that the completion time of job j on machine i is equal to the completion time of job j on the previous machine (i-1), plus the processing time of job j on machine i and the setup time on machine i.

$$C_{mj} - d_j \leq T_j \qquad j = 1, \dots, n \tag{11}$$

Model 11 indicates that the difference between the completion time of job j on machine m and the due date of job j is less than or equal to the tardiness.

$$\sum_{j \neq k} y_{jk} = 1 \qquad k = 1, \dots, n \tag{12}$$

Model 12 ensures that job j has a successor job k.

$$\sum_{k \neq j} y_{jk} = 1 \qquad j = 1, \dots, n \tag{13}$$

Model 13 ensures that job k has a predecessor job j.

$$y_{jk} = \{0,1\} \qquad j, k = 1,2, \dots, n'; \; j \neq k \tag{14}$$

$$Z_{jk} = \{0,1\} \qquad j, k = 1,2, \dots, n'; \; j \neq k$$
$$C_{ij} \geq 0 \qquad i = 1,2, \dots m; \quad j = 1,2, \dots, n$$
$$E_j \geq 0 \qquad j = 1,2, \dots, n$$
$$T_j \geq 0 \qquad j = 1,2, \dots, n'$$

Model 14 is a constraint for binary variables.

5. Discussion

To test the performance of the proposed model, a case study was simulated using Lingo 18.0 mathematical modelling software. The variables used in the simulation model are based on the following simulated data:

Tab. 2. Simulation parameter

Variable	Parameter
Number of Machine	3 machine
Express Job After	Job 2
Processing Time a	7 hrs
Processing Time b	6 hrs
Processing Time c	6 hrs
Setup Time	1 hrs
Due date	7 days
Reguler Cost	$70
Earliness Cost	$120
Tardiness penalty	$30

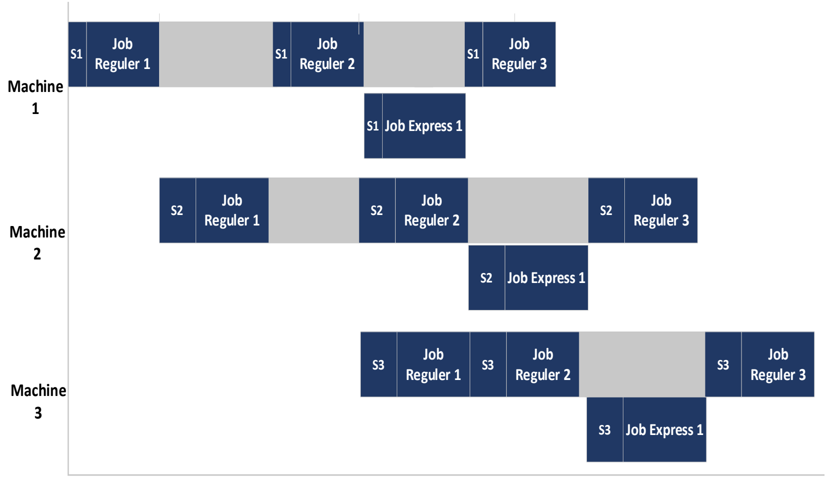

Fig. 4. Gant chart result

Figure 4 is the Gant Chart flow shop scheduling result. Express job simulated exist after job regular 2 is done. All of the express jobs can be completed right on schedule without any waiting time. In regular job 3, there is a delay, resulting in tardiness penalties. After calculating the total costs generated through this simulation experiment, the production cost is $300.

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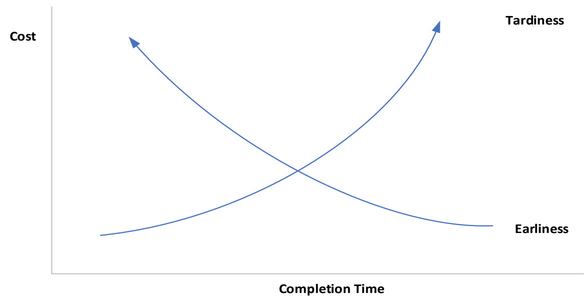

Fig 5. Comparison cost and completion time

Figure 5 expresses that as delay increases with the addition of completion time, it increases cost, while earliness decreases costs. The research shows that the proposed model can address the flow shop scheduling problems by considering multi-item testing operations, multiple due dates, and sequence-dependent setup times. From the analysis and experimentation through mathematical model simulation, job costs can be minimized with this model even when interruptions from express jobs need to be prioritized.

