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AEROSPACE MANUFACTURING INDUSTRY: A SIMULATION-BASED DECISION SUPPORT FRAMEWORK FOR THE SCHEDULING OF COMPLEX HOIST LINES

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ABSTRACT: The hoist scheduling problem is a critical issue in the design and control of Automated Manufacturing Systems. To deal with the major complexities appearing in such problem, this work introduces an advanced simulation model to represent the short-term scheduling of complex hoist lines. The aim is to find the best jobs schedule that minimizing the make span while maximizing throughput with no defective outputs. Several hard constraints are considered in the model: single shared hoist, heterogeneous recipes, eventual recycles flows, and no buffers between workstations. Different heuristic-based strategies are incorporated into the computer model in order to improve the solutions generated over time. The alternative solutions can be quickly evaluated by using a graphical user interface developed together with the simulation model.

Keywords: Simulation. Hoist Scheduling Problem. Optimization. Chemical Tanks.

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1 INTRODUCTION

Due to the increased efficiency of industrial production, scheduling problems has had an increasing impact on practical problems in the last years. Particularly, the Hoist Scheduling Problem is one of the harder to solve for practitioners and researchers in Automated Manufacturing Systems (Crama, 1997; Riera et al., 2002). This problem consists of a set of tanks between which the parts to be treated are transported by a shared automated transfer device (hoist). Hoist transportation devices are used commonly in the manufacture of printed circuit boards (PCBs) in electroplating plants and also in the automated wet-etch station (AWS) in semiconductor manufacturing systems (Aguirre et al., 2014; Aguirre et al., 2011) but also for Hoist operation in constructions (Xiang et al., 2016).

Generally, real-world scheduling problems are highly complex and virtually impossible to solve by using pure mathematical approaches (El Amraoui et al., 2016). However, the increasing availability of simulation languages, the increase of computational power and the development of simulation techniques have made simulation an appropriate tool to deal with this kind of problems (Banks et al., 2004). In contrast to optimization methods, simulation models are "run" rather than solve, allowing the model to be observed. Simulation allows experimenting and analyzing different operation procedures of an organization. The companies can model their process in virtual settings, reducing the time and cost requirements associated with physical testing. Therefore, complex systems operations can be assessed by developing a discrete event simulation model. Moreover, some simulation packages provide a user-friendly 3D graphical interface which allows obtaining a better visual experience to the world of simulation models. It provides rich 3D objects to make the simulation looks more realistic. In addition, simulation models can easily be tweaked and adjusted, providing rapid responses to even the most abstract situations.

The hoist scheduling problem is usually very complex. Many exact solution approaches and heuristic procedures have been proposed in literature to solve this problem (Kujawski et al., 2010; Manier et al., 2003). Moreover, the developments presented by Fröhlich et al. (2009), Che et al. (2012) and Che et al. (2015) are able to work with multiple hoists in the same track. However, such techniques do not efficiently represent the major complexities appearing in real-world industrial problems. The control and schedule of the hoist are critical for the system performance, especially when chemical processes are involved. This is due to the hoist transports the products, one at a time, between chemical tanks. The processing time of each product in each tank is restricted to a minimum and a maximum duration. Besides, a zero-wait police is followed between stages. Not reaching the minimum processing time, or exceeding the maximum allowed time may cause not only waste of materials but also loosing the critical resource of production time. In this way, the main goal of the hoist scheduling problem is to minimize the makespan while maximizing throughput with no defective product (waste).

This paper aims at developing a modern discrete-event simulation model to evaluate, analyze and design the operation of electroplating for the aerospace industry based on the hoist scheduling problem. The main advantage of simulation technique, with regards to the solution approaches referenced above, is that it permits to systematically reproduce the complex company process in an abstract and integrated form, visualizing the dynamic behavior of its constitutive elements over time (Aguirre et al., 2008). The computer model allows exploring different sequences of jobs entered to the hoist line. The results given by the simulation model are then presented through a user graphical interface, which is particularly useful for the decision-making process.

The manuscript is organized as follows: Section 2 describes the main features of the surface-treatment process. Afterwards, in Section 3, an explanation of how the simulation model was developed is given. Moreover, the verification and validation stages of simulation project are explained in this section. Section 4 presents a case study with its corresponding sensitivity analysis, and the results obtained. Furthermore, the results from simulation studies are presented and discussed. Finally, the article concludes with some discussion and remarks in Section 5.

2 PROBLEM DEFINITION

2.1 Problem characteristic

The hoist problem deals with a set of jobs that must be processed through a sequence of chemical tanks from the input buffer to the output buffer (Grubbs, 2002). Jobs are transported from one tank to another by a shared automated transfer device (hoist). The line can process several types of products, which generally follow different recipes. A recipe is defined by both the sequence of stages (or tanks) that an item must follow and the minimum and maximum processing time in each stage. In practice, jobs vary in size or other properties and require different sequences or processing times. Each produced item type has its own sequence of visiting workstations, processing intervals, etc.

