Aerospace Manufacturing Industry: A Simulation-based Decision Support Framework for the Scheduling of Complex Hoist Lines

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ABSTRACT. This paper presents an advanced simulation model for short-term scheduling of complex hoist lines. This problem, generally found in aerospace and electroplating industries, includes several hard constraints that should be considered: single shared hoist, heterogeneous recipes, eventual recycle 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 aim is to reduce the number of products that must be discarded while minimizing the makespan. In addition, a graphical user interface was developed for quickly evaluating simulated schedules.

Keywords: Simulation, Hoist Scheduling Problem, Chemical Tanks, Job-shop Scheduling Problem

1 Introduction

The research into scheduling problems has drawn a great attention in the last decades with the aim to increase the effectiveness of industrial production. Particularly, the Hoist Scheduling Problem becomes much harder to solve for practitioners and researchers in Automated Manufacturing Systems [1] [2]. This problem deals with the processing of a set of jobs that has to be transferred through several operation stages by using 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 [3] [4].

The hoist scheduling problem is usually very complex. Many exact solution approaches and heuristic procedures have been proposed in literature to solve this problem[5] [6]. However, such techniques are not able to 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 [7]. 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.

2 Problem Definition

2.1 Problem characteristic

The hoist problem consists in a set of jobs that must be processed by a sequence of chemical tanks from the input buffer to the output buffer [8]. Jobs are transported from one tank to another by a single automated 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. For example, the recipe for the titanium sulfuric anodized is given in Table 1. 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 of the hoist comprises the traveling time from the actual position to the tank, the loading time, the traveling time to the destination tank, and the unloading time. The loading and unloading times are constant and known in advance. The traveling time depends on the distance between the tanks. The processing time starts when the hoist unloads the item in the tank and finishes when the hoist picks up the item. If the duration of the processing time is below or above the predefined time window, the item becomes defective and must be discarded.

Each tank operates independently and has a unary capacity. In addition, 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. A picture representing the hoist line is shown in Fig. 1.

Table 1. The recipe for titanium sulfuric anodized

Stage	Tank	Minimum Time (min)	Maximum 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

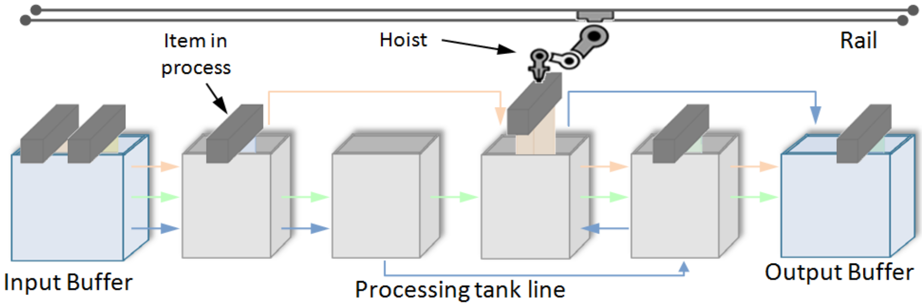

Fig.1. Automated job-shop system with heterogeneous recipes.

2.2 Different 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 [9]:

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 B, and destination tank of job B is the current location of job A (see Fig. 2).
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 Fig. 3) to verify the status of both the robot and the jobs waiting for it.

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.

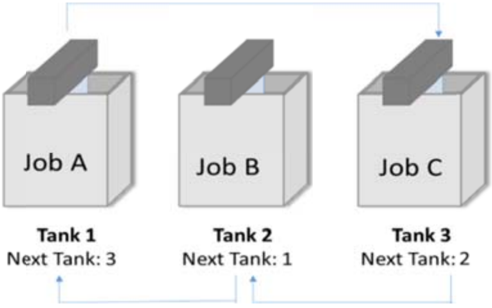

Fig. 2. Conflict by tank availability.

