

SOFT-COMPUTING APPROACHES FOR RESCHEDULING PROBLEMS IN A MANUFACTURING INDUSTRY

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Abstract. Flexible manufacturing systems as technological and automated structures have a high complexity for scheduling. The decision-making process is made difficult with interruptions that may occur in the system and these problems increase the complexity to define an optimal schedule. The research proposes a three-stage hybrid algorithm that allows the rescheduling of operations in an FMS. The novelty of the research is presented in two approaches: first is the integration of the techniques of Petri nets, discrete simulation, and memetic algorithms and second is the rescheduling environment with machine failures to optimize the makespan and Total Weighted Tardiness. The effectiveness of the proposed Soft computing approaches was validated with the bottleneck of heuristics and the dispatch rules. The results of the proposed algorithm show significant findings with the contrasting techniques. In the first stage (scheduling), improvements are obtained between 50 and 70% on performance indicators. In the second stage (failure), four scenarios are developed that improve the variability, flexibility, and robustness of the schedules. In the final stage (rescheduling), the results show that 78% of the instances have variations of less than 10% for the initial schedule. Furthermore, 88% of the instances support rescheduling with variations of less than 2% compared to the heuristics.

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1. INTRODUCTION

Competition forces organizations to act quickly to preserve their position in the market Flexible manufacturing systems (FMS) allow the production of a variety of products to meet demand. FMS are the result of technological innovations generated through the years, where these problems are classified as highly complex (NP-Hard) [13]. The shop floor is a dynamic environment affected by the arrival of new activities, customer, and materials. The dynamic factors to consider are machine breakdowns, absenteeism from work, the arrival of new orders, and a change in the priority of work. Immediately consideration of dynamic factors in production is

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known as reactive or real-time schedules [34]. Seeking the optimization of manufacturing processes, inventories and manufacturing costs has a significant impact on the organizational management of a company, and these have impacts on the decision-making process [10, 15, 16, 23, 32, 48]. The plant floor will always require optimized tasks, to better meet all customers' requirements [40, 41, 47]. The processes are aimed to be sustainable, efficient, and profitable [36, 50, 56]. Customers will recognize the effective management of an organization by factors such as quality, time, opportunity, and economy in goods and services [24, 51, 59].

The research proposes a three-stage hybrid algorithm that allows the rescheduling of operations in an FMS. The novelty of the research is presented in two approaches: One is integration of the techniques of Petri nets, discrete simulation, and memetic algorithms and second is rescheduling environment with machine failures to optimize the makespan and Total Weighted Tardiness. The hybrid algorithm was called "PetNMA". The PetNMA algorithm is composed of three (3) sub algorithms. The first performs the initial scheduling of the jobs. The second simulates the initial scheduling until the machine fails, so a rescheduling is required. The third generates a reactive scheduling through the application of a memetic algorithm. The proposed algorithm is validated with problems of the FMS library. The results of the initial scheduling are compared with the bottleneck and dispatch rules, and the reactive scheduling was compared with the dispatch rules.

The model has a novel proposal that integrates the Petri net technique as an effective method for production scheduling. The innovative component of the proposed model has two key elements. First integrates the Petri nets with a genetic algorithm to develop active initial scheduling and second integrates the use of memetic algorithms with Petri nets for a production rescheduling environment. The integration of Petri net starts from the generation of active schedules and their configuration when the machine failure occurs. This research is considered a pioneer in a memetic algorithm decoded by Petri nets in an environment of rescheduling when there are failures or breakdowns of machines.

The proposed model establishes a modification of the libraries with different ranges of scenarios. The failure of the machine is considered in four instances with the fault simulations in different periods. This analysis identifies the flexibility and robustness of production schedules. This paper is organized as follows: the theoretical framework and literature review are in Section 2. In Section 3, the applied methods are described, such as Petri nets, genetic algorithms, memetic algorithms, simulated annealing, and local search. In Section 4, the algorithm "PetNMA" is presented and explained. In Section 5, the results obtained with the "PetNMA" algorithm. The findings, conclusions, and discussion are in Section 6.

2. BACKGROUND AND LITERATURE REVIEW

Production scheduling is the assignment and sequence of jobs to resources for the manufacture of goods or services [45]. Production schedule are aimed at optimizing deadlines, delivery times, setups, inventories, and the use of machines [45]. There are many methods and strategies used to develop a production schedule [5]. Among the basic and efficient strategies are the well-known dispatch rules. These consider the allocation and sequencing based on delivery dates, processing time, machine loading, among other strategies, as follows: Shortest Processing Time (SPT), Largest Processing Time (LPT), Most Remaining Work Time (MRWT), Earliest Due Date (EDD), Critical Ratio (CR), Apparent Tardiness Cost (ATC), and Minimum Slack (MSLACK). The objectives are used to evaluate the most important production schedule are: Makespan, Maximum Tardiness, Total Tardiness, Total Weighted Tardiness, Total Flow, and Total Weighted Flow [45].

2.1. Flexible manufacturing system (FMS)

An FMS is a system with a technological and automated component that can produce a variety of operations and tasks for production. The route of a job within the system is flexible and is taken in the scheduling process. An FMS be a flexible job shop with an additional number of restrictions [44]. The flexibility within a production system allows us to diversify products, anticipate demand, forecast inventory, increase the efficiency and quality of processes [28, 49, 53].

Low and Wu [31] symbolically represented the FMS as a set of machines $M^T = \{m_1, m_2, \dots, m_M\}$ and a set of jobs $J = \{J_1, J_2, \dots, J_N\}$, where each job $J_j, \forall j \in \{1, 2, \dots, N\}$ has a delivery date d_j promised and it consists of a sequence of n_j operations. Each operation $O_{i,j}, \forall i \in \{1, 2, \dots, N\}$ and $\forall j \in \{1, 2, \dots, n_i\}$, it can be processed continuously on any machine m_k of set of machines $M^S, (M^S \subseteq M^T)$ in a processing time $p_{i,j,k}$, it is including setup time on the machine. Each machine $m_k, \forall k \in \{1, 2, \dots, M\}$ can process only one operation. It is assumed that all $p_{i,j,k}, d_j$ and n_j are deterministic as well as the jobs available ($r_j = 0, \forall j$). From an Operations Research perspective, scheduling in FMS is a more complex version of the classic flexible scheduling problem, which is known to be NP-hard [13]. This complexity is caused by the versatility, flexibility, and alternate routes in the operations. An FMS contains many variables and restrictions that change over time, and these characteristics justify the use of dynamic scheduling [28].

2.2. Reactive scheduling

Random events involve the rescheduling of production, which affects initial scheduling and the level of customer service. This action is known as reactive scheduling [11]. The dynamic production environment is exposed to constant adjustments. Among them: machine failures, the arrival of new jobs, change of priorities, job cancellation, supplier failures, low-quality materials, absenteeism, and variability in jobs (processing times or delivery dates), changes in due dates. Most of the approaches to reactive scheduling or rescheduling, had been based on the generation of a basic predictive schedule. The three most common methods for rescheduling are: regeneration, partial rescheduling, and right-shift scheduling [60]. Regeneration includes all operations. Partial rescheduling only considers affected operations. The right shift method postpones the remaining operations; This method leads to more stable schedules.

2.3. Machine failure or breakdowns

One of the most frequent random events is machine failure or breakdown. This event may require two types of rescheduling. Total repair or reprocessing of the schedule. Repair refers to the local configuration of the current schedule, while the total rescheduling of a new schedule is generated from the base. To address rescheduling, machine failures must determine which jobs have been completed and which are affected. A job is called “complete” if it is completed before the failure. A task is considered “affected” if it needs to be relocated due to the interruption. Reactive scheduling is based on the affected jobs [19].

In a manufacturing system, the unavailability of a machine can be known in advance and better managed, compared to when an unexpected failure occurs. A robust schedule is one that can contain interrupts, such as events that were considered in their original planning [2]. The probability of failure of the machines is quantified by the time the machine has been occupied divided by the total time. A machine with higher occupancy is more likely to fail. If a manufacturing system has historical data to provide an approximate distribution of machine failures, it can be used to predict the time of machine failure and repair time to obtain a robust and stable predictive schedule [33].

2.4. Literature review

The literary review synthesizes the previous contributions of authors in the field of flexible manufacturing systems and their scope in reactive scheduling or rescheduling. In summary, Table 1 outlines all these findings.

Hatono *et al.* [20] used a Stochastic Petri Nets to describe the uncertain events of stochastic behavior in the FMS, such as machine failures, repair time, and processing time. Cho [8] developed a Petri net model for message manipulation and event monitoring in an FMS cell. ElMaraghy and Elmekawy [12] proposed scheduling algorithm that used Petri nets to deal with machine faults in real-time. Chen and Chen [6] simulated a Petri net in its method for non-hierarchical control for the performance of an FMS. Chen and Chen [7] developed an algorithm for the rescheduling of random events such as machine failures in an FMS. Acevedo and Mejía [1] carried out a Genetic Algorithm for reactive scheduling in FMS with arrivals of new jobs and priority changes.

TABLE 1. Contributions of previous authors.

Author(s)	Production system	Scheduling strategy	Rescheduling strategy	Event	Objective(s)	Petri nets	Heuristic(s)
Hatono <i>et al.</i> [20]	FMS	Petri nets	Hierarchical structures	Machine failures, repair and, processing time	Total time	Stochastics	FMS simulation
Cho [8]	Shop Floor Control System (SFCS)	Petri nets	×	×	Equipment, workstation, and shop	Interpreted Petri nets	Hierarchically decomposed
ElMaraghy and ElMekkawy [12]	FMS	Petri nets	Deadlock-free	Machine breakdowns	Total time	Timed and minimal siphons	×
Chen and Chen [6]	FMS	Petri nets	Client-server paradigm	Object-oriented approach	Total time	Colored Petri net simulation	×
Chen and Chen [7]	FMS	Adaptive scheduling	Rolling horizon	Machine failures, repair time	Completion time	×	Markov process
Kumar <i>et al.</i> [27]	FMS	Fuzzy-based	Operation machine allocation vector	Machine loading problem	System imbalance, throughput	Extended neuro-fuzzy Petri net	×
Acevedo and Mejía [1]	FMS	Petri nets	Reactive schedule	Machine breakdowns, new jobs	Total time	Timed Petri nets	Memetic algorithm
Mejía and Acevedo [34]	FMS	Reactive scheduling	Simulation	Machine breakdowns, new jobs	Total time	Timed Petri nets	Genetic algorithm
Tanimizu <i>et al.</i> [54]	FMS	Reactive scheduling	Based reactive	Delay and new jobs	Total time	×	Genetic algorithms
Kim <i>et al.</i> [25]	FMS	Reactive scheduling	RTA* and rule-based supervisor	Due date	Total time, tardiness	Timed Petri net	A reactive fast graph
Tashnizi <i>et al.</i> [55]	FMS	×	×	Sharing resources and processing times	Total time	Petri net	×
Tüysüz and Kahraman [58]	FMS	Petri nets fuzzy sets	×	Uncertainty in system	Time-critical	Stochastic	Fuzzy mathematics
Zhao <i>et al.</i> [61]	FMS	Petri nets	×	Discrete events	Total time	Timed Petri net	Genetic algorithm
Patel and Joshi [43]	FMS	Petri nets, simulation deadlock	×	×	Throughput, completion time	Stochastic	×
Han <i>et al.</i> [17]	FMS	Petri nets, deadlock	×	×	Makespan	Timed Petri net	Genetic algorithm
Baruwa <i>et al.</i> [4]	FMS	Petri nets, deadlock-free	×	×	Makespan	Timed colored Petri net	Anytime heuristic search algorithm
Başak and Albayrak [3]	FMS	Petri nets, real-time scheduling	×	×	Timed marked graph	Object-oriented Petri nets	Artifex PN
Han <i>et al.</i> [18]	FMS	Petri nets, deadlock	×	Lot sizes, resource capacities, and routing flexibility	Makespan	Timed Petri net	Simulated annealing, swarm optimization
Li <i>et al.</i> [30]	FMS	Petri nets	×	Available time of shared resources	Makespan	Transition-timed Petri nets	Heuristic search function
Lei <i>et al.</i> [29]	FMS	Petri nets, deadlock	×	Deadlock-free	Makespan	Timed Petri nets	Heuristic search strategies
Mejía and Niño [35]	FMS	Petri nets	×	×	Makespan	Timed place Petri net	Beam search strategy
Huang <i>et al.</i> [22]	FMS	Petri nets	×	×	Makespan	Timed place Petri net	Ordered binary decision diagrams
This paper	FMS	Petri nets Active schedule	Reactive, Robust, Simulation	Machine breakdowns	Makespan, tardiness	Timed Petri nets	Genetic algorithm, simulated annealing, local search

Mejia and Acevedo [34] development an integrated system of Petri nets to model an FMS. They presented a prototype that simulated the production plan and implemented dispatch rules to resolve possible conflicts.

Tanimizu *et al.* [54] developed a genetic algorithms of continuous rescheduling for the arrival of new jobs. Kim *et al.* [25] presented a new method for an FMS based on Petri nets and a reactive graphical search algorithm, looking for the minimization of the makespan and the total tardiness. Tashnizi *et al.* [55] develop a Petri nets with non-linear scheduling. Tüysüz and Kahraman [58] modeled a flexible manufacturing cell using stochastic Petri nets with fuzzy parameters. Patel and Joshi [43] developed a model for an FMS with deadlock and analyzed it to generate the reachability tree using Petri net system. Han *et al.* [17] proposed a scheduling method that provides a new approach to evaluate the performance of different deadlock controllers with Petri nets and genetic algorithms. Baruwa *et al.* [4] investigated a deadlock-free scheduling method for an FMS based on timed colored Petri nets with a heuristic.

Başak and Albayrak [3] presented a Petri net-based decision system modeling in real-time scheduling and control of an FMS. Han *et al.* [18] proposed an effective hybrid particle swarm optimization algorithm with a timed Petri net model to solve the deadlock-free scheduling problem of an FMS. Li *et al.* [30] modeled scheduling problems with a transition timed Petri net and an improved heuristic function that also considers the available time of shared resources within an FMS. Lei *et al.* [29] solved a deadlock-free scheduling of FMS with the controlled backtracking strategy based on the execution of the Petri nets. Mejía and Niño [35] developed a fast and efficient Beam Search strategy based on Petri Nets for FMS scheduling. Huang *et al.* [22] developed an FMS scheduling based on binary decision diagram and Petri net.

Based on the state-of-the-art review, several studies have addressed the problem of scheduling and rescheduling due to machine failure in an FMS. Research has focused on developing efficient algorithms, improving performance metrics, time and computational cost. In recent years, the use of genetic algorithms combined with local search techniques has been emphasized to obtain better results. However, the results found by its authors are still susceptible to improvement, through the development of new hybridization structures. In this subject, new applications are always required to improve the computational process in its structure, compilation, and integration. These innovations always allow us to find better solutions.