The hoist is capable of transferring only one item at a time from one chemical tank to another. The transferring time is computed by the traveling time from the actual position of the hoist to the source tank plus the loading time plus the traveling time to the destination tank plus the unloading time. The loading and unloading times are constant and known in advance. Therefore, the traveling time depends on the distance between the tanks. The processing time starts when the hoist unloads the item in a tank and finishes when the hoist picks up the job. If the duration of the processing time is below or above a predefined time window, the item becomes defective and must be discarded.

Each tank operates independently with a single capacity. There is no buffer between adjacent workstations. That is to say, once the item has been processed, it has to be moved directly to next stage without intermediate storage. Some critical tanks have an exact processing, which implies that as soon as the processing time is finished, the item should be moved immediately to the next stage. A picture representing the hoist line is shown in Figure 1.

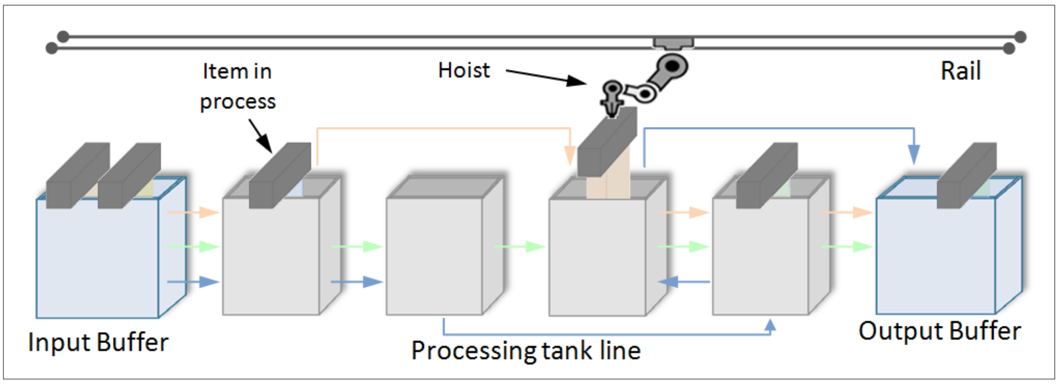

Figure 1 – Automated job-shop system with heterogeneous recipes

2.2 Schedule Feasibility: Solving conflicts

When the hoist problem is solved, it is needed to assure that feasible schedules are generated. When the work-in-progress (WIP) of the system is higher than 1, three types of conflicts can be presented (Yih, 1994):

1. *Conflict by tank availability:* a conflict may occur when a job finishes its processing in a stage and the next tank in the recipe is busy. In this case, the hoist must first serve the job that is in the destination tank before moving the first job. Unfortunately this is not always possible because when the second tank is released the job in the first tank may be defective. The worst version of this conflict is when the destination tank of job A is the current location of job C, the destination tank of job C is the current tank of job B, and the destination tank of job B is the current location of job A (see Figure 2).

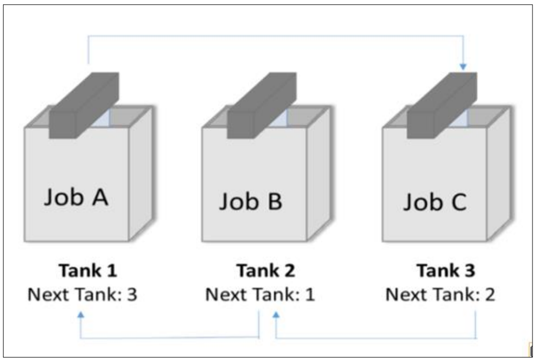

Figure 2 – Conflict by tank availability

2. *Conflict by hoist availability:* a conflict may occur when a job is ready to be transported and the hoist is being utilized by other job. The job should wait until the hoist is idle, but sometimes is too late. This becomes more critical when the minimum and maximum processing times are equal, because there is no extra time to wait for the hoist. In this way, it was needed to develop an algorithm (see Figure 3) to verify the status of both the robot and the jobs waiting for it.

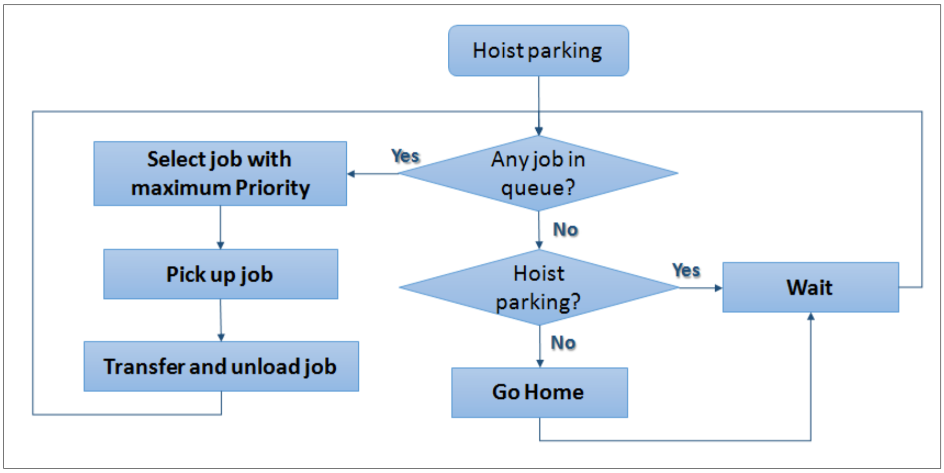

Figure 3 – Hoist decision diagram

3. *Conflict by hoist location:* a conflict may occur when a job needs to be transported but the hoist is too far and when the hoist arrives is too late. This conflict is more common when the hoist is unloading in one extreme of the transportation line.

