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Flexible Job Shop Scheduling With Operators in Aeronautical Manufacturing: A Case Study

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ABSTRACT This paper analyzes a flexible job shop scheduling problem with operators and is motivated by a real-life case study of the aeronautical industry, where each process can be performed on alternative machines (shared by multiple products) and requires not only machines but also some operators to execute the process. One goal of this scheduling is to minimize the number of operators and airframes that are needed in the assembly line. Minimizing the number of airframes in the assembly line, which is particularly important due to the cost of each airframe, is generally ignored in production planning models that are used in prior studies. Moreover, the output of the program refers to a set of schedules that includes different combinations of number of operators and intermediate stock, to enable a better decision making. A mixed integer linear programming model is presented to solve this problem. Experimentation was conducted using real-life examples from the aeronautical industry. The solutions that are presented in this paper outperformed current industrial methods in both quality and calculation time. To the best of our knowledge, this variant has not been addressed in prior studies either in scheduling or in aeronautics contexts. However, minimizing the number of operators and intermediate stock could have significant implications for numerous labor intensive industries, contributing to enhanced and more agile decision making processes.

INDEX TERMS Case Study, aeronautical industry, flexible job shop with operators, mixed integer linear programming.

I. INTRODUCTION

Nowadays, industries are facing a new era of extraordinary challenges. End users are increasingly asking for customized products, at the same time as product life-cycles get shorter. In addition, the impact of industrial production on the environment is severe and the consumption of non-renewable resources needs to be reduced. Therefore, it is a must to achieve more flexible, agile and efficient production systems [1]. Aircraft manufacturers have also been affected by this and must learn to cope with increasing product complexity, a reduction in time to market, and production lead times and costs [2], [3].

As an answer to these and other challenges, there is an upcoming fourth industrial revolution, triggered by the introduction of the Internet of Things and services into the manufacturing environment, that has been named Industry 4.0 [4]. Although Industry 4.0 means a deep transformation for the total enterprise, smart factories constitute a key feature. They must be capable of managing complexity being at the same time more flexible, more efficient and greener. To do so, they integrate physical objects with information systems such as MES and ERP [5].

Conversely, a wide range of product lifecycle management (PLM) tools have been deployed in the aeronautical industry and have resulted in highly digitalized processes from aircraft design to aircraft maintenance. However, scheduling and line balancing have consistently remained unaffected. Most of the activities that are related to these processes continue to use manual procedures that rely on the knowledge of experts. Nevertheless, the digitalization of scheduling processes is a must not only for MES systems implementation but also for Industry 4.0 deployment.

In consequence, this study analyses the scheduling of an airframe assembly plant from one of the major aircraft manufacturers. Our results enable the digitalization of the process and provide a more efficient and agile decision making process, directly related to an increase in productivity.

The manufacturing of an aircraft includes two primary steps. First, main airframes are manufactured throughout scattered sites. Then, the final assembly lines assemble these airframes and perform the aircraft final furbishing and test. The production processes that occur between the final assembly line and the main assemblers must follow the same pace because inventory holding costs are extremely high.

In an airframe assembly line, different variations of the same assembly are often produced and each variation may have a different production rate. Per airframe, several jobs must be performed using a set of the existing machines. Because the assembly is labour intensive, human resources are a major asset of these production sites. Managers should determine a production schedule and assign machines and resources (mainly workers) for each element. One objective of these managers is to reduce costs.

Prior studies have not adequately addressed the simultaneous assignment of machines and operators to processes in a Flexible Job Shop scheduling problem with operators and shared resources. Nevertheless, because of the ongoing industrial transformation, there is a major concern regarding the ability of flexible job-shop scheduling problems to model real-life manufacturing environments [6]. In this study, we present a new mixed integer linear programming (MILP) formulation for a Cycle Flexible Job Shop with operators and multiple modes per job. To the best of our knowledge, this problem has not yet been addressed. This study applies this problem to the scheduling of an aeronautical airframe assembly line.

Another contribution of this study is that we consider two different objective functions: minimizing the number of workers and minimizing the work in progress. Unfortunately, frequently the planning process ignores the possibility of minimizing the number of airframes in the plant although this is an important issue in the aeronautic sector because of the high cost of the products and a risk of damage while stored.

First, the two different objective functions were individually tested. In addition, the combination of both objectives is studied in depth. We used CPLEX for solving real-world examples that included as many as 20 jobs (180 operations), 15 machines and 25 operators.

Our model provided superior results when compared to the results that were obtained with currently used methods in terms of both solution quality and time. Using older methods, a feasible solution was obtained after more than 40 working hours. Using our proposed methods, optimal solutions are reached within seconds and at most, 2.5 hours. Furthermore, solutions that were provided by manual methods were far from the optimal solutions, which required an extra buffer and/or operator.

The main contribution of this study is the model for a real-life aeronautic scheduling problem. It includes some not previously tackled features such as the simultaneous assignment of operators, time slot and machines and the existence of multiple modes. We have provided an industrial point of view using a Pareto front with a bi-objective function within short solving times. This is more relevant for a real decision maker than just providing the optimal solution of each objective function.