This study presents a new hybrid algorithm construction that combines the Petri Nets and Genetic Algorithm for the initial schedule. This combination allows the achievement of very good solutions within active schedules in environments of an FMS. In reactive rescheduling due to machine breakdowns, the Petri Nets and Memetic Algorithms are integrated with local search techniques and Simulated Annealing. The integration allows robust schedules after the occurrence of machine failure and unavailability. The proposed model allows us to avoid conflicts, blocks, and implement real-time controls. The proposed model is justified by its robustness and stability, the ability to manage uncertainty due to machine failure, its resilience and flexibility to adapt easily to different circumstances. Finally, the novelty of the research is to consider the integration of efficient scheduling methods. Additionally, it is proposed to optimize two important metrics (makespan and tardiness) and simulate failures by scenarios to analyze in context of the complexity of an FMS.

3. METHOD AND MATERIAL

In this section, we describe Petri Nets, Genetic Algorithms, Memetic Algorithms, Simulated Annealing, and Local Search, as backgrounds.

3.1. Petri Net

A Petri Net (PetN) is a directed graph, heavy and bipartite, consisting of places, transitions, and arcs, where the arcs go from a place to a transition or a transition to a place. In the graphical representation places are represented by circles, transitions for bars, and bows by arrows. A marking on the PetN indicates the distribution of an integer (positive or zero) token for each position [8]. Murata [38] formally defined Petri Nets as six-folder presentation $\text{PetN} = (P, T, O, I, M, W)$, where:

- n , number of places in the PetN.

- m , number of transactions in the PetN.
- $P = \{p_1, p_2, \dots, p_n\}$ is set of n places are drawn as circles, for $n > 0$.
- $T = \{t_1, t_2, \dots, t_m\}$ is set of m transitions are drawn as bars or boxes, with $P \cup T \neq \emptyset$ and $P \cap T = \emptyset$ for $m > 0$.
- $O : T \times P \rightarrow N$ is the set of input arcs directed from T to P , where $N = \{0, 1, 2, \dots\}$.
- $I : P \times T \rightarrow N$ is the set of output arcs directed from P to T , where $N = \{0, 1, 2, \dots\}$.
- $M(p) : P \rightarrow N$ is the marking in the p th place or the token number in the p th place at some point. An initial labeling is denoted by $M(0)$. Tokens (black dots) reside in places and represent the truth of the condition of action associated with the corresponding place. Tokens move throughout the net by effect of transition firings.
- W is the set of weights associated with the arcs.

For purposes of simplifying the other definitions in the Petri Nets, Murata [38] use the following symbolic representations, which have been adopted for purposes of this research:

- $K(p)$, the maximum number of tokens that can hold the place p .
- $w(p, t)$, weight of the arc that communicates the place p with the transition t .
- $w(t, p)$, weight of the arc that communicates the transition t with the place p .
- $\bullet t$, set of places of input to the transition t .
- $t \bullet$, set of output locations transition t .
- $\bullet p$, set of input transitions to place p .
- $p \bullet$, set of output transitions to place p .
- $R(M(0))$, set of possible markings made from $M(0)$.
- $L(M(0))$, the set of sequences to fire $M(0)$.
- $C = \{C_{i,j}\}$, incidence matrix of $n \times m$, such that if all weights are assumed as one, so: $C_{i,j} = 1$ if the place i is an output place for the transition j , $C_{i,j} = -1$ if the place i is an input place for the transition j , and $C_{i,j} = 0$ otherwise.

In Petri nets, a transition t is said to be enabled if all its input places are marked at least $w(p, t)$ tokens. Also, a transition can be fired if enabled. When a transition is fired, $w(p, t)$ tokens are removed from their input places and they put $w(t, p)$ tokens in their output places, considering the constraints of the system. A transition without input place is called an enabled transition, while a transition without output place is a final transition. A transition t and a place p form a loop if p is, at the same time, input, and output place of t .

One of the great advantages of the application of Petri nets to real systems is the ability to monitor their evolution. The evolution of the net allows us to identify the movements of the tokens between the places, which in turn define the vector of marking and its changes in time. If in a finite capacity PetN transition t fires, it is satisfied that the number of tokens in each output place p of that transition, does not exceed its maximum capacity $K(p)$, which is represented by: $M'(p) + w(t, p) \leq K(p)$. The equations of state make use of $C = \{C_{i,j}\}$, where $C_{i,j} = C_{i,j}^+ - C_{i,j}^-$, with $C_{i,j}^+ = w(i, j)$ and $C_{i,j}^- = w(j, i)$. The evolution of the system from one step to another, is represented by the equation of state $M(k+l) = M(k) + C \cdot u(k)$, where $M(k)$ represents vector marking, after of k fired transitions, l the net change in the tokens in place i when transition j is fired, and $u(k)$ the vector transition firing, which contains zeros except j th position containing a 1, indicating that j th transition is fired after k events. If a marking $M(d)$ destination is reachable from $M(0)$ through a firing sequence $\{u_1, u_2, \dots, u_d\}$, the state equation is written as: $M(d) = M(0) + C \cdot \sum_{k=1}^d u(k)$, or as $\Delta M = C \cdot X$, if makes $M(d) - M(0) = \Delta M$ and $\sum_{k=1}^d u(k) = X$, with X column vector whose input the j th position is the number of times the transition has been fired j . Figure 1 illustrates a Petri Nets model of an FMS with two jobs.

The benefit of using the Petri Nets as a tool for modeling the systems is the knowledge about the state at each moment of its evolution using the vectors of markings. It is known as the evolution of the network every step it takes over time, that is, the movement of the tokens between the places after the fire of the transitions. Two types of properties of the Petri Nets have been identified, those that depend on the initial state or marking

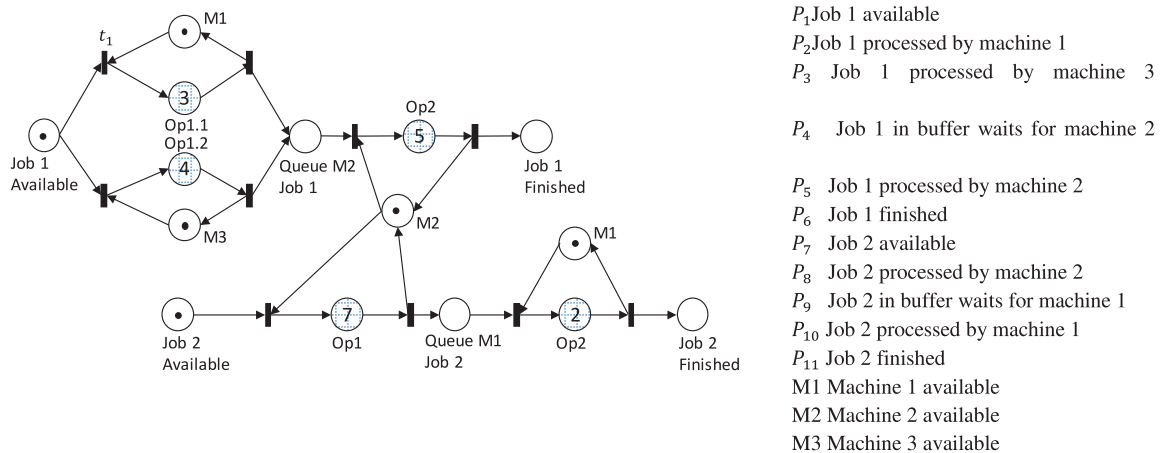


FIGURE 1. Petri Nets model for FMS with two jobs and three machines [1].

of the Petri Nets, called behavioral, and the properties that depend on the structure of the network, called structural. The marking of a Petri Net changes after each fire a transition.

Petri Nets have been widely used for the scheduling and rescheduling of production in manufacturing systems. A Petri Nets is most often used as a tool to model and control the production process in an FMS [3, 18, 22, 29, 35, 39]. Due to the graphic nature, descriptive capacity, Petri Net as a powerful tool to play an important role in modeling and analysis [27, 28, 43].

3.2. Memetic algorithm

Memetic Algorithm (MA) is an optimization technique that combines other metaheuristics (population-based search and local improvement). The MA is based on individual improvements of the solutions in each of the agents along with cooperation processes and competitions. Moscato and Cotta [37] related the origins of MA in the late eighties when evolutionary strategies and genetic algorithms began to take advantage. The name Memetic comes from the term meme introduced by Richard Dawkins to represent a unit of cultural evolution. In the context of optimization, a meme represents a learning or development strategy. MA contributes to the solution of production scheduling in optimal or near-optimal solutions, avoiding local minima or premature convergence [9]. MA convergence is treated with local search techniques [14].

The MA starts from a genetic algorithm, it plays an important role in its structure. They constitute the global search tool providing the coverage of diversity while the local search provides the intensification. Genetic algorithms are part of the evolutionary algorithms that constitute a general technique for solving search and optimization problems [46]. The form in which evolutionary algorithms work is related to how species evolve in nature. Genetic algorithms use a set of possible solutions or individuals to calculate adaptation measures. Through an iterative process this population changes and each iteration are called generation. For an individual to survive and pass on to the next generation it must have a high level of adaptation and participate in genetic operations, with which new individuals are created who constitute the next generation. These algorithms allow us to address problems of great complexity of search and optimization. The most popular evolutionary algorithms are given its efficiency and ease of implementation. Solutions are represented as a bit string before being decoded. The behavior is defined as the following parameters: the size of the initial population, the number of generations, the percentages of mutation and crossover. A schematic representation of the procedure of the genetic algorithm is shown in Figure 2.

Next, the simulated annealing, and the local search are related, as a hybrid strategy within the memetic algorithms. Local search is a search process in the space of possible solutions. The search begins for a random

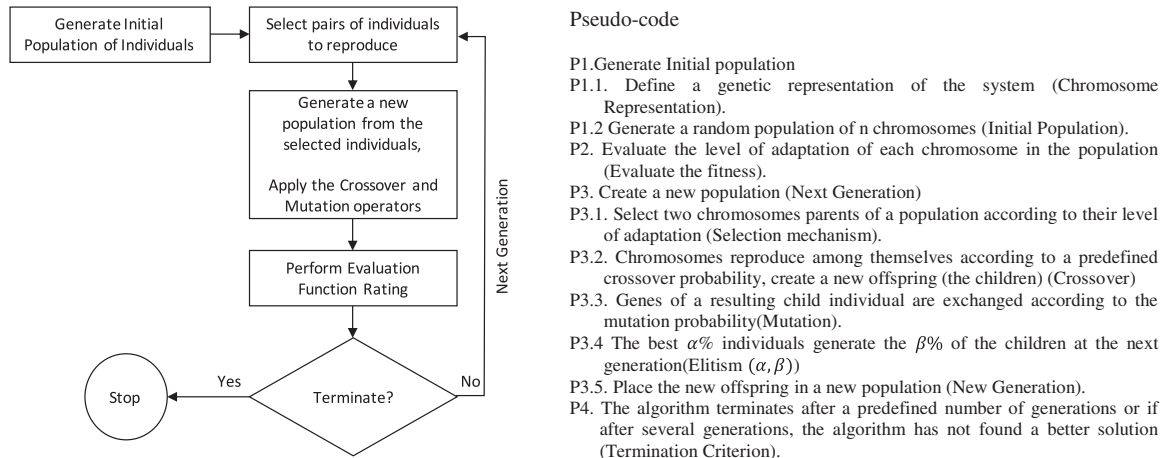


FIGURE 2. Flow diagram and pseudocode of a genetic algorithm.

solution and then focuses on neighboring solutions iteratively. Iterations are made by setting a parameter by the memory of the found solutions [21]. The local search has as components: a search space, a set of feasible solutions, a neighborhood relation, an initialization function, a step function, and a completion condition. Simulated annealing was proposed by Kirkpatrick *et al.* [26] motivated by the annealing of the solids, a process in which the solids are heated and subsequently cooled slowly to obtain perfect crystal structures. The main idea of SA is an observed analogy between a complex system optimization and a description of the physical behavior of a system. This method is applied in many domains: operational research, production scheduling, and many others. Simulated annealing can be considered as a process in which in a neighborhood you try to move from one current solution to another of your neighbors. SA generates a new solution S' in the neighborhood of the current solution, then calculates the change $d = C(S') - C(s)$, where $C(s)$ the value of the objective function of the initial solution. The algorithm must be designed using certain methods to represent solutions, generate neighboring solutions, and reduce the temperature. The parameter T decreases gradually by a cooling function until a stop condition is satisfied.

4. PROBLEM DEFINITION, ASSUMPTIONS, AND NOTATION

This section contains problem definition, assumptions followed by notation are used such as it is much easier to understand the model. The hybrid PetNMA algorithm is composed of three (3) sub algorithms. The first performs the initial scheduling of the jobs. The second simulates the initial scheduling until the machine fails that results a rescheduling. The third generates a reactive scheduling through the application of a memetic algorithm.

4.1. Notation

The notation used to represent mathematically what happens with the set of operations that enter the reactive scheduling of the production is the following:

n : number of places.

The places are operational (O) or resources (R): $P = \{p_1, p_2, \dots, p_n\} = O \cup R$.

m : number of transitions.

ump : vector of enabled transitions.

$X_{i,j,k}$: time when the i th operation of the job j on the machine k starts in the initial schedule.

- $p_{i,j,k}$: processing time of the i th operation of the j th job on the machine k .
 $C_{i,j,k}$: completion time of the i th operation of the j th job on the machine k .
 $O_{i,j,s}$: i th operation of j th job on a machine of workstation s .
 $O_{i,j,k}^R$: i th operation of j th job on k th machine.
 T_k^R : time availability of k th machine reactive scheduling.
 α : percentage of the makespan in the weighted objective.
 β : percentage of total weighted tardiness in the weighted objective.
CONP: set of undeveloped operations.
PSize: represents the GA parameter, associated with the size of the population.
 nbd : represents the number of faults of simulated machines.
 r : r th reactive scheduling activity, due to failure number $r = (1, 2, \dots, nbd)$.
 t_{bd} : instant when the failure occurs.
NTPI: number of transitions programmed to be fired in the initial schedule.
 $NES(t_{bd})$: number of transitions fired during the simulation until the moment of failure.
 ng : number of genes that make up the chromosome.
 ng_r : number of genes that make up the chromosome for reactive scheduling, due to failure r .
 ng_{r-1} : number of genes that formed the chromosome in reactive scheduling, due to the failure $r - 1$. When $r = 1, ng_0 = 2 \sum_{j=1}^{N_0} n_j$.

The operational place represents the action “Operation $O_{i,j,k}$ in process” and the conditions “job available”, “job completed” and “job Waiting at workstation s ”. The resource places represent the “availability of a machine”, where the initial marking of the resource places is 1 for all resources. All resource places are untimed.