3 PROPOSED SIMULATION MODEL

In this paper, a simulation model, developed with SIMIO software, was constructed to represent the operation of the electroplating line. SIMIO is a simulation modeling framework based on intelligent objects (Thiesing et al., 1990). An object can be a machine, robot, airplane, customer, doctor, tank, bus, ship, etc. A model is built by combining objects that represent the physical components of the system. It is worth to remark that SIMIO allows building 3D animated model which provides a moving picture of the system in operation. The methodology used in this simulation analysis is described in the Figure 4. The following subsections describe the major components of the computer model.

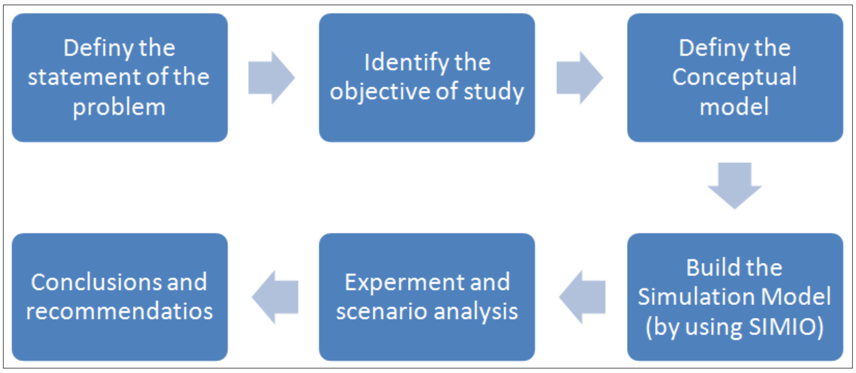

Figure 4 – Stages for developing the simulation model of hoist problem

3.1 Model assumptions

The major assumptions for constructing the simulation model are:

- There are *N* types of jobs following a given production sequence (recipe).
- Each item has to be processed by a sequence of chemical tanks from the input buffer to the output buffer (some tanks may be skipped in the process).
- There are re-entrant and possible recycle flows to the same unit.
- Each stage has a specific time windows of processing time in each tank; products will become spoiled if the processing time falls outside of the time window.
- There are *M* workstations (chemical tanks).
- Each tank has a single capacity, specific functionality, and never breaks down.
- There is no intermediate storage between stages.
- There is a single automated material-handling device (hoist), which can transport one item at time.
- The loading and unloading times and travelling speed are constant and known in advance.
- The hoist is subject to breakdowns and can transport one item at a time.

3.2 Input variables

The major input variables used in the simulation model, among others, are:

- *Max_WIP:* Maximum number of jobs that could simultaneously be in the system.
- *Input_Order:* It is the sequence in which the jobs enter the system; it is defined by different proposed heuristics.
- *Interarrival_Time:* Minimum period of time between the inputs of two orders.
- *Priority:* Three different alternatives were used to assign the priority to request the hoist. The first takes into consideration the time to become defective, assigning highest priority to the jobs next to expire. Similarly to the first strategy, the second one assigns the highest priority to the jobs that are more advanced. The third option takes into consideration the time that the job has exceeded the minimum processing time.

3.3 Output variables

The performance indicators are:

- *Makespan*: representing the time in which the last job is completed. The problem aims to minimize this variable.
- *Job Finished / Defective*: Computing the quantity of non-defective jobs completed and the number of defective outputs. This last quantity should be minimized.
- *Cost*: determining the total cost incurred for processing all the orders. It is computed as the sum of the operation cost of the line plus the cost of the defective units. This variable should be minimized.

3.4 Computer model

The proposed SIMIO-based simulation model is based on the conceptual model developed, where elements and properties of the real process are represented. Figure 5 shows the conceptual model of the system where all components mentioned above and their relationships are represented. As shown, the system includes (i) products to be treated, (ii) chemical tanks, (iii) hoist, and (iv) treated products.