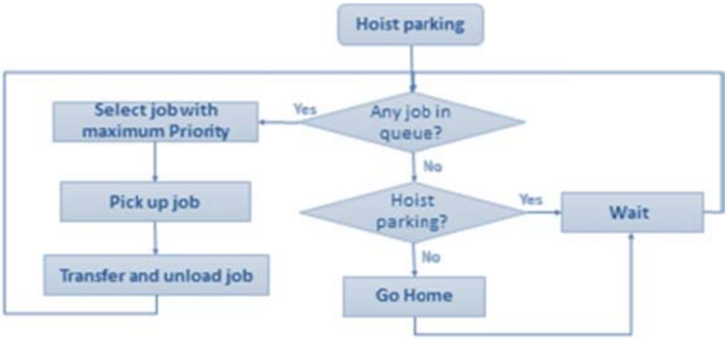

Fig. 3. Hoist decision diagram.

3 Proposed Simulation Model

Generally, real-world systems are highly complex and virtually impossible to solve by using pure mathematical approaches. 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 [10]. 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 an 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.

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 [11]. 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 to build 3D animated model which provides a moving picture of the system in operation. The following subsections describe the major components of the computer model.

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); they have 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 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 specific functionality; has a single production unit per stage; never breaks down; no intermediate storage between stages.
- There is a single automated material-handling device (hoist), which transports jobs between the tanks. Its loading / unloading speeds are constants. Its capacity is one item at a time. The travelling speed is constant. The hoist can experience breakdowns.

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 methods 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 method, the second one assigns highest priority to the jobs that are more advanced. The third method

takes into consideration the time that the job has exceeded the minimum processing time.

3.3 Output variables

The performance indicators are:

- Makespan: The time in which the last job is completed. This variable aims to be minimized.
- Job Finished / Defective: The number of non-defective jobs that are completed and the defective jobs. The latter should be minimized.
- Cost: It represents the total cost to manufacture 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 simulation model is integrated by the following components:

- Tanks / workstation: where different chemicals processes are performed, e.g. sulfuric aluminum anodized, chromic anodized, passivation, chroming by immersion, cleaning and so on. Each tank is represented by a Server object. In SIMIO, a Server object is used for representing a capacitated process such as a machine or service operation.
- Jobs: they are represented as Entities. An entity is a dynamic object that can be generated / destructed during the simulation run.
- Hoist: device materials transferring the jobs between tanks. It is represented by a Resource object.

A 2D view of the simulation model is given in Fig. 4 while the 3D animation view is given in Fig. 5.

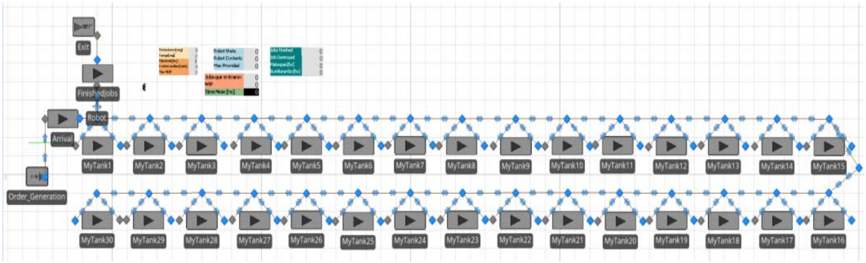

Fig. 4. 2D view of the simulation model.

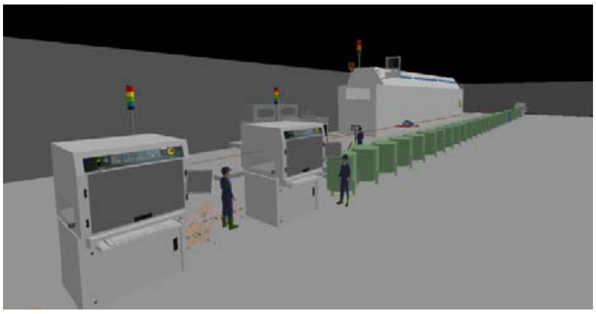

Fig. 5. 3D view of the simulation model.