4.2. Assumptions

The problem of reactive scheduling due to machine failures in an FMS, is formally declared with the following assumptions:

- (1) The FMS is composed of a set of machines $M^T = \{m_1, m_2, \dots, m_k, \dots, m_M\}$ and a set of work orders $J = \{J_1, J_2, \dots, J_j, \dots, J_N\}$.
- (2) Each work order J_j has a delivery date d_j committed to the customer, a priority defined by their level of importance w_j and consists of a sequence of operations $O_j = \{O_{1,j}, O_{2,j}, \dots, O_{i,j}, \dots, O_{n_j,j}\} \forall j$.
- (3) Each machine $m_k \forall k$ can process only one operation until failure $P(\text{Fault})_k$ occurs in the scheduling horizon.
- (4) Assumed that all $p_{i,j,k}$, d_j and w_j are deterministic and processing time $p_{i,j,k}$ includes the time of preparation or setup on the machine. Where k represents the index of machines ($k = 1, 2, \dots, M$), j is the index of work orders ($j = 1, 2, \dots, N$), and i is the index of operations ($i = 1, 2, \dots, n_j$).
- (5) Each workstation s has a space at the beginning which is used for temporary storage of all jobs will be processed. where s is the index of workstations ($s = 1, 2, \dots, S$).
- (6) When a job is completely processed in a workstation, it is moved to the next workstation or inventory of finished products.
- (7) The interruption of the scheduling is generated due to machine failures.
- (8) In the reactive scheduling, the operations are in process in a machine without failure, *i.e.*, are not interrupted. Any operation that is being processed on a machine that fails, will be break and will have to be reinitialized.
- (9) All operations conform to reschedule operations that have not been done and the operations are affected by the failure of the machine.
- (10) The objective functions considered here is to minimize Makespan ($C_{\max} = \max(C_j)$), Total Weighted Tardiness ($\sum_{j=1}^N w_j T_j$) and weighted objective ($\alpha C_{\max} + \beta \sum_{j=1}^N w_j T_j$) with $\alpha + \beta = 1$.

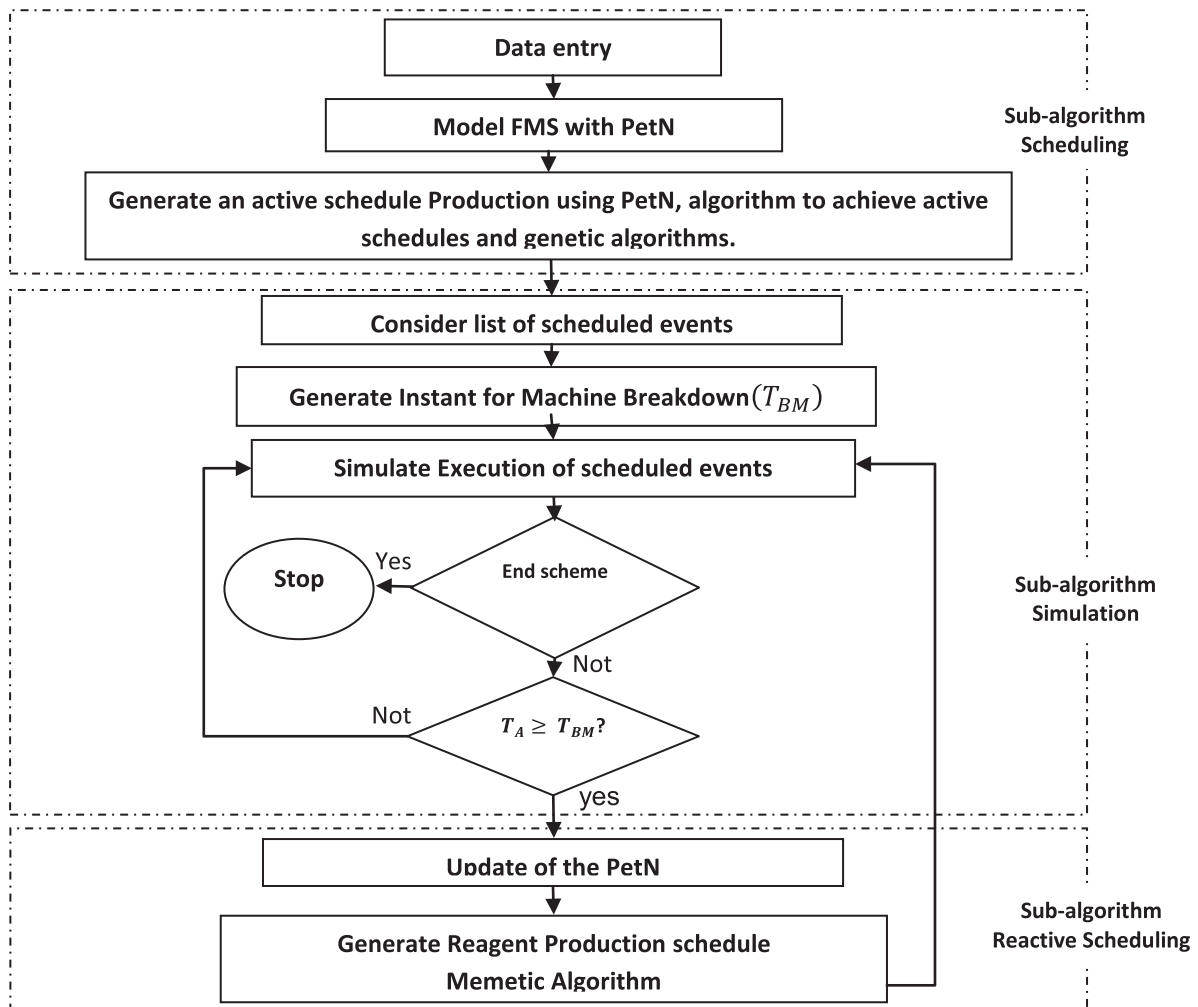


FIGURE 3. PetNMA: Reactive scheduling algorithm of an FMS with machine failure.

4.3. Scheduling and system simulation

The PetNMA algorithm is based on a series of sub-algorithms which develop in a sequence of three stages: Sub-algorithm of Scheduling, Sub-algorithm of Simulation and Sub-algorithm of Reactive Scheduling (see Fig. 3).

4.3.1. Sub-algorithm scheduling

The sub-algorithm is to structure an initial production schedule in an FMS with all jobs j , using modeling Petri nets, the algorithm for obtaining active schedules, and genetic algorithms. The sub-algorithm is supported by the LEKIN software. The initial scheduling is constructed, by establishing the sequence of fired transitions supported by the dispatch rules (SPT, LPT, MRWT, EDD, CR, ATC, and MSNACK). The Sub-algorithm Scheduling has the objective of obtaining active schedules. Therefore, genetic algorithms are applied to obtain new schedules. In the implementation of the Sub-algorithm Scheduling in Microsoft Visual Studio 2010, the format of the Petri net class was taken from the Afs-Petrinet Algorithm [1] and adapted to represent machine failures. Below are the detailed steps of the Sub-algorithm Scheduling (see Algorithm 1).

Algorithm 1. Initial scheduling.

- P.1 Create the FMS in the software "LEKIN".
- P.2 Create PetN of the FMS.
- Read files generated by LEKIN (*.job and *.mch)
 - Create the finite set of places (P), with $= N_0 + S + 2M + \sum_{j=1}^{N_0} \sum_{i=1}^{n_j} m_{ij}$.
 - Create the finite set of transitions (T), with $m = 3 \sum_{j=1}^{N_0} \sum_{i=1}^{n_j} m_{ij} + M$.
 - Create the set of arcs directed from t to $p(TxP)$ and set of arcs directed from p to (PxT) .
 - Create the vector of marking M_p for the PetN, initializing it (M_0).
 - Create the time vector "PT" of the places of the PetN. The times associated with the machines, storage at the entrance of the stations and termination of the work order, are always zero (0).
 - Create the remaining time vector "Mr" with value zero (0).
 - Create the vector of time remaining work "rw".
 - Establish the incidence matrix negative (C^-) and positive (C^+) of the PetN.
- P.3 Generate the initial scheduling through the algorithm of active programs.
- Create the vector of enabled transitions (ump).
 - Select the transition to fire.
 - Calculate $C_{i,j,k}$ operations available to be programmed. Organize high to low and store in a matrix C along with the transitions that would begin operations.
 - Detect available machines (m^*) in which the minimum time of termination (f) occurs.
 - Create the matrix G , how of the set operations that can be initiated on the machine m^* , and which initial time is lesser than f .
 - Make assignments of available resources (machines) considering first operations would end later to have a gap in scheduling. Dispatching rules are used.
 - Identify the related transition with the selected operation on the machine m^* and fire.
 - Moving the transition fired of ump to transition fired vector (u) and update vectors "Mp", "Mr" and "rw".
 - Update ump . If the ump is empty, a workable program for the FMS has been obtained, otherwise go to step P3.b.
 - Save the seven sequences obtained in the corresponding vectors and their objective values.
- P.4 Generate Initial Schedule by GA.
- Chromosome Representation: Realize the genetic representation of the system with a sequence of ng genes obtained randomly in the interval $[0, ng - 1]$, in an indirect representation chromosome, which is then decoded to represent transitions to be fired. The chromosome is a string of integer numbers ranging from 1 to a sufficiently large number, typically 10 to 100 times the total number of operations. The length of the chromosome corresponds to twice the total number of operations. This equals the total number of transitions to be fired.
 - Initial population: All individuals were generated randomly except as even which were generated with the rules of dispatch (Active Programs), associated with $PSize$.
 - Decoding: The module function (%) uses the vector enabled transitions (ump) to obtain the vector of transitions firing (u). The firing transition is selected by taking the module of the integer division between the gene and the number of enabled transitions. The selected transition fires, the marking of the net changes and a new set of transitions is enabled. The next gene in the chromosome determines the new transition to fire. This chromosome always guarantees a feasible sequence of transition firings.
 - Adaptation level: The level of adaptation of the GA evaluates the chromosome, and thus the target values (makespan, total weighted tardiness or the weighted value).
 - Generate a new population
 - Selection mechanism: The tournament strategy is used: A first pair individuals is chosen randomly among the current population and the fittest is selected to be the first parent. Another pair of individuals is chosen and a second parent is selected in the same manner. The two selected parents will reproduce according to the crossover probability. Choose the best individual of the population.
 - Crossover: The classical one-point crossover strategy was followed: a random position (crossover point) in a chromosome is chosen.
 - Mutation: Two genes of a resulting child individual are exchanged according to the mutation probability.
 - Elitism (α, β): The best $\alpha\%$ individuals generate the $\beta\%$ of the children at the next generation.
 - Evaluate the fitness of new individuals.
 - Next generation: The best individuals among parents and children produce the next generation.
 - Termination criterion: The algorithm terminates after a predefined number of generations ($maxGenerations$) or if the algorithm has not found a better solution.
 - Consider the best solution to the current population, as the seventh sequence of transitions.
- P.5 Select the best solution as the sequence of transitions to generate the schedule.
- P.6 Change the sequence of fire transitions (u) select to a sequence in Gant, according to the format of the *.seq file of LEKIN and follow the Sub-algorithm Simulation.

The genetic algorithms notice that the completion of an operation requires the firing of a pair of transitions: The first transition of the pair marks the start and the second represents the termination of any operation. The decoding is based on the work done by Mejia and Acevedo [34], *e.g.*, take Figure 4 and the following chromosome: The three transitions that are enabled at this state conform the array $ump(0) = [t_1, t_2, t_5]$. Transitions are put into the array in lexicographic order. The remainder of the integer division between the first gene (6) and the size (3) of the array ump is 0. Thus transition t_1 in the 0th position of ump is selected to fire. Transition t_1 is fire and changes the state of the net, generating a new vector of enabled transitions $ump(1) = [t_3, t_5]$ (see Fig. 4). The second gene (77) is taken. The remainder of the gene (77) and the size of the array (2) is 1 and the 1th position is selected. This corresponds to transition t_5 . The process is repeated until reaching the final marking.

4.3.2. Sub-algorithm simulation

To perform a simulation of the events we must consider the vector of fired transitions obtained in the Scheduling Sub algorithm. This vector relates the times in which each operation must be performed. This list of

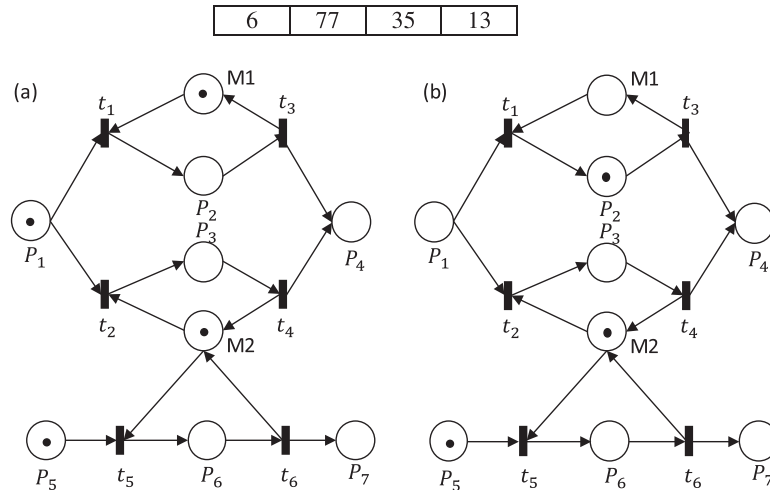


FIGURE 4. Example of chromosome decoding.

events to be performed varies with time as each event takes place. However, the operations are carried out in some machines can present failures. This is what should be done reactive scheduling or rescheduling of production. Previously, it is necessary to perform a simulation of the execution of operations that have been programmed and machine failures. It should be noted that it does not have historical data, which is why the failure to generate the methodology used by Mehta [33]. To determine the time when the failure occurs the normal probability distribution is used, to determine the machine fault, since all machines have the same probability of failure. However, in this study to determine the repair time of the machine we use the Log-Normal distribution to establish the failure time (Repair time). The time of each failure or repair time, is given by $LN(\ln(\gamma_1 p), \gamma_2)$. Where, $\ln(\gamma_1 p)$ is the average of the function, p is the average processing time of the system, γ_1 is the percentage of p which is part of the repair time and γ_2 is the variance. Below are the detailed steps of the Sub-algorithm Simulation of scheduled events and failures of machines (see Algorithm 2).

Algorithm 2. Sub-algorithm simulation – Part A.

- P.1 Scheduled Events list
 - a. Consider the u in the Sub-algorithm Scheduling, as a LIST OF PROGRAMMED EVENTS.
 - b. Create a list of random events that represent the failures machines. In this list of events you must specify the nbd , t_{bd} and the T_k^R it does it.
- P.2 Simulation of the execution of Scheduled Events
 - a. Remove the first entry of the LIST OF SCHEDULED EVENTS to the list of events executed.
 - b. Forward the clock time to the time associated with the removed event and update the state of the system to the occurrence of the event.
 - c. Evaluate if the list of scheduled events is empty (if STOP, otherwise go to P2.d).
 - d. Evaluate if the clock time is greater than or equal to the associated time of the machine failure (If, execute the Sub-algorithm Reactive Scheduling, otherwise go to step P2.a).

To carry out the Reactive scheduling in PetNMA, all the operations that at the time of the failure had not been executed must be considered, as well as the operation that was being processed in the machine at that moment, forming the set CONP. The operations that were being processed during the failure inoperable machines are not interrupted until they have been completed. The following is a series of steps to obtain the list of those operations (see Algorithm 3).