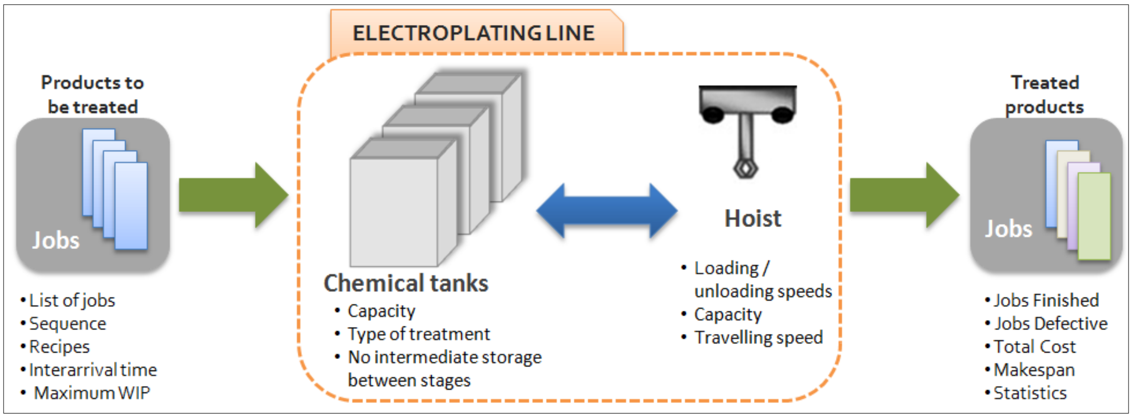

Figure 5 – Conceptual model

SIMIO software provides an object-based approach to system modeling (Pedgen, 2009). Each physical component of the conceptual model, such as the robot, jobs or workstations are represented by an object with a predefined behavior. A 2D view of the simulation model is given in Figure 6 while the 3D animation view is given in Figure 7. As shown in Figure 6, Source, Server, and Sink objects, connected by multiple TimePath Objects, have been used to build the simulation model. All objects used in the model are included in the Standard Library of SIMIO software. A detailed description of components of the electroplating line is explained below.

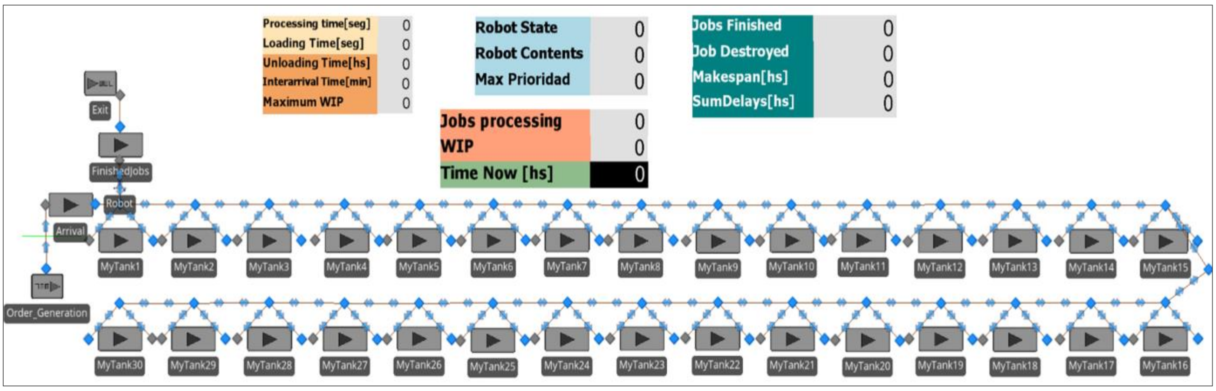

Figure 6 – 2D view of the simulation model

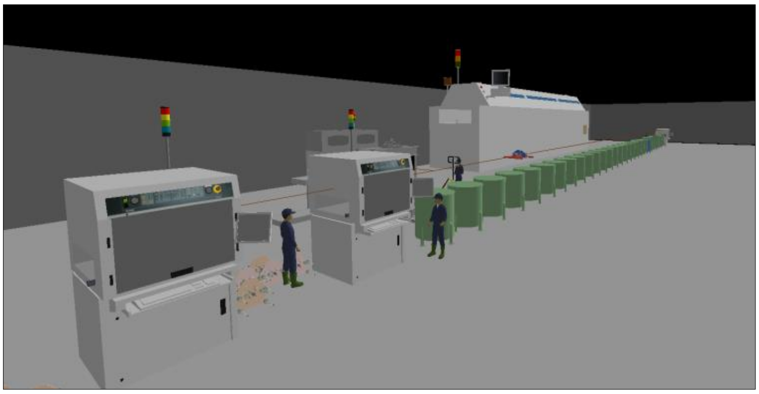

Figure 7 – 3D view of the simulation model

3.4.1 Jobs

The aeronautical parts produced are called Jobs. As shown in Figure 8, they are represented as Entities. An entity is a dynamic object that can be generated / destructed during the simulation run. Each job has a unique recipe represented by a sequence table, which then is referred in the *ModelJob* properties (see Figure 8). For instance, the recipe for Titanium sulfuric anodized is given in Table 1. As seen this table, each recipe determines the minimum and maximum residence time that a job can stay in each tank. The different recipes could vary in the path or in the processing times of each tank. A tank could be visited more than once (for example in Table 1, tank 16 is visited in stage 5 and 8). A job could move backward in the line (tank 22 is followed by tank 16) and not all tanks are visited for all recipes. The difference between the maximum and minimum times could be zero, i.e. fixed and exact processing time (see stage 10). Following the recipe keeping the exact time in each tank ensures that the chemical process is done. Failure to do so may cause the work piece to become unusable.