5.1. Sensitivity analysis

Tab. 3. Simulation parameter

Variable	Parameter	
	Case 1	Case 2
Number of Machine	3 machine	3 machine
Express Job After	Job 1	After Job 3
Processing Time a	7 hrs	7 hrs
Processing Time b	6 hrs	6 hrs
Processing Time c	6 hrs	6 hrs
Setup Time	1 hrs	12 hrs
Due date	6 days	8 days
Reguler Cost	$70	$70
Earliness Cost	$120	$120
Tardiness penalty	$30	$30

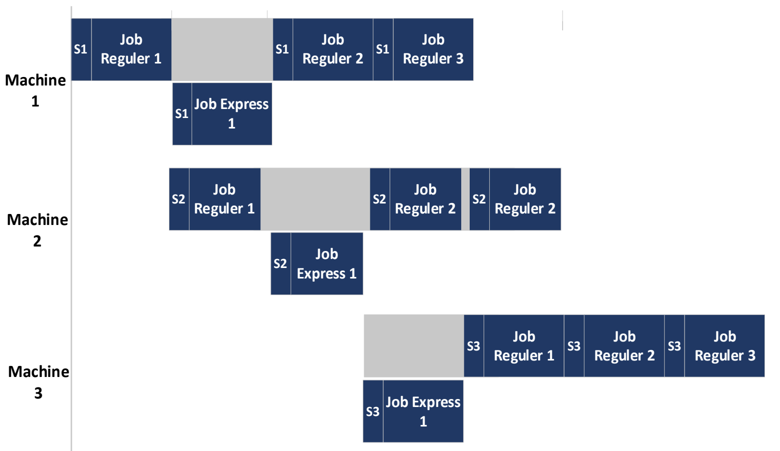

Fig. 6. Gant chart result case 1

Figure 6 is the Gant Chart result for case 1. Express job simulated exist after job regular 1 is done. All of the express jobs can be completed right on schedule without any waiting time. In all regular job, there is no delay.

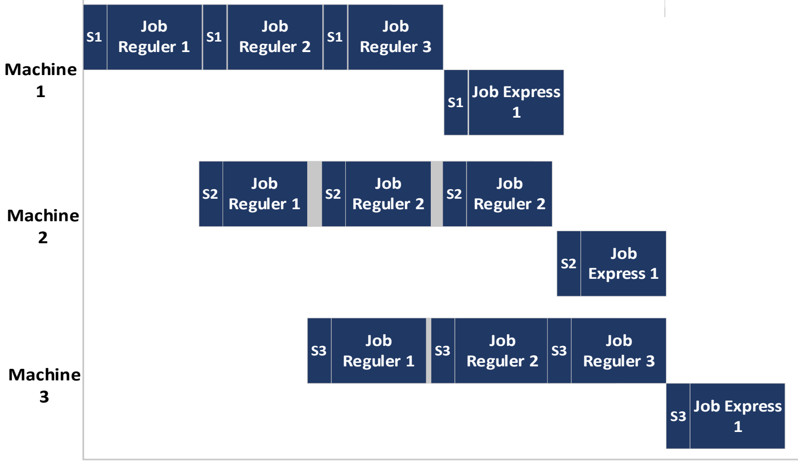

Fig. 7. Gant chart result case 2

Figure 7 is the Gant Chart result for case 2. Express job simulated exist after job regular 3 is done. All of the express jobs can be completed right on schedule without any waiting time. In all regular job, there is no delay.

6. Conclusions

This model effectively handles the complex scheduling testing operations in inspection companies for multiple items, multiple due dates, sequence-dependent setup times, and priority jobs, focusing on minimizing production costs. This can help companies schedule their production more effectively. After calculating the total costs generated through this simulation experiment, the most negligible cost is $300. Regular jobs 1 and 2 can be completed on time. The model can accommodate express jobs and can be completed right on schedule without any waiting time. However, regular job 3 is delayed, resulting in tardiness penalties. In sensitivity analysis, if an express job exists after jobs 1 and 3, the simulation result is that all regular and express jobs can be done in time.

For future development, this model still needs to consider the existence of defective products where product defects include reworked products and scrap products.

7. Acknowledgement

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