Algorithm 3. Sub-algorithm simulation – Part B.

- P.1 Start with an empty set $CONP = \emptyset$.
- P.2 Add to $CONP$ the operation that was being processed at the time of the machine failure ($CONP = \{O_{i,j,k}^R\}$).
- P.3 Add to $CONP$ all the operations that at the time of the failure had not been executed of the initial program ($CONP = CONP + \{O_{r,j,k}\} \forall r, j, k$), where it is satisfied that $X_{r,j,k} \geq t_a$ and $j \leq N$.

TABLE 2. Route of the operations of two jobs in a manufacturing system with four machines.

Operation	Job 1	Job 2
(Operation 1)	M1(6)	M2 (7)
(Operation 2)	M3 (8) o M4 (8)	M4 (5)

4.3.3. Sub-algorithm of reactive scheduling

When a machine failure occurs during the development of the Sub-algorithm, the rescheduling must be done through the Sub-algorithm Reactive Scheduling. For this scheduling, all operations in CONP must be considered. The MA used consists of an evolutionary algorithm and a local search technique. The GA was selected for the evolutionary part. Meanwhile, as a local search technique, the simulated annealing algorithm runs after each generation. The Sub-algorithm Reactive Scheduling is composed of the following steps (see Algorithm 4).

Algorithm 4. Sub-algorithm of reactive scheduling.

- P.1 Update of the PetN
 - a. Set the clock time at the time the machine failure occurs.
 - b. Update the vector of remnant process times according to the time of the clock in the simulation.
- P.2 Generate Reactive Scheduling for MA
 - a. Chromosome Representation: Realize the genetic representation of the system with a sequence of ng_g genes obtained randomly in the interval $[0, ng_g - 1]$, in an indirect representation chromosome ng_g depends on the state of the PetN in the instant machine failure occurs and is given by $ng_g = NTPI - NES(t_{ar}) + 2$.
 - b. Initial population: All individuals were generated randomly except a seven which were generated with the rules of dispatch (Active Programs).
 - c. Decoding: The module function (%) uses the vector enabled transitions (ump) to obtain the vector of transitions firing (u).
 - d. Adaptation level: The level of adaptation of the GA evaluates the chromosome, and thus the target values (makespan, total weighted tardiness or the weighted value).
 - e. Choose the best individual of the population.
 - f. SA is applied with the technique of LS.
 - i. The best solution obtained from the latest generation (local optima) is chosen.
 - ii. The initial temperature and the final temperature are initialized.
 - iii. A neighbor is generated by exchanging two genes of the local optimum.
 - i. The fitness neighbor is evaluated and a delta equivalent to the neighboring fitness least local optimum fitness is generated.
 - ii. The termination criterion is evaluated, if the neighbor's fitness is less than optimal local new local optimum will be the neighbor, but probabilistic acceptance criteria is evaluated.
 - iii. The temperature is updated.
 - iv. If the temperature is higher than the final temperature, return to step 2.f.iii, otherwise continue with step P2.g.
 - g. Generate a new population
 - i. Select chromosomes for reproduction (tournament).
 - ii. Apply crossover (one-point strategy) and mutation (two genes are exchanged according to the mutation probability), elitism operators (α, β).
 - iii. Evaluate the fitness of new individuals.
 - iv. Next generation: The best individuals among parents and children produce the next generation.
 - h. Termination criterion: The algorithm terminates after a predefined number of generations ($maxGenerations$) or if the algorithm has not found a better solution.
 - i. Consider the best solution to the current population, as the seventh sequence of transitions.
- P.3 Select the best solution as the sequence of transitions to generate the reactive scheduling.
- P.4 Change the sequence of fire transitions (u) select to a sequence in Gantt the Reactive Scheduling.

5. EXPERIMENTAL EVALUATION

The experimental tests were developed by running on a Dell Inspiron computer with an Intel Inside CORE I5 processor, 8 gigs of RAM, 1 TB of memory, and Windows 7. The algorithms were developed in Microsoft Visual Studio 2010 in C++ language.

5.1. Numerical illustration of the sub-algorithm scheduling

To better understand this stage of the algorithm, corresponding to phase 1 of the Sub-algorithm Scheduling, an example of its application is specified using a numerical example. A manufacturing system develops two (2) jobs with two (2) operations with an established sequence and four (4) machines in the system. The path of each job is shown in Table 2, where the process times of each operation are shown in parentheses.

The modeling system described above is as follows:

The input and output functions of Petri nets used to represent the manufacturing system in Figure 5, can be represented using the following incidence matrices (Tabs. 3–5):

In the present study, the Timed Petri Nets were used to model the FMS together with the random faults of the machines. In Figure 6, the system represented above can be evidenced with additional places and transitions

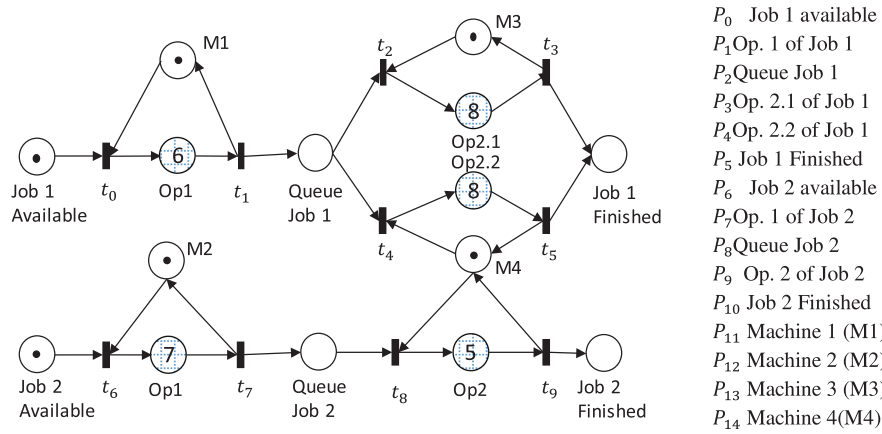


FIGURE 5. PetN model for a Job Shop with two jobs, four machines.

TABLE 3. Positive incidence matrix for the job shop represented in Figure 5.

	p_0	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}	p_{13}	p_{14}
t_0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
t_1	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
t_2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
t_3	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
t_4	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
t_5	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
t_6	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
t_7	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
t_8	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
t_9	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1

TABLE 4. Negative incidence matrix for the job shop represented in Figure 5.

	p_0	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}	p_{13}	p_{14}
t_0	-1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0
t_1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0
t_2	0	0	-1	0	0	0	0	0	0	0	0	0	0	-1	0
t_3	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0
t_4	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	-1
t_5	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0
t_6	0	0	0	0	0	0	-1	0	0	0	0	0	-1	0	0
t_7	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
t_8	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	-1
t_9	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0

TABLE 5. Incidence matrix for the job shop represented in Figure 5.

	p_0	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}	p_{13}	p_{14}
t_0	-1	1	0	0	0	0	0	0	0	0	0	-1	0	0	0
t_1	0	-1	1	0	0	0	0	0	0	0	0	1	0	0	0
t_2	0	0	-1	1	0	0	0	0	0	0	0	0	0	-1	0
t_3	0	0	0	-1	0	1	0	0	0	0	0	0	0	1	0
t_4	0	0	-1	0	1	0	0	0	0	0	0	0	0	0	-1
t_5	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	1
t_6	0	0	0	0	0	0	-1	1	0	0	0	0	-1	0	0
t_7	0	0	0	0	0	0	0	-1	1	0	0	0	1	0	0
t_8	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	-1
t_9	0	0	0	0	0	0	0	0	0	-1	1	0	0	0	1

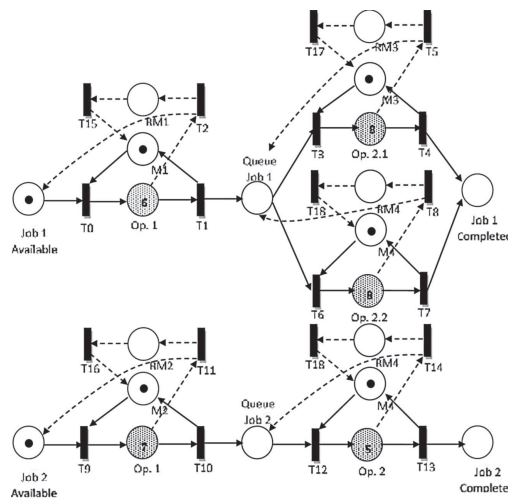


FIGURE 6. Petri Net model for a Job Shop with 2 jobs, 4 machines, considering machine failures.

that correspond to the machines under repair after a failure. Transitions machine failures are fired when the corresponding machine simulation has failed while the operation is processed. For this, one must consider the M_k vector marking at the time the machine fails. When the corresponding transition is fired, the token that is in the operation place is removed and two tokens are added to the place corresponding to the repair of the machine and to the available job place (if the operation was the initial one) or to the queue from a job. At the end of the repair time of the machine, the corresponding transition is fired, and the token is returned to the machine so that it is available again.

Where, Op. 1 Operation 1; Op. 2 Operation 2; Op. 2.1 Operation 2 option 1; Op. 2.2 Operation 2 option 2; M1 Machine 1; M2 Machine 2; M3 Machine 3; M4 Machine 4; RM1 Repair of the machine 1; RM2 Repair of the machine 2; RM3 Repair of the machine 3; RM4 Repair of the machine 4; T0, T3, T6, T12 Transitions that start operations; T1, T4, T7, T10, T13 Transitions that end operations; T2 Failure M1 while working in Op. 1 of job 1; T5 M3 failure while working in Op. 2.1 of job 1; T8 M4 failure while working in Op. 2 of job 1; T11 M2 failure while working in Op. 1 of job 2; T14 M4 failure while working in Op. 2 of job 2; T15 Enables M1 after being repaired; T16 Enables M2 after being repaired; T17 Enables M3 after being repaired; T18 Enables M4 after being repaired. When the failure of a machine is generated, the rescheduling of the activities must be carried out with many strategies, through the sub-algorithm of reactive scheduling.

TABLE 6. Description of the 10 problems chosen to perform the experimental tests.

No. of problem	No. of jobs	No. of workstations	No. of machines
1	6	10	19
2	9	8	20
3	10	5	10
4	10	5	12
5	10	5	12
6	10	7	18
7	10	10	20
8	15	5	12
9	15	6	17
10	20	6	13

5.2. Experimental tests of the scheduling sub algorithm in PetNMA

To obtain the initial schedules with the Scheduling Sub algorithm in PetNMA, ten (10) problems that characterize an FMS were used (see Appendix A). Problems that were used for testing were adapted from the problems developed by Mejia and Acevedo [34] and the classic problems LA and ORB. Each problem has a few jobs to be scheduled in a few workstations and machines (see Tab. 6).

- The route of the work by stations in the FMS consists of times each of their operations. These times were set randomly within the range [36, 37], to obtain variability problems.
- In the classical problems, the assignment of the machines to each of the workstations is performed randomly within the interval [10, 13, 34]. An assignment of machines stations than three (3) system produces downtime machines throughout the scheduling.
- The job weights were assigned randomly considering the uniform distribution within the interval [10, 13, 34].
- In the delivery times of each work, the total work rule (TWK) was used, where $d_j = kP_j$, where P_j is the sum of the process times of all operations of work j and k . However, a normal distribution with a range [1.3, 1.5] was used to give more diversification to the delivery times.
- In designing experiments to validate the parameters, the problems according to the number of jobs in small, medium, and large are classified. Considering the classification problems from 1 to 3 correspond to small, from 4 to 7 to medium and from 8 to 10 to large.

To evaluate the performance of the Scheduling Sub algorithm in PetNMA, the results have been compared with the dispatch rules SPT, LPT, MRWT, CR, ATC, MSLACK, and with the results obtained with the bottleneck. The comparison is made between the objective functions evaluated, in this case the makespan, total weighted tardiness, and weighted objective. For each of the objectives it has conducted a factorial design experiment to choose the best parameters for the genetic algorithm. The parameters chosen for the bullfights were taken from previous studies identified in the literature review. Three types of problems (small problem (2), medium problem (7), and large problem (9)) are chosen to perform the parametrization runs in the experimental design (see Tab. 7). The results of the runs, the experiment design and its graphs are in Appendix B. In the case of the weighted objective, the tests were carried out with all the weighting options for alpha and beta with one decimal, to choose the combination that finds the best results, varying them simultaneously from 0 to 1. In accordance with the tests and the experimental design and Pareto graphs, the weighted objective combination was selected 50–50. Considering the results obtained, the following values were chosen for the parameters of the genetic algorithm of the Initial Scheduling Sub algorithm:

Next, the results of 10 runs of each of the 10 problems studied are shown with the parameters chosen for each problem (see Tabs. 8–10).

TABLE 7. Parameters selected for the genetic algorithm of initial Scheduling in PetNMA.

Parameters	Nomenclature	Values	Makespan			TWT			Weighted objective		
			S	M	B	S	M	B	S	M	B
Number of generations	Maxgen	100; 200	100	100	100	200	200	200	200	200	200
Size of the initial population	P	100	100	100	100	100	100	100	100	100	100
Probability of crossing	Tc	60%; 90%	60%	60%	60%	90%	90%	90%	60%	60%	90%
Probability of mutation	Tm	10%; 50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
Intensity of mutations	Im	1; 2; 4	2	2	2	4	4	4	4	4	4
Elitism	Te1	Off, On 25%; 50%	50%	50%	Off	50%	50%	50%	50%	50%	50%

Notes. S: Small; M: Medium; B: Big.

TABLE 8. Results of the initial sub-algorithm scheduling in PetNMA for minimization Makespan.

Problem	Bottleneck	Dispatch rules									
		SPT	LPT	MRWT	EDD	CR	ATC	M. SLACK	Min		
FMS01	412	436	464	436	464	436	436	464	436		
FMS02	316	377	346	346	377	324	324	361	324		
FMS03	536	726	757	536	703	632	632	593	536		
FMS04	395	470	483	401	487	483	489	418	401		
FMS05	412	476	472	390	516	447	447	506	390		
FMS06	342	332	382	357	375	352	352	349	332		
FMS07	1143	1152	1146	1149	1110	1132	1155	1209	1110		
FMS08	470	561	559	459	574	569	552	555	459		
FMS09	269	288	288	263	298	261	275	299	261		
FMS10	753	836	935	759	814	912	873	779	759		
Problem	Active schedules with dispatch rules							Genetic algorithm			
	SPT	LPT	MRWT	EDD	CR	ATC	M. SLACK	Min	Min	Max	Average
FMS01	480	456	412	480	456	456	456	412	436	436	436
FMS02	369	357	326	377	341	367	361	326	324	324	324
FMS03	736	754	536	856	632	662	771	536	536	536	536
FMS04	483	478	395	524	465	569	478	395	394	394	394
FMS05	541	475	379	555	515	469	512	379	390	390	390
FMS06	408	468	368	394	380	398	379	368	332	332	332
FMS07	1291	1198	1164	1149	1158	1160	1323	1149	994	1036	1019.3
FMS08	682	581	487	671	582	633	693	487	442	459	453.8
FMS09	394	344	287	396	318	328	291	287	249	256	252.7
FMS10	924	977	800	995	845	999	809	800	753	753	753

TABLE 9. Results of the initial sub-algorithm scheduling in PetNMA for minimization TWT.