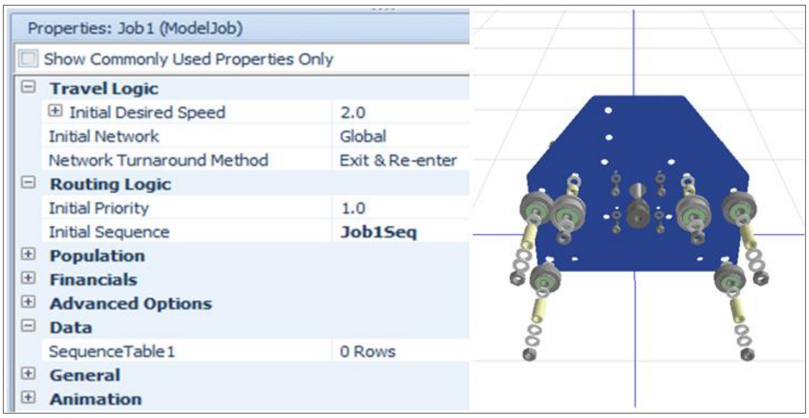

Figure 8 – Dynamic entities, their properties and sequence table

Stage	*Tank*	*Minimum Residence Time (min)*	*Maximum Residence Time (min)*
1	***5***	10	15
2	***6***	5	6
3	***13***	1	2
4	***12***	5	5.5
5	***16***	3	10
6	***21***	10	15
7	***22***	10	15
8	***16***	3	10
9	***20***	5	20
10	***3***	20	20

Table 1 – The recipe for Titanium sulfuric anodized

3.4.2 Tanks / workstation:

Tanks represent the units where different chemicals processes are performed, e.g. sulfuric aluminum anodized, chromic anodized, passivation, chroming by immersion, cleaning, etc. Tanks operate independently without buffers (Non intermediate Storage), and never break down. The processing time in a tank is determined by the minimum processing time of each job (see Table 1). After this time the job will become defective. Each tank is represented by Server objects (see Figure 9). In SIMIO software, a Server object is used for representing a capacitated process such as a machine or service operation.

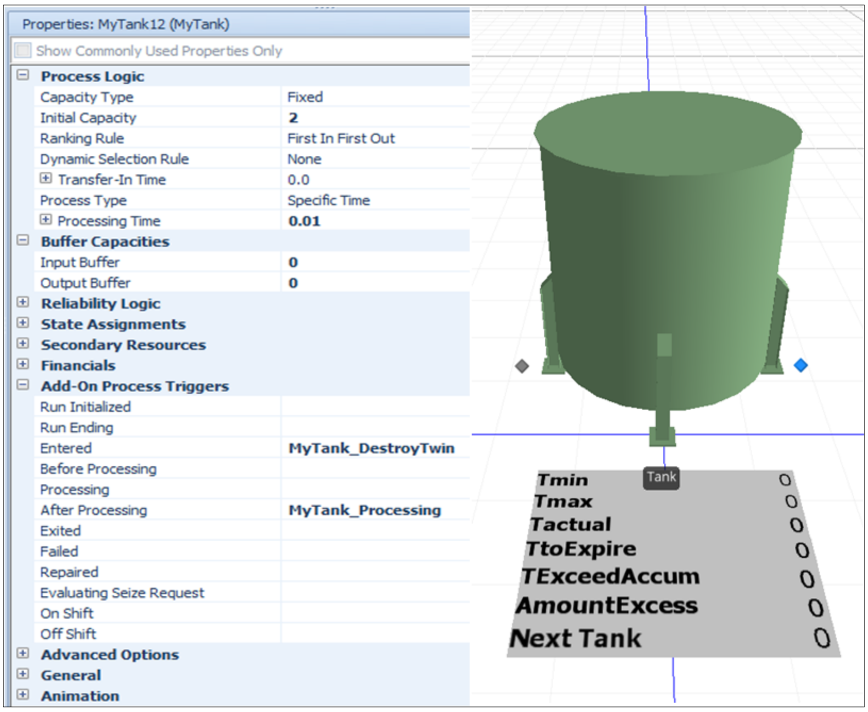

Figure 9 – 2D and 3D SIMIO model (chemical tanks)

Taking into account the processing times in tanks, the jobs can be in the following stages:

- *State 1:* when a job has not yet reached its minimum processing time in the tank and neither the minimum time required for the hoist picks it up. Consequently, the job does not request the hoist.
- *State 2:* when a job has not yet completed its minimum processing time in the tank but it has reached the minimum time required for the robot picks it up. So, job requests the robot with a high priority.
- *State 3:* when a job has reached its minimum processing time but is in its tolerance range (between the minimum and maximum processing time). Also, it has not reached yet the threshold time required to be considered urgent. Job requests the robot with a medium priority to avoid becoming defective.
- *State 4:* when a job is in the most critical state because it has completed its processing and has reached the threshold time to be considered urgent. In this way it has the highest priority to request the hoist.

It is worth to remark that if the Job is not serviced by the hoist before reaching its maximum processing time, it must be discarded because of the high quality standards for the aeronautical components. The algorithm developed for evaluating the stages of a job is given in Figure 10. Note that it is not necessary that a job is in all states. In this figure the parameter "WarningT" is threshold that the hoist needs to move from any point of the line to the other extreme of the tank, while "Tmin" is the minimum processing time and "Tmax" is the maximum time before becoming defective. "Wait" and "Job processing" make reference to keep the time passing.