3.5 Heuristics

After several experimentation and suggestions from the operator of the real-world system, the following heuristics were implemented in the simulation model to perform experimental designs. The job sequences were created by considering the following heuristics:

- 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 short jobs and long 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.
- Heuristic 5: OptQuest is used to identify the best job sequence. OptQuest is a simulation-based optimization package that evaluates different values of the input variables to optimize the response variables.

The simulation results obtained by evaluating alternative heuristics were used to develop an iterative optimization process. Such process, described in Fig. 6, is used to found the best values for the response variables defined.

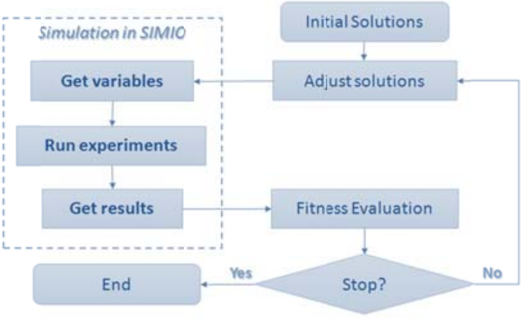

Fig.6. Optimization by Simulation for the electroplating line.

4 SIMULATION RESULTS

The simulation model was used to analyze the performance of an electroplating line working in a real-world aeronautical manufacturing system. 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. A multifactorial experimental design was executed for determining the factors that affect the response variables. Each scenario was run 5 times. The configuration and results for the top 10 scenarios are given in Table 2. Note that the type of heuristic used to define the initial sequence of jobs is one of the control variables. Here it is worth to remark that Heuristic 5 was not listed in Table 2 because the computational time required for this strategy was higher than the other proposed heuristics.

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

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

From experimental results, it follows that there are no significant differences in simulation results when the Max WIP is equal to 3, but when this 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.

After evaluating all results, the best configuration that minimizes both the makespan and the number of defective products is shown in Fig.7 and 8. The jobs schedule is given in Fig. 7 while the hoist schedule is depicted in Fig. 8.

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.

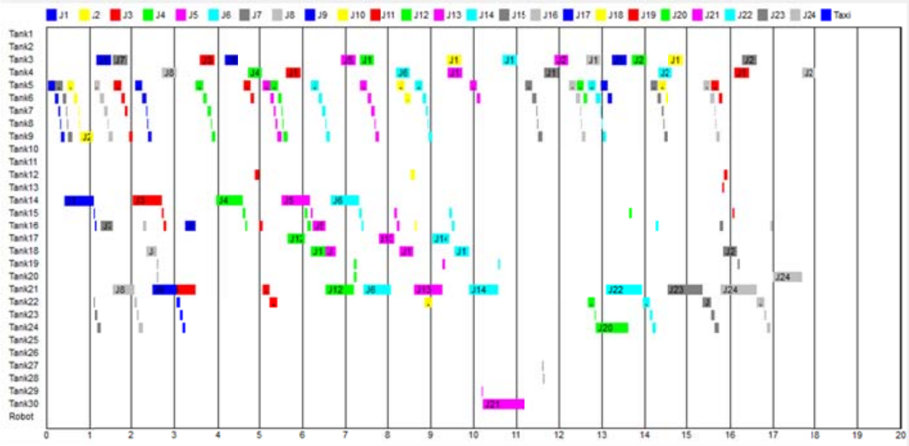

Fig.7. Jobs Schedule.

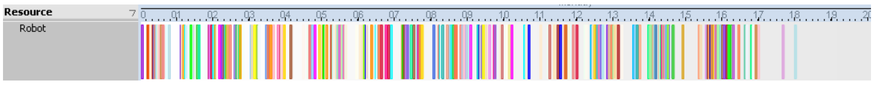

Fig. 8. Hoist Schedule.

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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