Problem	Bottleneck	Dispatch rules									
		SPT	LPT	MRWT	EDD	CR	ATC	M. SLACK	Min		
FMS01	0	0	0	0	0	0	0	0	0		
FMS02	0	0	0	0	0	0	0	0	0		
FMS03	1716	1919	2525	2387	2332	2177	2130	2183	1919		
FMS04	50	208	390	205	326	152	404	183	152		
FMS05	156	226	669	472	347	410	519	240	226		
FMS06	0	0	130	0	0	0	0	0	0		
FMS07	359	1852	1946	0 2672	1325	1917	2415	2369	1325		
FMS08	304	548	1882	1043	648	477	995	439	439		
FMS09	0	4	310	421	1	69	205	1	1		
FMS10	5891	8449	11 815	12 099	7347	10 642	11 293	8647	7347		
Problem	Active schedules with dispatch rules							Genetic algorithm			
	SPT	LPT	MRWT	EDD	CR	ATC	M. SLACK	Min	Min	Max	Average
FMS01	0	10	0	0	0	0	0	0	0	0	0
FMS02	0	0	0	0	3	29	0	0	0	0	0
FMS03	2008	2656	2418	3676	2158	2462	2733	2008	1577	1604	1581.6
FMS04	202	454	349	295	159	706	131	131	40	40	40
FMS05	446	1172	1014	829	679	702	614	446	144	169	155.5
FMS06	210	436	0	27	37	85	0	0	0	0	0
FMS07	3761	3079	3375	1793	2300	2664	4041	1793	476	630	563.5
FMS08	1896	2518	1933	1634	755	2065	936	755	150	294	230.2
FMS09	902	1126	654	396	186	731	0	0	0	0	0
FMS10	11 041	14 153	13 321	9160	11 586	15 680	9309	9160	6159	6944	6564.5

According to the results in the first phase of the algorithm, significant results were obtained using the GA (see Fig. 7). Makespan was improved in 50% of the instances. In these instances, an average improvement of 4% was achieved. Total weighted tardiness improved in 70% of instances. In these instances, an average improvement of 53% was achieved. The weighted objective (Makespan 50% – TWT 50%) achieved an improvement in 70% of the instances. The average improvement in these instances was 20%. The initial scheduling sub-algorithm in PetNMA has improved the results in the larger instances by comparing them with the dispatch and bottleneck rules, because in small instances the same results can be achieved in the first cycles of the sub-algorithm.

5.3. Experimental tests of the reactive scheduling sub algorithm in PetNMA

To obtain the reactive schedules with the Reactive Sub-algorithm Scheduling in PetNMA, a design of experiments was carried out using the three selected problems. For each of the objectives was conducted Taguchi Robust Design to choose the best parameters for the GA considering factors that cannot be controlled when having a breakdown machine. The factors considered to assess the performance of algorithm: Control factors (A: Number of generations, B: Size of the population, C: Probability of crossing, D: Probability of mutation, E: Intensity of mutations, F: Elitism, G: Factor decremental) and Noise factors (H: Instance of the fault, I: Variation of repair time, J: Mean time to repair). Failure scenarios two forms were generated, depending on when the scheduling horizon in which the failure occurs, the percentage of the average processing time used for the repair time of the machine, and the time variation repair. The scenarios can be identified using the following coding: $B(C_x, \gamma_1, \gamma_2)$ where, C_x corresponds to the medium and takes values from 1 to 2, γ_1 corresponds to the percentage of the average processing time and takes values 0.5 and 1.0, and γ_2 represents the variation

TABLE 10. Results of the initial sub-algorithm scheduling in PetNMA for minimization weighted global (Makespan (50%) and TWT (50%)).

Problem	Dispatch rules							
	SPT	LPT	MRWT	EDD	CR	ATC	M. SLACK	Min
FMS01	218	232	218	232	218	218	232	218
FMS02	188.5	173	173	188.5	162	162	180.5	162
FMS03	1322.5	1641	1461.5	1517.5	1404.5	1381	1388	1322.5
FMS04	342.5	466	372	409.5	312	637.5	304.5	304.5
FMS05	351	570.5	431	431.5	428.5	483	373	351
FMS06	166	256	178.5	187.5	176	176	174.5	166
FMS07	1502	1546	1910.5	1217.5	1524.5	1785	1789	1217.5
FMS08	554.5	1220.5	751	611	523	773.5	497	497
FMS09	146	299	342	149	165	240	150	146
FMS10	4642.5	6375	6429	4080	5777	6083	4713	4080

Problem	Active schedules with dispatch rules (PetNMA)							Genetic algorithm			
	SPT	LPT	MRWT	EDD	CR	ATC	M SLACK	Min	Min	Max	Average
FMS01	240	233	206	240	228	228	228	206	218	218	218
FMS02	184.5	178.5	163	188.5	172	198	180.5	163	162	162	162
FMS03	1372	1705	1477	2264.5	1395	1562	1752	1372	1114.5	1123	1115.4
FMS04	339	436.5	303	406.5	317.5	446.5	300.5	300.5	242.5	242.5	242.5
FMS05	493.5	823.5	696.5	692	597	585.5	563	493.5	303.5	320	306.8
FMS06	309	452	184	210.5	208.5	241.5	189.5	184	166	166	166
FMS07	2526	2138.5	2269.5	1471	1729	1912	2682	1471	784.5	847.5	823.1
FMS08	1289	1549.5	1210	1152.5	668.5	1349	814.5	668.5	358.5	404	376.7
FMS09	648	740	470.5	396	252	529.5	145.5	145.5	128	130.5	128.7
FMS10	5982.5	7565	7060.5	5077.5	6215.5	8339.5	5059.5	5059.5	3559.5	3735.5	3632.9

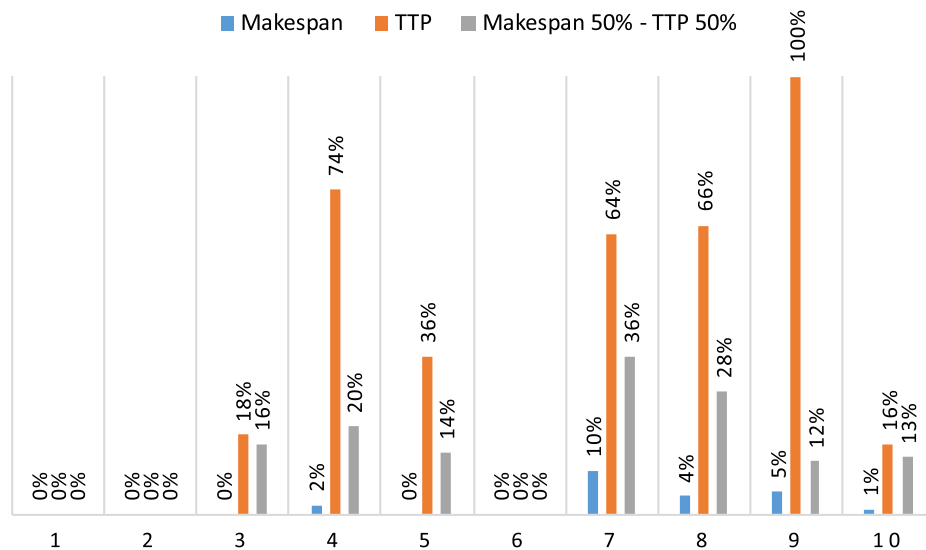


FIGURE 7. Variation of the objectives in the GA with respect to the dispatch rules. Note: TTP: Total Weighted Tardiness.

TABLE 11. Values for MA in sub-algorithm of reactive scheduling.

Parameters	Makespan			TWT			Weighted objective		
	S	M	B	S	M	B	S	M	B
Number of generations	100	100	100	200	200	200	200	100	200
Size of the initial population	100	100	50	100	100	50	50	100	50
Probability of crossing	90	90	60	60	60	90	90	90	90
Probability of mutation	10	50	10	50	50	50	10	50	50
Intensity of mutations	1	2	1	2	2	2	4	4	1
Elitism	50	0	0	0	0	50	0	0	50
Factor decremental	0.1	0.01	0.01	0.1	0.1	0.01	0.1	0.01	0.01

Notes. S: Small; M: Medium; B: Big.

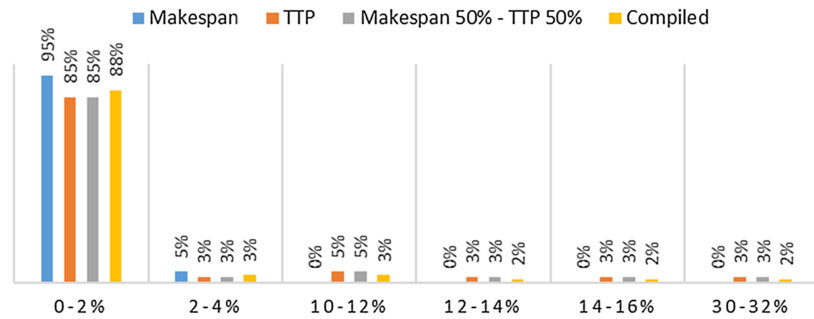


FIGURE 8. Percentage of improvement of the final objective with respect to the rules of dispatch.

with values of 0.02 and 0.05. According to the results obtained in the experimental design (see Appendix B) the following values have been selected for the memetic algorithm of the Reactive Scheduling Sub algorithm in PetNMA (Tab. 11).

The small problem always gets the best result both for the makespan and for the Total weighted tardiness in the first generation because few operations must be programmed in a few machines, so the dispatch rules get good schedules. For the total weighted tardiness, both the small problem and the large one gets good answers, the medium problem has high delays because most of the jobs start in the same stations and therefore, they are bottled in them. For the weighted objective, good results are obtained in the small and large instances, the same inconvenience of the total weighted tardiness in the medium instances is had. The results and graphs of the designs of the experiments carried out can be seen in Appendix C. Next, the results of a run of each of the 10 problems studied are shown in the Tables 12–14.

Considering the results, we can present the following conclusions of the experimental tests developed:

- 95%, 85%, and 85 of the results in the rescheduling of production with PETNMA generated improvements between 0% and 2% with respect to the values obtained by the dispatch rules for the makespan. Total weighted tardiness and the objective weighted respectively. 12% of the instances evaluated have improvements greater than 2% (see Fig. 8).
- The algorithm was able to generate different variations in the different instances and rescheduling minimized those variations. On average 58% of the results had variations between 0% and 2% with respect to the initial scheduling. 33% of the instances had variations between 2% and 60%. While 10% exceeded 100% variations (see Fig. 9).

For the weighted objective, in scenarios 1 and 4, the machine failure occurs in the first half of the initial scheduling horizon shows that the variation of the final scheduling is greater than the initial scheduling.

TABLE 12. Results of the PetNMA for the evaluation of the Makespan.

Instance	Failure scenario	Schedule initial	SPT	LPT	MRWT	EDD	CR	ATC	M. SLACK	Memetic algorithm	Variation (%)
FMS01_6_10_19	1	412	468	468	468	1566	1497	1578	1000	452	9.71
	2	412	413	413	413	826	751	810	630	413	0.24
	3	412	412	412	412	537	492	513	487	412	0.00
	4	412	412	412	412	1162	1074	1141	695	412	0.00
FMS02_9_8_20	1	324	324	324	324	2215	2009	2217	591	324	0.00
	2	324	324	324	324	647	578	636	489	324	0.00
	3	324	324	324	324	533	505	529	400	324	0.00
	4	324	324	375	324	1467	1296	1454	636	324	0.00
FMS03_10_5_10	1	536	632	624	536	1711	1388	1726	949	536	0.00
	2	536	623	623	623	623	623	623	623	623	16.23
	3	536	536	536	536	573	573	573	537	536	0.00
	4	536	719	711	623	1581	1264	1522	1001	623	16.23
FMS04_10_5_12	1	394	406	426	394	1655	1471	1675	1136	394	0.00
	2	394	394	394	394	918	763	918	762	394	0.00
	3	394	394	394	394	873	763	868	736	394	0.00
	4	394	417	432	401	2224	1934	2247	1162	394	0.00
FMS05_10_5_12	1	379	437	472	406	1665	1314	1672	856	406	7.12
	2	379	408	408	408	417	408	408	417	408	7.65
	3	379	420	420	420	420	431	431	431	420	10.82
	4	379	491	472	438	2222	2048	2198	807	438	15.57
FMS06_10_7_18	1	332	332	349	332	1536	1279	1541	581	332	0.00
	2	332	404	439	367	1226	1040	1238	573	359	8.13
	3	332	332	335	332	1133	858	1117	566	332	0.00
	4	332	332	351	333	2314	2030	2278	632	332	0.00
FMS07_10_10_20	1	1012	1032	1091	1061	3878	3704	3884	2780	1032	1.98
	2	1012	1015	1051	1015	1998	1806	1969	1573	1015	0.30
	3	1002	1002	1002	1002	1808	1592	1811	1401	1002	0.00
	4	1002	1007	1089	1007	3746	3502	3686	2660	1007	0.50
FMS08_15_5_12	1	451	464	489	1477	1806	1471	1772	1073	464	2.88
	2	451	544	544	544	544	544	544	544	544	20.62
	3	456	583	526	493	1479	1351	1523	1012	493	8.11
	4	448	580	586	514	2842	2441	2871	1335	499	11.38
FMS09_15_6_17	1	253	264	269	259	1736	1513	1754	861	259	2.37
	2	254	274	274	274	288	299	299	299	274	7.87
	3	254	271	271	271	286	299	299	299	271	6.69
	4	254	273	276	259	1578	1282	1578	930	259	1.97
FMS10_20_6_13	1	753	758	767	753	1634	1422	1605	1478	753	0.00
	2	753	804	839	782	1274	1130	1274	1293	782	3.85
	3	753	813	813	813	813	813	813	813	813	7.97
	4	753	758	935	754	2722	2387	2698	2291	754	0.13
Average variation											4.21

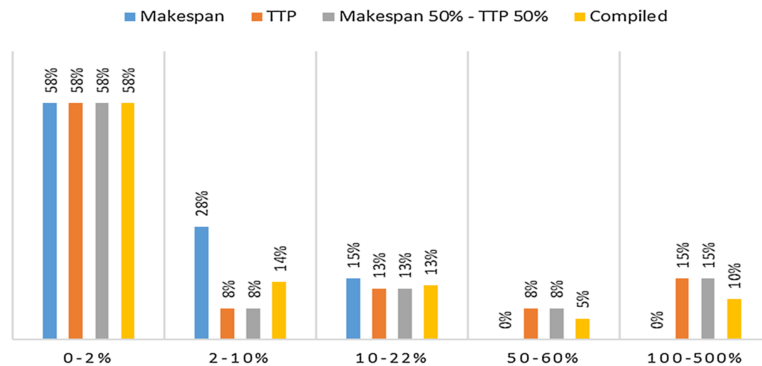


FIGURE 9. Percentage of variation of the final objective with respect to the initial scheduling.