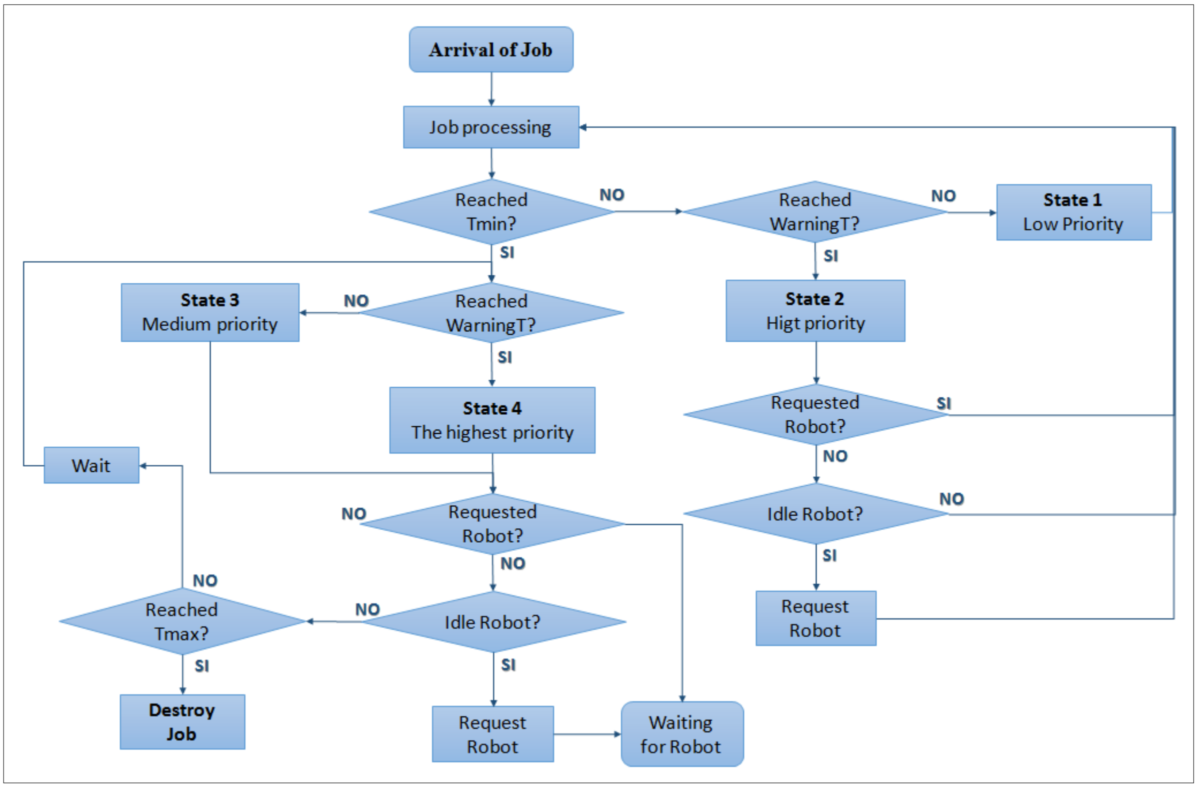

Figure 10 – Flow chart of the states of the chemical tanks

3.4.3 Hoist

It is the device that transfers the jobs between tanks. The hoist is represented in the simulation model by using a Vehicle object. The hoist can accomplish the transportation request of any job. The loading and unloading times of the jobs are constants. When the hoist is idle, it parks at the middle of the line at an intermediate node called "Home". The hoist evaluates the priority of the jobs by using the process that shows Figure 3. This process is a crucial part of the logic of the model due the Jobs can only be load or unload from each tank by the Hoist. A late arrival could cause that the Job is spoiled.

3.5 Verification and validation

Output variables of the model are used to obtained conclusions for the real system, consequently it is very important to develop a model that guarantees credibility and accuracy. For this reason, verification and validation processes are carried out during the development of the model.

Verification process is concerned with correctly building of the conceptual model, and it is utilized in the comparison of this model to the computer representation implemented for that conception (Law, 2007). Several requirements concerning expected values and system behavior were determined, such as arrival rates, production rates, use of resources, restrictions of entry and operation, etc. These output values of the simulator were compared with expected values. The similarity of the values proves that the model was implemented correctly in the computer, and the input parameters and logical structure of the model are properly represented.

Furthermore, validation is utilized to determine that a model is an accurate representation of the real system. Validation is usually achieved through the calibration of the model, an iterative process of comparing the model to actual system behavior and using the discrepancies between the two, and the insights gained, to improve the model. This process is repeated until model accuracy is judged to be acceptable. Hence, several iterative comparisons between output variables obtained by the simulator and information regarding of the real system are performed to carry out necessary changes and adjustments, and achieve the desired values.