TABLE 13. Results of the PetNMA for the evaluation of the TWT.

Instance	Failure scenario	Schedule initial	SPT	LPT	MRWT	EDD	CR	ATC	M. SLACK	Memetic algorithm	Variation (%)
FMS01_6_10_19	1	0	0	0	0	4452	5962	5086	549	0	0.00
	2	0	0	0	0	407	1179	720	160	0	0.00
	3	0	0	0	0	2	0	0	0	0	0.00
	4	0	0	0	0	4349	5532	4951	978	0	0.00
FMS02_9_8_20	1	0	0	0	0	9700	9690	11 525	2997	0	0.00
	2	0	0	0	0	0	0	0	0	0	0.00
	3	0	0	0	0	78	0	0	0	0	0.00
	4	0	0	0	0	10 433	8994	11 349	2003	0	0.00
FMS03_10_5_10	1	1577	1602	1832	1728	10 215	9791	10 539	4415	1602	1.59
	2	1577	1721	1721	1721	1721	1721	1721	1721	1721	9.13
	3	1577	1625	1625	1625	1820	1644	1820	1761	1625	3.04
	4	1577	1814	2350	2273	18 336	11 920	15 360	9844	1751	11.03
FMS04_10_5_12	1	40	58	58	58	4188	5518	6625	2439	40	0.00
	2	40	79	64	79	808	1115	1311	1008	64	60.00
	3	40	108	108	108	1461	2977	3262	1208	108	170.00
	4	40	211	660	480	19 068	19 116	18 957	4644	211	427.50
FMS05_10_5_12	1	155	390	558	694	16 057	15 124	14 067	4848	390	151.61
	2	155	326	326	326	587	794	794	587	326	110.32
	3	155	392	392	392	392	392	392	392	392	152.90
	4	155	339	567	577	10 366	11 112	10 916	6662	339	118.71
FMS06_10_7_18	1	0	3	10	0	17 552	18 933	20 755	970	0	0.00
	2	0	14	14	14	38	92	92	26	14	1400.00
	3	0	10	93	0	6386	5559	6605	1190	0	0.00
	4	0	10	93	0	6313	6363	7370	1486	0	0.00
FMS07_10_10_20	1	580	900	1216	1433	30 793	35 793	37 894	11 996	900	55.17
	2	623	935	935	935	1113	1572	1572	1113	935	50.08
	3	623	653	653	653	4551	5703	9386	2295	653	4.82
	4	565	806	743	565	12 214	19 047	20 570	8494	565	0.00
FMS08_15_5_12	1	6302	8390	8263	8764	20 039	17 132	22 439	15 851	7120	12.98
	2	6371	6415	6424	6415	6446	6484	6441	6446	6415	0.69
	3	6304	6308	6308	6308	6351	6370	6474	6364	6308	0.06
	4	6602	9351	9319	9903	22 234	26 654	31 504	17 629	7846	18.84
FMS09_15_6_17	1	0	0	100	270	39 606	30 797	35 605	11 571	0	0.00
	2	0	0	0	0	258	728	728	258	0	0.00
	3	0	0	0	0	816	1216	1328	700	0	0.00
	4	0	12	0	12	8784	8577	11 671	3643	0	0.00
FMS10_20_6_13	1	6187	8486	10 114	12 188	41 807	61 377	72 272	15 509	7501	21.24
	2	6660	6714	6771	6714	8752	8109	9562	8898	6714	0.81
	3	6465	6475	6475	6475	6475	6475	6475	6475	6475	0.15
	4	6420	8318	10 100	11 189	31 016	45 209	63 663	19 604	7454	16.11
Average variation											69.92

The variation of the time of the major machine failure is where the variation of the final scheduling is greater than the initial scheduling. For the Total Weighted Tardiness, in scenarios 3 and 4 with the longest failure time of the machine, the variation of the final scheduling is greater than the initial scheduling (see Fig. 10).

6. CONCLUSION

The model is a novel proposal that integrates the Petri net technique as an effective method for production scheduling. The innovative component of the proposed model has two key elements considering the state of the art. First integrate the Petri nets with a genetic algorithm to develop active initial scheduling, second integrate the use of Memetic algorithms with Petri nets for a production rescheduling environment. The integration of Petri net starts from the generation of active schedules that guarantees closer to good results, and their configuration when the machine failure occurs allows to validation of the busiest machines and the workflow to reduce the disturbance for rescheduling. This research is considered a pioneer in a memetic algorithm decoded by Petri nets in an environment of rescheduling when there is a failure or breakdown of machines. The proposed model establishes a modification of the libraries usually used to have different ranges of scenarios. The stages

TABLE 14. Results of the PetNMA for the evaluation of the weighted objective.

Instance	Failure scenario	Schedule initial	SPT	LPT	MRWT	EDD	CR	ATC	M. SLACK	Memetic algorithm	Variation (%)
FMS01_6_10_19	1	206	222	232	222	2519	3459	3126	1376.5	213	3.40
	2	206	206	206	206	296	368	370.5	253.5	206	0.00
	3	206	209	209	209	227	246.5	246.5	223	209	1.46
	4	206	220	224	224	1814.5	1628	1733.5	844.5	220	6.80
FMS02_9_8_20	1	162	162	162	162	6355.5	5001.5	7551.5	790	162	0.00
	2	162	162	162	162	1580	1461	2017.5	229.5	162	0.00
	3	162	162	162	162	452	729	907.5	240	162	0.00
	4	162	168.5	167	167	9826.5	7813.5	9952.5	478.5	167	3.09
FMS03_10_5_10	1	1114.5	1559.5	1686.5	1569	5821.5	4393	4736.5	2535.5	1490.5	33.74
	2	1114.5	1338	1314.5	1300.5	3011	2103.5	3672	1674.5	1300.5	16.69
	3	1123	1123	1123	1123	1594.5	1290	1614	1240	1123	0.00
	4	1114.5	1284	1481.5	1404.5	12 349	10 229.5	10 847.5	4929.5	1284	15.21
FMS04_10_5_12	1	242.5	313.5	348	351	9730	9588	10 172	4516	271	11.75
	2	242.5	242.5	242.5	242.5	894.5	890.5	1046	532	242.5	0.00
	3	242.5	242.5	242.5	242.5	259.5	295	295	270	242.5	0.00
	4	242.5	344.5	433.5	296.5	10 458	9714	10 139	4654	284.5	17.32
FMS05_10_5_12	1	306.5	389.5	379	382	7171	6262	6309	3213	379	23.65
	2	307	374	374	374	432	432	432	432	374	21.82
	3	306.5	324	324	324	532	447.5	447.5	432.5	324	5.71
	4	307.5	409	522	497.5	6498	6651	6458.5	4973	393	27.80
FMS06_10_7_18	1	166	171	174.5	171	6256.5	6059	6718.5	2239.5	171	3.01
	2	166	192	180.5	178.5	3736.5	4332.5	4431.5	877	178.5	7.53
	3	166	182	190	182	2026	2131.5	2662.5	658.5	182	9.64
	4	166	206.5	198	175.5	8319	9067.5	9477	936.5	175.5	5.72
FMS07_10_10_20	1	833	1064	1292	1021.5	7489	8891.5	8768	3740	1021.5	22.63
	2	823	917.5	917.5	917.5	1119.5	1342.5	1342.5	1119.5	917.5	11.48
	3	849	888	882.5	888	1009.5	1415.5	1611	1263	882.5	3.95
	4	838	1008	1513.5	1167.5	17 187	17 997.5	19 797	9656	885	5.61
FMS08_15_5_12	1	386.5	559	742	735.5	16 469	16 095	19 489.5	4278.5	559	44.63
	2	390	465.5	465.5	465.5	1852.5	2191	2723.5	940.5	465.5	19.36
	3	389	422	422	422	1057.5	908.5	908.5	669	422	8.48
	4	389	575	763	788.5	5443	6725	9196.5	2788	559.5	43.83
FMS09_15_6_17	1	128	195.5	245.5	227.5	13 500.5	12 903	13 781	4510.5	147	14.84
	2	128	130	130	130	137.5	145.5	145.5	142	130	1.56
	3	128	175	164.5	161	2961	2712.5	3650	1085	154.5	20.70
	4	128	130.5	146	204	8533.5	8093.5	9545.5	3243.5	130	1.56
FMS10_20_6_13	1	3707.5	4911.5	6044	6446.5	16 751.5	25 896.5	28 613.5	8555.5	4479.5	20.82
	2	3589	3665.5	3665.5	3665.5	3833.5	3696	3767	3833.5	3665.5	2.13
	3	3609.5	3806.5	3924.5	4158	8959	7162.5	9012	6029	3608.5	-0.03
	4	3721	4661	5643	6199	22 585	35 414.5	36 346.5	10 281.5	4147.5	11.46
Average variation											11.18

of failure of the machine were considered in four instances that allow the introduction or simulation of faults in different stages of production.

PetNMA is able to generate small variations in the different test instances of the algorithm. On average, 58% of the results obtained had variations in the performance measures, with respect to the initial scheduling between 0% and 2%. The initial scheduling sub-algorithm in PetNMA manages to improve the results considering the makespan and total weighted tardiness objectives, comparing them with the dispatch rules. The use of Simulated Annealing prevents the algorithm from falling into local optima. The low response variability in the rescheduling is a sample of the robustness and flexibility of the new method proposed.

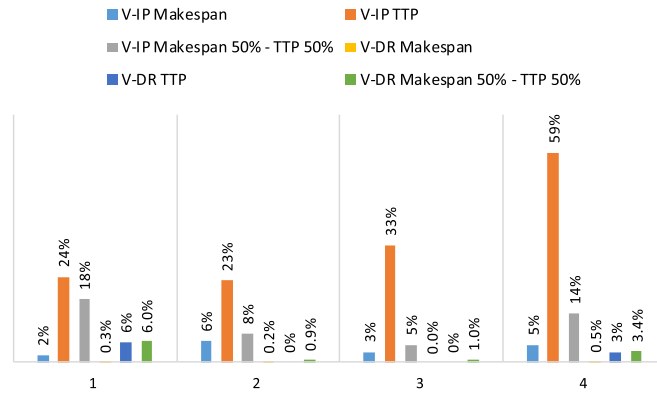


FIGURE 10. Variation of the final objective *vs.* initial scheduling and dispatch rules in machine failure scenarios.

6.1. Managerial insight and industrial application

There are key factors for the implementation and management of the proposed model for the reactive scheduling of production due to the occurrence of machine breakdowns in the FMS, which justify it:

- Instant when the fault occurs: when the failure occurs in the last quartile of the scheduling horizon, it is more difficult to find a good reactive production schedule. However, computational times are less when the failure happens at the beginning of production because the chromosome is more extensive.
- Repair time of the machine that fails: when the repair time is longer, the variation of the final objective with respect to the initial objective tends to be larger, because a machine is disabled for a longer time.
- The number of machines in the system: when the systems are larger, there is a greater probability of finding good reactive production schedules since the operations can be rescheduling in the other machines of the station where the machine with the fault is located.

6.2. Future research

As future research, the implementation of the algorithm in a real environment is proposed, due to the occurrence of machine failure. Tian *et al.* [57] describe that in practical applications of scheduling and rescheduling, optimization of multiple objectives often are involved. Another option is the inclusion of new parameters such as machine setup times depending on the sequence of operations and transport time between stations [52]. Consideration of other random events on the plant floor, such as order cancellations, new jobs, and change in processing priorities [42]. Use of new neighborhood structures for the Memetic Algorithm, as a strategy to explore the solution space of active schedules in an FMS environment. Such efforts would contribute to extend and enrich the body of knowledge in the areas of static and dynamic production scheduling in FMS [28].

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APPENDIX A. USED PROBLEMS

The following are the specifications of the problems used to evaluate the PetNMA algorithm with the following coding system:

FMSXX_J_S_M with: XX. Identification of the Problem Number (01, 02, ...).

J. Number of Jobs to Schedule.

S. Number of stations in the FMS.

M. Total number of machines in the FMS.

To represent the characteristics of the system and each of the works, the following structures are used:

- Vectors two positions to characterize the information of each station.

(Identification of the Station, Number of Machines in the Station)

- Three-position vectors to characterize the job information.

(Id, Time Availability, Delivery Date)

- Vectors two positions opposite each job to characterize the operations information. The order in which the operations are recorded in front of the works, represent their sequence by the stations.

(Station, Processing Time)

FMS01_6_10_19

Six (6) jobs, ten (10) stations and a total of nineteen (19) machines.

(W001, 2)(W002, 2)(W003, 1)(W004, 2)(W005, 2)(W006, 1)(W007, 3)(W008, 2)(W009, 1)(W010, 3)
 (1, 0, 397) (W008, 23)(W002, 44)(W009, 34)(W004, 48)(W001, 43)(W003, 28)(W006, 42)(W005, 44)(W010, 41)(W007, 50)
 (2, 0, 325) (W001, 44)(W008, 39)(W010, 34)(W006, 36)(W005, 21)(W007, 24)(W004, 37) (W002, 35)(W009, 35)(W003, 20)
 (3, 0, 373) (W003, 33)(W006, 35)(W002, 23)(W010, 44)(W009, 31)(W004, 41)(W007, 42) (W008, 49)(W001, 49)(W005, 26)
 (4, 0, 313) (W009, 29)(W008, 39)(W003, 20)(W007, 32)(W005, 25)(W004, 27)(W010, 42) (W006, 45)(W001, 28)(W002, 26)
 (5, 0, 294) (W006, 23)(W001, 47)(W008, 31)(W005, 20)(W010, 30)(W009, 20)(W003, 25) (W002, 31)(W007, 46)(W004, 21)
 (6, 0, 390) (W005, 46)(W002, 41)(W006, 48)(W008, 24)(W001, 44)(W003, 48)(W007, 24) (W004, 26)(W009, 40)(W010, 49)

FMS02_9_8_20

Nine (9) jobs, eight (8) stations and a total of twenty (20) machines.

(W001, 2)(W002, 3)(W003, 2)(W004, 3)(W005, 2)(W006, 3)(W007, 3)(W008, 2)
 (1, 0, 310) (W001, 40)(W006, 42)(W005, 31)(W003, 24)(W008, 42)(W007, 43)(W004, 38)(W002, 50)
 (2, 0, 235) (W003, 27)(W001, 31)(W008, 23)(W007, 34)(W006, 28)(W005, 29)(W002, 40) (W004, 23)
 (3, 0, 314) (W003, 42)(W001, 49)(W002, 42)(W008, 40)(W007, 31)(W004, 32)(W005, 28) (W006, 50)
 (4, 0, 250) (W002, 25)(W004, 32)(W006, 21)(W005, 21)(W007, 48)(W008, 33)(W001, 22) (W003, 48)
 (5, 0, 271) (W004, 31)(W002, 40)(W005, 38)(W001, 38)(W006, 28)(W003, 29)(W007, 33) (W008, 34)
 (6, 0, 254) (W003, 29)(W005, 37)(W006, 20)(W008, 36)(W004, 29)(W007, 45)(W001, 24) (W002, 34)
 (7, 0, 265) (W004, 50)(W002, 42)(W003, 35)(W007, 29)(W006, 21)(W008, 25)(W005, 35) (W001, 28)
 (8, 0, 272) (W006, 35)(W004, 32)(W002, 34)(W003, 40)(W001, 46)(W005, 40)(W007, 24) (W008, 21)
 (9, 0, 269) (W007, 38)(W008, 40)(W003, 35)(W004, 31)(W001, 32)(W005, 24)(W006, 25) (W002, 44)

FMS04_10_5_12

Ten (10) works, five (5) stations and a total of twelve (12) machines.

(W001, 3)(W002, 2)(W003, 2)(W004, 3)(W005, 2)
 (1, 0, 231) (W001, 20)(W004, 87)(W002, 31)(W005, 76)(W003, 17)
 (2, 0, 180) (W005, 25)(W003, 32)(W001, 24)(W002, 18)(W004, 81)
 (3, 0, 280) (W002, 72)(W003, 23)(W005, 28)(W001, 58)(W004, 99)
 (4, 0, 394) (W003, 86)(W002, 76)(W005, 97)(W001, 45)(W004, 90)
 (5, 0, 180) (W005, 27)(W001, 42)(W004, 48)(W003, 17)(W002, 46)
 (6, 0, 231) (W002, 67)(W001, 98)(W005, 48)(W004, 27)(W003, 62)
 (7, 0, 180) (W005, 28)(W002, 12)(W004, 19)(W001, 80)(W003, 50)
 (8, 0, 280) (W002, 63)(W001, 94)(W003, 98)(W004, 50)(W005, 80)
 (9, 0, 394) (W005, 14)(W001, 75)(W003, 50)(W002, 41)(W004, 55)
 (10, 0, 180) (W005, 72)(W003, 18)(W002, 37)(W004, 79)(W001, 61)

FMS05_10_5_12

Ten (10) jobs, five (5) stations and a total of twelve (12) machines.

(W001, 2)(W002, 3)(W003, 3)(W004, 2)(W005, 2)
 (1, 0, 272) (W002, 23)(W003, 45)(W001, 82)(W005, 84)(W004, 38)
 (2, 0, 159) (W003, 21)(W002, 29)(W001, 18)(W005, 41)(W004, 50)
 (3, 0, 212) (W003, 38)(W004, 54)(W0005, 16)(W001, 52)(W002, 52)
 (4, 0, 284) (W005, 37)(W001, 54)(W003, 74)(W002, 62)(W004, 57)
 (5, 0, 297) (W005, 57)(W001, 81)(W002, 61)(W004, 68)(W003, 30)
 (6, 0, 349) (W005, 81)(W001, 79)(W002, 89)(W003, 89)(W004, 11)
 (7, 0, 230) (W004, 33)(W003, 20)(W001, 91)(W005, 20)(W002, 66)
 (8, 0, 203) (W005, 24)(W002, 84)(W001, 32)(W003, 55)(W004, 8)
 (9, 0, 220) (W005, 56)(W001, 7)(W004, 54)(W003, 64)(W002, 39)
 (10, 0, 157) (W005, 40)(W002, 83)(W001, 19)(W003, 8)(W004, 7)

FMS06_10_7_18

Ten (10) jobs, seven (7) stations and a total of eighteen (18) machines.

(W001, 2)(W002, 2)(W003, 3)(W004, 2)(W005, 3)(W006, 3)(W007, 3)
 (1, 0, 272) (W007, 25)(W006, 44)(W005, 45)(W004, 42)(W001, 27)(W002, 49)(W003, 40)
 (2, 0, 287) (W005, 40)(W007, 28)(W004, 46)(W006, 46)(W003, 41)(W002, 39)(W001, 47)
 (3, 0, 247) (W003, 32)(W001, 49)(W002, 39)(W004, 43)(W005, 20)(W006, 35)(W007, 29)
 (4, 0, 259) (W004, 26)(W005, 25)(W003, 35)(W001, 46)(W002, 50)(W007, 35)(W006, 42)
 (5, 0, 244) (W004, 26) (W005, 29)(W006, 27)(W001, 43)(W002, 44)(W007, 37)(W003, 38)
 (6, 0, 272) (W003, 48) (W007, 36)(W004, 21)(W001, 42)(W005, 36)(W002, 46)(W006, 43)
 (7, 0, 217) (W005, 38) (W006, 21)(W004, 20)(W002, 40)(W003, 36)(W001, 36)(W007, 26)
 (8, 0, 271) (W005, 39) (W007, 49)(W004, 37)(W006, 36)(W002, 42)(W001, 42)(W003, 26)
 (9, 0, 271) (W004, 32) (W003, 39)(W007, 22)(W001, 46)(W005, 42)(W006, 40)(W002, 50)
 (10, 0, 258) (W005, 46) (W007, 42)(W003, 50)(W002, 20)(W006, 20)(W004, 39)(W001, 41)

FMS07_10_10_20

Ten (10) jobs, ten (10) stations and a total of twenty (20) machines.

(W001, 2)(W002, 1)(W003, 2)(W004, 2)(W005, 3)(W006, 2)(W007, 3)(W008, 2)(W009, 2)(W010, 1)
 (1, 0, 523) (W001, 72) (W002, 64)(W003, 55)(W004, 31)(W005, 53)(W006, 95)(W007, 11)(W008, 52)(W009, 6)(W010, 84)
 (2, 0, 667) (W001, 61) (W004, 27)(W005, 88)(W003, 78)(W002, 49)(W006, 83)(W009, 91) (W007, 74)(W008, 29)(W010, 87)
 (3, 0, 489) (W001, 86) (W004, 32)(W002, 35)(W003, 37)(W006, 18)(W005, 48)(W007, 91) (W008, 52)(W010, 60)(W009, 30)
 (4, 0, 509) (W001, 8) (W002, 82)(W005, 27)(W004, 99)(W007, 74)(W006, 9)(W003, 33)(W0010, 20)(W008, 59)(W009, 98)
 (5, 0, 476) (W002, 50) (W001, 94)(W006, 43)(W004, 62)(W005, 55)(W008, 487)(W003, 5)(W009, 36)(W010, 47)(W007, 36)
 (6, 0, 407) (W001, 53) (W007, 30)(W003, 7)(W004, 12)(W002, 68)(W009, 87)(W005, 28) (W010, 70)(W008, 45)(W006, 7)
 (7, 0, 502) (W003, 29) (W004, 96)(W001, 99)(W002, 14)(W005, 34)(W008, 14)(W006, 7) (W007, 76)(W009, 57)(W010, 76)
 (8, 0, 695) (W003, 90) (W001, 19)(W004, 87)(W005, 51)(W002, 84)(W006, 45)(W010, 84)(W007, 58)(W008, 81)(W009, 96)
 (9, 0, 617) (W003, 97) (W002, 99)(W005, 93)(W001, 38)(W008, 13)(W006, 96)(W004, 40)(W010, 64)(W007, 32)(W009, 45)
 (10, 0, 524) (W003, 44) (W001, 60)(W009, 29)(W004, 5)(W007, 74)(W002, 85)(W005, 34)(W008, 95)(W010, 51)(W006, 47)

FMS08_15_5_12

Fifteen (15) jobs, five (5) stations and a total of twelve (12) machines.

(W001, 3)(W002, 2)(W003, 2)(W004, 2)(W005, 3)
 (1, 0, 258) (W002, 21)(W003, 34)(W005, 95)(W001, 53)(W004, 55)
 (2, 0, 186) (W004, 52)(W005, 16)(W002, 71)(W003, 26)(W001, 21)
 (3, 0, 222) (W003, 31)(W001, 12)(W002, 42)(W004, 39)(W005, 98)
 (4, 0, 354) (W004, 77)(W002, 77)(W005, 79)(W001, 55)(W003, 66)
 (5, 0, 237) (W005, 37)(W004, 34)(W003, 64)(W002, 19)(W001, 83)
 (6, 0, 330) (W003, 43)(W002, 54)(W001, 92)(W004, 62)(W005, 79)
 (7, 0, 413) (W001, 93)(W004, 69)(W002, 87)(W005, 77)(W003, 87)
 (8, 0, 246) (W001, 60)(W002, 41)(W003, 38)(W005, 83)(W004, 24)
 (9, 0, 233) (W003, 98)(W004, 17)(W005, 25)(W001, 44)(W002, 49)
 (10, 0, 370) (W001, 96)(W005, 77)(W004, 79)(W002, 75)(W003, 43)
 (11, 0, 241) (W005, 28)(W003, 35)(W001, 95)(W004, 76)(W002, 7)
 (12, 0, 210) (W001, 61)(W005, 10)(W003, 95)(W002, 9)(W004, 35)
 (13, 0, 271) (W005, 59)(W004, 16)(W002, 91)(W003, 59)(W001, 46)
 (14, 0, 200) (W005, 43)(W002, 52)(W001, 28)(W003, 27)(W004, 50)
 (15, 0, 221) (W001, 87)(W002, 45)(W003, 39)(W005, 9)(W004, 41)

FMS09_15_6_17

Fifteen (15) jobs, six (6) stations and a total of seventeen (17) machines.

(W001, 3)(W002, 3)(W003, 2)(W004, 2)(W005, 3)(W006, 4)
 (1, 0, 156) (W001, 24)(W004, 20)(W002, 13)(W003, 27)(W006, 38)(W005, 34)
 (2, 0, 181) (W006, 32)(W004, 18)(W002, 37)(W001, 32)(W005, 23)(W003, 39)
 (3, 0, 116) (W003, 15)(W004, 11)(W006, 10)(W002, 29)(W005, 13)(W001, 38)
 (4, 0, 213) (W005, 27)(W006, 18)(W003, 47)(W002, 28)(W001, 50)(W004, 43)
 (5, 0, 169) (W004, 39)(W005, 26)(W003, 14)(W002, 14)(W001, 31)(W006, 45)
 (6, 0, 177) (W003, 32)(W001, 50)(W005, 23)(W006, 28)(W004, 19)(W002, 25)
 (7, 0, 170) (W002, 49)(W003, 38)(W004, 23)(W005, 14)(W001, 32)(W006, 14)
 (8, 0, 210) (W006, 29)(W001, 15)(W003, 48)(W002, 50)(W005, 36)(W004, 32)
 (9, 0, 222) (W006, 44)(W005, 28)(W004, 45)(W001, 26)(W002, 47)(W003, 32)
 (10, 0, 192) (W005, 23)(W004, 50)(W006, 36)(W003, 25)(W002, 30)(W001, 28)
 (11, 0, 148) (W001, 40)(W002, 24)(W004, 18)(W005, 12)(W006, 17)(W003, 37)
 (12, 0, 153) (W006, 21)(W002, 31)(W005, 12)(W003, 30)(W001, 27)(W004, 32)
 (13, 0, 227) (W005, 35)(W003, 10)(W006, 50)(W001, 49)(W002, 35)(W004, 48)
 (14, 0, 201) (W006, 45)(W004, 35)(W001, 30)(W002, 29)(W003, 31)(W005, 31)
 (15, 0, 130) (W001, 22)(W003, 25)(W002, 13)(W004, 38)(W006, 17)(W005, 15)

FMS10_20_6_13

Twenty (20) jobs, six (6) stations and a total of thirteen (13) machines.

(W001, 2)(W002, 1)(W003, 3)(W004, 3)(W005, 3)(W006, 1)
 (1, 0, 178) (W005, 40)(W003, 33)(W006, 26)(W001, 22)(W002, 26)(W004, 31)
 (2, 0, 239) (W004, 50)(W002, 34)(W005, 32)(W003, 46)(W001, 38)(W006, 39)
 (3, 0, 248) (W005, 31)(W004, 24)(W003, 47)(W001, 49)(W006, 47)(W002, 50)
 (4, 0, 218) (W001, 38)(W003, 43)(W004, 37)(W005, 36)(W006, 38)(W002, 26)
 (5, 0, 204) (W005, 21)(W002, 50)(W001, 29)(W003, 35)(W006, 47)(W004, 22)
 (6, 0, 191) (W003, 31)(W001, 27)(W005, 44)(W002, 21)(W004, 39)(W006, 29)
 (7, 0, 206) (W004, 33)(W005, 22)(W001, 28)(W002, 45)(W006, 39)(W003, 39)
 (8, 0, 211) (W001, 45)(W002, 21)(W005, 46)(W006, 33)(W004, 30)(W003, 36)
 (9, 0, 171) (W001, 36)(W003, 33)(W005, 24)(W002, 21)(W006, 35)(W004, 22)
 (10, 0, 196) (W004, 40)(W003, 30)(W002, 32)(W006, 36)(W005, 24)(W001, 34)

(11, 0, 241) (W006, 44)(W002, 42)(W001, 24)(W003, 36)(W005, 46)(W004, 49)
 (12, 0, 170) (W004, 23)(W005, 30)(W001, 37)(W003, 30)(W006, 21)(W002, 29)
 (13, 0, 223) (W005, 48)(W003, 47)(W004, 31)(W001, 26)(W006, 28)(W002, 43)
 (14, 0, 210) (W006, 36)(W003, 33)(W004, 37)(W001, 23)(W005, 46)(W002, 35)
 (15, 0, 193) (W003, 27)(W002, 40)(W004, 30)(W006, 42)(W001, 24)(W005, 30)
 (16, 0, 245) (W001, 44)(W005, 36)(W006, 42)(W004, 40)(W002, 48)(W003, 35)
 (17, 0, 223) (W003, 27)(W004, 32)(W002, 43)(W005, 37)(W001, 50)(W006, 34)
 (18, 0, 174) (W003, 20)(W002, 25)(W001, 29)(W005, 26)(W004, 30)(W006, 44)
 (19, 0, 204) (W001, 31)(W002, 23)(W004, 22)(W005, 38)(W006, 50)(W003, 40)
 (20, 0, 188) (W005, 26)(W004, 22)(W001, 20)(W006, 43)(W002, 29)(W003, 48)

APPENDIX B. DESIGN OF EXPERIMENTS SUB ALGORITHM INITIAL SCHEDULING

The experimental tests for the parameterization of the initial scheduling sub-algorithm were made in 3 previously selected problems. The small problem yielded the same results regardless of the combination of parameters, in which experiments in medium and large targets problems are studied. Design experiments were performed in Statgraphics Centurion software (Figs. B.1 and B.2, Tabs. B.1–B.6).

TABLE B.1. Experiment designs (Makespan – Medium Problem – No. 7): analysis of variance improved.