3.6 Heuristics

After several experimentation and suggestions from the operator of the real-world system, the following heuristics were implemented in the simulation model for creating job sequences:

- *Heuristic 1:* Jobs are sequenced according to the total production time. Jobs with smaller total processing times are placed first in the sequence.
- *Heuristic 2:* Jobs are sequenced according to the total production time but in this case, the jobs sequence is generated by alternating small and large jobs.
- *Heuristic 3:* Jobs are ordered according to the use of critical tank. The tank processing the major quantity of jobs is defined as the “critical tank”.
- *Heuristic 4:* Jobs are sequenced based on their last processing tank.

The heuristics detailed above were used to perform experimental designs with the simulation model. An iterative procedure was created (see Figure 11) for evaluating the simulating results given by each alternative of job sequence. The aim was to rank the best scenarios for the response variables defined in Section 3.3.

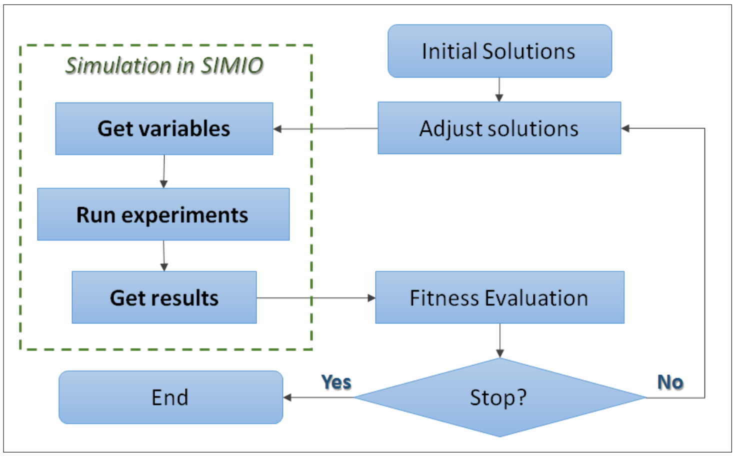

Figure 11 – Algorithm for evaluating simulation results

4 SIMULATION RESULTS

After an exhaustive verification and validation of the simulation model, the performance of an electroplating line working in a real-world aeronautical manufacturing system was analyzed. This problem comprises 30 chemical tanks and one single hoist. There are 24 types of jobs, each one with its specific processing sequence. Some jobs can visit the same tank more than once.

After constructing the simulation model, several alternative scenarios were defined in order to run experimental designs. Particularly, a multifactorial experimental design was executed for determining the factors that can affect the response variables defined in Section 3.3. The aim was to select the best scenarios that minimizing the makespan while maximizing throughput with no defective outputs. After testing the different combination of heuristics, the input variables maximum WIP, Inter arrival time and priority type were selected for experimenting with more than 500 scenarios. As result, the top 10 scenarios given in Table 2 were obtained. Note that the type of heuristic used to define the initial sequence of jobs is too one of the control variables.

From experimental results, it follows that there are no significant differences in simulation results when the maximum WIP is equal to 3 since the difference in cost or makespan not exceed the 3.2%. When the maximum WIP value is increased to 4, the only sequence (heuristic) that does not generate defective jobs is the Heuristic 4. A maximum WIP below 3 jobs increases the cost since the system has idle capacity. Maximum WIP above 5 increases the cost since the number of defective units is higher.

	Control Variables				Results				
Scenario	Heuristic	Max WIP	Inter. Time	Priority	Cost	MK	Def. Jobs	Δ Cost vs. 1	Δ MK vs. 1
1	4	4	12	2	189.176	18.9176	0	0	0
2	4	3	13	2	195.042	19.5042	0	3.0	3.0
3	1	3	13	2	195.209	19.5209	0	3.1	3.1
4	2	3	13	2	195.209	19.5209	0	3.1	3.1
5	3	3	13	2	195.209	19.5209	0	3.1	3.1
6	1	3	12	2	195.237	19.5237	0	3.1	3.1
7	2	3	12	2	195.237	19.5237	0	3.1	3.1
8	3	3	12	2	195.237	19.5237	0	3.1	3.1
9	4	3	12	2	195.309	19.5309	0	3.1	3.1
10	4	3	14	2	195.376	19.5376	0	3.2	3.2

Table 2 – Best results obtained for different scenarios solved by the simulation model

After evaluating all results, the best configuration that minimizes both the makespan and the number of defective products is shown in Figure 12. The first 12 hours of the jobs schedule is given in this figure.

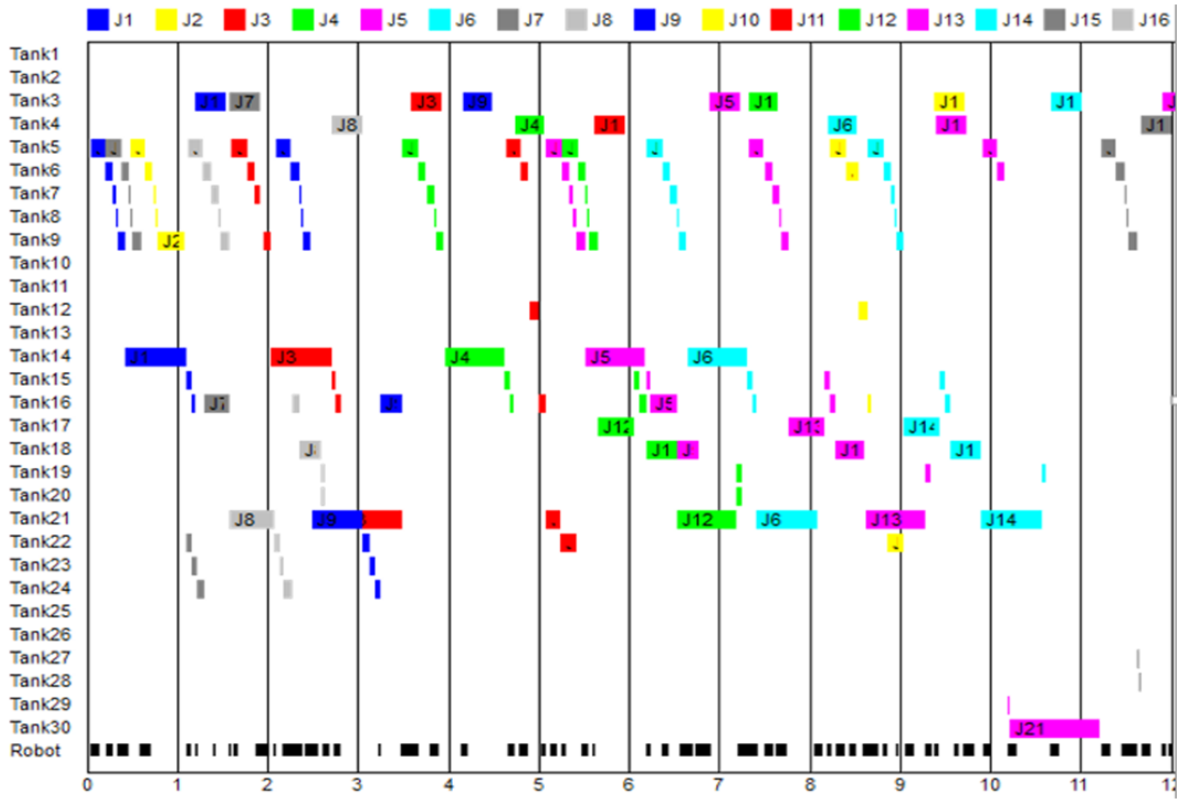

Figure 12 – Jobs schedule for the first 12 hours

In the Figure 12, we could appreciate that the *Jobs* are moved from one tank to another by the hoist (robot). The different jobs follow different paths through the tanks, but there are some tanks that are busier than others, for example the tank 30 is only used once or not used like tank 11. Other Tanks like tank 5 has a high utilization but it is clear that the busiest resource it the hoist (robot). The system maintains a work in progress (WIP) of three jobs, when a job is finished the next one enters. The hoist is main bottle neck for increasing the WIP; for instance, during the day 8 the hoist is extremely busy. When the simulator tries to increase the WIP during this work peaks, the system failed because the hoist cannot attend the jobs.

Note that the results reported by simulation runs are represented graphically by using a user-graphical interface. This interface is integrated with the simulation model for quickly evaluating simulation results and helping the decision-making process.

5 CONCLUSIONS

This paper has presented an innovative discrete event simulation for dealing with the short-term scheduling of a complex hoist line. This type of systems are used commonly in the manufacture of printed circuit boards (PCBs) in electroplating plants and also in the automated wet-etch station (AWS) in semiconductor manufacturing systems. Simulation is a proper approach to solve this challenging scheduling problem. The proposed strategy was capable of generating near-optimal schedules for many scenarios in a short time period. The aim is to find the best job sequence that allows minimizing the total makespan while the number of defective products is reduced. Different heuristics were embedded into the simulation model in order to test different job sequences to be processed in the system.

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INDÚSTRIA DE FABRICAÇÃO AEROESPACIAL: UM QUADRO DE APOIO DE DECISÃO BASEADO EM SIMULAÇÃO PARA O PROGRAMAÇÃO DE LINHAS COMPLEXAS

RESUMO: O problema de agendamento em linhas de elevação é um problema crítico na concepção e controle de sistemas automatizados de fabricação. Para lidar com as principais complexidades que aparecem nesse problema, este trabalho apresenta um modelo de simulação avançado para representar o agendamento de curto prazo de linhas de elevação complexas. O objetivo é encontrar o melhor cronograma de tarefas que minimiza o tamanho da marca, ao mesmo tempo em que maximiza o rendimento sem saídas defeituosas. São consideradas várias restrições difíceis no modelo: talha compartilhada única, receitas heterogêneas, eventuais cortes de recicla e sem tampões entre estações de trabalho. Diferentes estratégias baseadas em heurística são incorporadas no modelo de computador para melhorar as soluções geradas ao longo do tempo. As soluções alternativas podem ser avaliadas rapidamente usando uma interface de usuário gráfica desenvolvida em conjunto com o modelo de simulação.

Palavras-chave: Simulação. Problema de agendamento em linhas de elevação. Otimização. Tanques químicos.

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