Source	Sum of squares	Df	Mean square	F-ratio	P-value
Main effects					
A: Intensity of mutation	334.389	2	167.194	2.03	0.1494
B: Percentage of elitism	29.5556	2	14.7778	0.18	0.8366
C: Probability of crossing	100.0	1	100.0	1.21	0.2795
D: Probability of mutation	484.0	1	484.0	5.88	0.0218
Interactions					
Residual	2387.28	29		82.3199	
Total (Corrected)		3335.22		35	

TABLE B.2. Experiment designs (Makespan – Big Problem – No. 9): analysis of variance improved.

Source	Sum of squares	Df	Mean square	F-ratio	P-value
Main effects					
A: Intensity of mutation	9.05556	2	4.52778	1.27	0.2969
B: Percentage of elitism	0.388889	2	0.194444	0.05	0.9472
C: Probability of crossing	13.4444	1	13.4444	3.76	0.0622
D: Probability of mutation	16.0	1	16.0	4.48	0.0431
Interactions					
Residual	103.667	29		3.57471	
Total (Corrected)		142.556		35	

TABLE B.3. Experiment designs (TWT – Medium and Big Problem): analysis of variance improved.

Source	Sum of squares	Df	Mean square	<i>F</i> -ratio	<i>P</i> -value
Main effects					
A: Intensity of mutation	38 848.2	2	19 424.1	2.50	0.0998
B: Percentage of elitism	155 545	2	77 772.3	10.00	0.0005
C: Probability of crossing	2025.0	1	2025.0	0.26	0.6137
D: Probability of mutation	13 301.8	1	13 301.8	1.71	0.2012
Interactions					
Residual	225 483	29		7775.29	
Total (Corrected)		435 203		35	

TABLE B.4. Experiment designs (TWT – Big Problem): analysis of variance improved.

Source	Sum of squares	Df	Mean square	<i>F</i> -ratio	<i>P</i> -value
Main effects					
A: Intensity of mutation	6.23389	2	3.11694	3.59	0.0304
B: Percentage of elitism	0.842222	2	0.421111	0.49	0.5205
C: Probability of crossing	2.77778	1	2.77778	3.20	0.0741
D: Probability of mutation	3.86778	1	3.86778	4.46	0.0335
Interactions					
Residual	25.1672	29		0.867835	
Total (Corrected)		38.9		35	

TABLE B.5. Design of experiments for combination of the Weighted Objective (α Makespan + β TWT) in the Medium Problem (7).

Source/ Main effects	<i>P</i> -value 10–90	<i>P</i> -value 20–80	<i>P</i> -value 30–70	<i>P</i> -value 40–60	<i>P</i> -value 50–50	<i>P</i> -value 60–40	<i>P</i> -value 70–30	<i>P</i> -value 80–20	<i>P</i> -value 90–10
A: Intensity of mutation	0.0715	0.0108	0.7328	0.7271	0.1118	0.0311	0.0235	0.0000	0.0711
B: Percentage of elitism	0.0051	0.0255	0.0000	0.0262	0.0236	0.0449	0.0668	0.1574	0.6365
C: Probability of crossing	0.8857	0.3592	0.4780	0.0078	0.8120	0.9359	0.0114	0.0006	0.2208
D: Probability of mutation	0.5909	0.0622	0.0145	0.1377	0.8205	0.6596	0.9695	0.5104	0.6769

TABLE B.6. Design of experiments for combination of the Weighted Objective (α Makespan + β TWT) in the Big Problem (9).

Source/ effects	Main	<i>P</i> -value 10–90	<i>P</i> -value 20–80	<i>P</i> -value 30–70	<i>P</i> -value 40–60	<i>P</i> -value 50–50	<i>P</i> -value 60–40	<i>P</i> -value 70–30	<i>P</i> -value 80–20	<i>P</i> -value 90–10
A: Intensity of mutation		0.0404	0.0629	0.2188	0.1948	0.2808	0.7184	0.9123	0.5951	0.1834
B: Percentage of elitism		0.6205	0.0354	0.0017	0.0611	0.0002	0.0122	0.0434	0.3536	0.8937
C: Probability of crossing		0.0841	0.0587	0.0614	0.3431	0.8013	0.4845	0.1843	0.0579	0.0024
D: Probability of mutation		0.0435	0.0805	0.0168	0.0173	0.8013	0.4078	0.1291	0.0089	0.5186

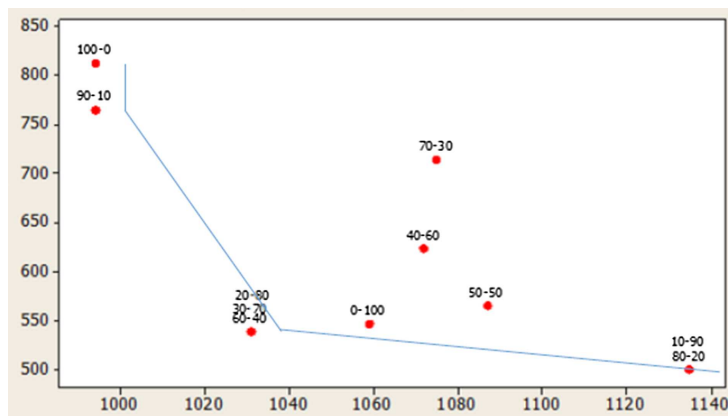


FIGURE B.1. Pareto diagram (Makespan (x) vs. TWT (y)) – Medium Problem.

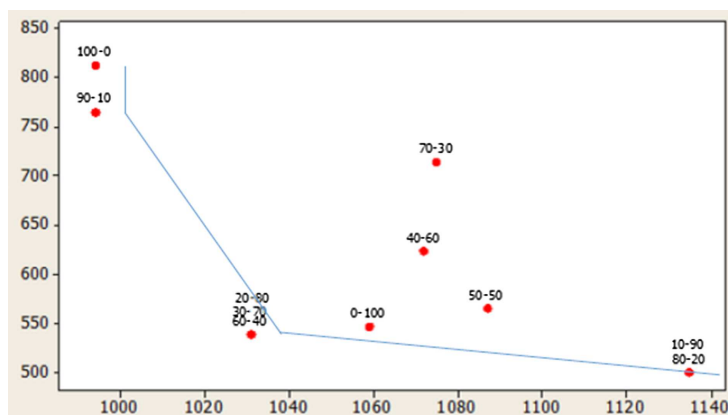


FIGURE B.2. Pareto diagram (Makespan (x) vs. TWT (y)) – Big Problem.

APPENDIX C. DESIGN OF EXPERIMENTS OF THE REACTIVE SCHEDULING SUB ALGORITHM

The experimental tests for the parameterization of the reactive scheduling sub-algorithm were made in 3 previously selected problems used for the initial scheduling sub-algorithm tests. Design experiments were performed in Statgraphics Centurion software (Tabs. C.1–C.10).

TABLE C.1. Robust design parameters for rescheduling.

Parameters of PetNMA	Nomenclature	Values
Number of generations	maxgen	100; 200
Size of the population	P	50; 100
Probability of crossing	Tc	0.6; 0.9
Probability of mutation	Tm	0.1; 0.5
Intensity of mutations	Im	1; 2; 4
Elitism	Te_1	Off. On (50%)
Decrease factor		0.01; 0.1
Instant of failure		1; 2
Repair time variation		0.02; 0.05
Average repair time		0.5; 1.0

TABLE C.2. Robust experiment design results (Taguchi) for the Makespan evaluation of the small problem.

Noise factor							H	1	2	2	1	Mean	Standard deviation	Noise/Signal
Control factor							I	0.5	0.5	1.0	1.0			
A	B	C	D	E	F	G	J	0.02	0.05	0.02	0.05	\bar{Y}	S	$-10 \log[\frac{1}{n} \sum_{i=1}^n Y_i^2]$
100	50	60	10	1	0	0.01		2.78	13.58	11.73	0.00	7.02	6.65	-19.16
100	50	60	50	2	50	0.1		5.25	0.00	0.00	4.01	2.31	2.72	-10.38
100	100	90	10	1	50	0.1		0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	100	90	50	2	0	0.01		5.25	0.00	0.31	0.00	1.39	2.58	-8.39
200	50	90	10	2	0	0.1		0.00	0.00	6.17	5.56	2.93	3.40	-12.37
200	50	90	50	1	50	0.01		0.00	4.94	0.00	0.00	1.23	2.47	-7.85
200	100	60	10	2	50	0.01		0.00	0.00	2.78	0.00	0.69	1.39	-2.85
200	100	60	50	1	0	0.1		6.79	7.10	5.56	0.00	4.86	3.31	-15.03

TABLE C.6. Robust experiment design results (Taguchi) for the TWT evaluation of the medium problem.

Noise factor							H	1	2	2	1	Mean	Standard deviation	Noise/Signal
							I	0.5	0.5	1.0	1.0			
Control factor							J	0.02	0.05	0.02	0.05	\bar{Y}	S	$-10 \log[\frac{1}{n} \sum_{i=1}^n Y_i^2]$
							A	B	C	D	E			
100	50	60	10	2	0	0.01	110.43	0.00	16.23	161.63	72.07	77.04	-39.84	
100	50	60	50	4	50	0.1	45.18	8.36	49.06	110.59	53.30	42.37	-36.22	
100	100	90	10	2	50	0.1	-3.07	47.11	7.35	235.01	71.60	111.06	-41.58	
100	100	90	50	4	0	0.01	50.00	5.63	67.22	33.11	38.99	26.24	-33.09	
200	50	90	10	4	0	0.1	120.65	16.73	0.00	79.87	54.31	56.02	-37.25	
200	50	90	50	2	50	0.01	64.53	8.62	5.81	94.22	43.30	43.40	-35.17	
200	100	60	10	4	50	0.01	30.47	0.55	3.75	99.67	33.61	46.04	-34.34	
200	100	60	50	2	0	0.1	55.17	50.08	4.82	0.00	27.52	29.13	-31.44	

TABLE C.7. Robust experiment design results (Taguchi) for the TWT evaluation of the big problem.

Noise factor							H	1	2	2	1	Mean	Standard deviation	Noise/Signal
							I	0.5	0.5	1.0	1.0			
Control factor							J	0.02	0.05	0.02	0.05	\bar{Y}	S	$-10 \log[\frac{1}{n} \sum_{i=1}^n Y_i^2]$
							A	B	C	D	E			
100	50	60	10	2	0	0.01	2100	0	0	2100	1050.00	1212.44	-63.43	
100	50	60	50	4	50	0.1	8100	3300	8400	7500	6825.00	2379.60	-77.06	
100	100	90	10	2	50	0.1	2100	0	5100	3900	2775.00	2223.17	-70.57	
100	100	90	50	4	0	0.01	0	5400	0	4700	2525.00	2929.59	-71.08	
200	50	90	10	4	0	0.1	0	0	0	1300	325.00	650.00	-56.26	
200	50	90	50	2	50	0.01	0	0	0	0	0.00	0.00	0.00	
200	100	60	10	4	50	0.01	11400	0	6000	2100	4875.00	5010.24	-76.29	
200	100	60	50	2	0	0.1	100	0	600	1200	475.00	550.00	-56.56	

TABLE C.8. Robust experiment design results (Taguchi) for the Weighted Objective evaluation of the Small problem.

Noise factor							H	1	2	2	1	Mean	Standard deviation	Noise/Signal
							I	0.5	0.5	1.0	1.0			
Control factor							J	0.02	0.05	0.02	0.05	\bar{Y}	S	$-10 \log[\frac{1}{n} \sum_{i=1}^n Y_i^2]$
							A	B	C	D	E			
100	50	60	10	2	0	0.01	0.00	12.65	11.42	4.32	7.10	5.99	-18.88	
100	50	60	50	4	50	0.1	4.32	2.16	10.49	0.00	4.24	4.52	-15.23	
100	100	90	10	2	50	0.1	0.00	0.00	12.65	0.00	3.16	6.33	-16.02	
100	100	90	50	4	0	0.01	0.00	13.89	3.09	0.00	4.24	6.59	-17.04	
200	50	90	10	4	0	0.1	0.00	0.00	0.00	3.09	0.77	1.54	-3.77	
200	50	90	50	2	50	0.01	5.25	0.00	1.54	8.33	3.78	3.75	-13.95	
200	100	60	10	4	50	0.01	0.00	0.00	12.65	0.00	3.16	6.33	-16.02	
200	100	60	50	2	0	0.1	0.00	13.89	3.09	0.00	4.24	6.59	-17.04	

TABLE C.9. Robust experiment design results (Taguchi) for the Weighted Objective evaluation of the Medium problem.

							H	1	2	2	1	Mean	Standard deviation	Noise/Signal
Noise factor							I	0.5	0.5	1.0	1.0			
							J	0.02	0.05	0.02	0.05			
Control factor												\bar{Y}	S	$-10 \log[\frac{1}{n} \sum_{i=1}^n Y_i^2]$
A	B	C	D	E	F	G								
100	50	60	10	2	0	0.01	11.28	1.31	4.36	87.61	26.14	41.19	-32.91	
100	50	60	50	4	50	0.1	50.15	11.33	40.96	12.54	28.74	19.77	-30.49	
100	100	90	10	2	50	0.1	30.15	0.45	1.73	30.69	15.75	16.94	-26.66	
100	100	90	50	4	0	0.01	22.63	11.48	3.95	5.61	10.92	8.45	-22.37	
200	50	90	10	4	0	0.1	11.74	56.55	48.13	9.88	31.58	24.24	-31.58	
200	50	90	50	2	50	0.01	5.50	9.69	25.80	32.86	18.46	12.99	-26.70	
200	100	60	10	4	50	0.01	90.57	4.24	0.00	20.81	28.90	42.08	-33.35	
200	100	60	50	2	0	0.1	33.86	31.67	5.06	107.44	44.51	43.95	-35.35	

TABLE C.10. Robust experiment design results (Taguchi) for the Weighted Objective evaluation of the Big problem.

							H	1	2	2	1	Mean	Standard deviation	Noise/Signal
Noise factor							I	0.5	0.5	1.0	1.0			
							J	0.02	0.05	0.02	0.05			
Control factor												\bar{Y}	S	$-10 \log[\frac{1}{n} \sum_{i=1}^n Y_i^2]$
A	B	C	D	E	F	G								
100	50	60	10	1	0	0.01	1.95	0.00	17.51	44.92	16.10	20.75	-27.65	
100	50	60	50	4	50	0.1	7.03	7.00	12.11	145.70	42.96	68.54	-37.30	
100	100	90	10	1	50	0.1	21.40	0.00	0.00	69.14	22.64	32.60	-31.17	
100	100	90	50	4	0	0.01	27.48	61.87	20.70	147.27	64.33	58.15	-38.24	
200	50	90	10	4	0	0.1	27.13	9.38	17.69	39.45	23.41	12.92	-28.28	
200	50	90	50	1	50	0.01	14.84	1.56	20.70	1.56	9.67	9.66	-22.13	
200	100	60	10	4	50	0.01	43.58	15.23	2.34	7.42	17.14	18.40	-27.39	
200	100	60	50	1	0	0.1	22.27	0.00	3.83	24.22	12.58	12.44	-24.38	

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