The remainder of this paper is structured as follows: Section 2 presents the industrial context and process. Section 3 describes in detail the problem we address. A literature review is provided in Section 4. The proposed formulation is presented in Section 5. Computational results are explained in Section 6. Finally, Section 7 provides the conclusions.

II. CASE COMPANY AND PRODUCTION PROCESS DESCRIPTION

This case study was developed at Airbus Defence and Space, which is a division of Airbus Group and is the largest defence and space manufacturer in Europe and the second largest manufacturer worldwide. The Airbus Group employs more than 40,000 employees and has been involved in the design and industrialization of aircraft since the middle of the 20th century [7]. The components of each airplane are produced throughout Europe. For example, the A400M model is produced in Belgium, France, Germany, Portugal, Spain, Turkey, and the U.K. among others To coordinate this supply chain and assemble the airplanes on time it is necessary to deliver each part on the due date or an entire airplane could be delayed because one part is missing. Production rates vary from 15 to more than 200 aircraft per year. Airframe assembly lines are generally dedicated to a single airframe type but they are able to concurrently produce multiple aircraft models; therefore, this manufacturing process may be considered a mixed model assembly line.

Although this type of production line is similar to automotive production lines, the cycle time in the automotive industry is in the range of minutes, and in our case, the range is in days or weeks. Another primary difference is that each airframe may visit a workstation multiple times and minimal time lags exist between processes. The majority of the process relies on a significant manual workload. For this reason, the number of workers is a significant cost contributor. Non-finished goods are another significant cost contributor because each airframe could cost several thousand euros and the number of parts required for each system could be in the range of tens to hundreds.

This case study focuses on an assembly line where a main airframe is assembled. Two units, a left side and a right side, are delivered for each aircraft. Airframes for two aircraft models share the assembly line. In all, 4 airframes are produced on the line, called: FC-A LH, FC-A RH, FC-B LH and FC-B RH.

During production, a FC must proceed through nine processes: preliminary tests, cutting, workbench assembly 1 and 2, equipping, furnishing, soft cutting, final test and final operations. Precedence constraints exist between the processes. In certain cases, the time lag between a process and its successor has a minimum or maximum value. For certain processes, there cannot be a pre-emption.

Figure 1 presents the assembly line layout and the path that is followed by an airframe during its production. The process number is identified by a circle in Figure 1. The airframe begins with Preliminary Tests in 1, then Cutting in 2, Workbench Assembly 1 in 3, Workbench Assembly 2 in 4, Equipping in 5; Furnishing in 6; Soft Cutting in 7; Final Tests in 8 and Final Operations in 9.

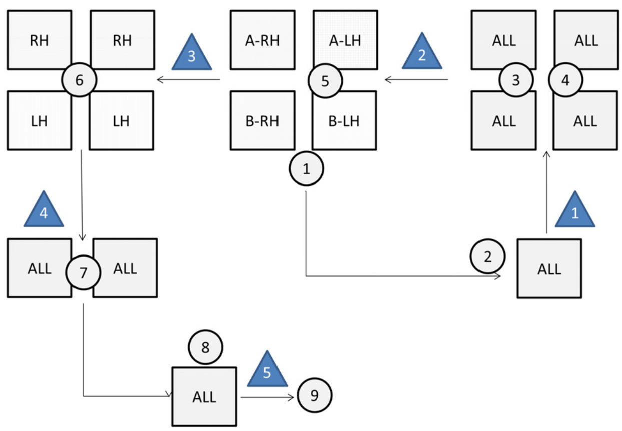

FIGURE 1. Plant Layout. The number of the processes appears inside the circles and the number of the buffers appears inside the triangles.

There are five buffers that exist between different processes. In Figure 1, the buffers are represented by the triangles that appear in the assembly line.

Although extra buffer spaces could be allocated, we try to avoid this for safety reasons and a high risk of damage.

A process requires the use of operators and machines. Operators' profiles vary depending on their qualifications. Each process can be performed using a subset of operator profiles. The number of operators working simultaneously on a process has an upper limit. To be completed, a process requires a fixed number of operator hours. The process is finished when the sum of the time each operator has invested in the process is equal to the process' workload, e.g., for an 8 hour process, we could assign 2 operators to work 4 hours or 1 operator to work 8 hours.

Two types of operator profiles are used in the assembly line: production and non-production. The first operators are paid when they are hired. The number of production operators per shift is uniform during the scheduling horizon. Therefore, the production operator's cost is proportional to the maximum number of operators that are used for each shift. Non-production operator profiles are only paid for their effective working hours. Their cost is related to the workload of the processes they are assigned to.

The assembly line involves several types of machines. Each machine is used for a subset of processes and airframes. Set-up costs are either irrelevant or too high to be considered as a possibility during serial production. A machine can only be used by one airframe at a time. Certain machines maintain their own calendar and can only be used during certain shifts. Other processes do not require the use of a machine. Table 1 provides a matrix that includes the types of machines in the first column, the quantity available in the second column, the airframes that require the machines in the third column, and the processes for which the machines are used in the final column.

TABLE 1. Machine usage per process and airframe model.

Machine	QTY	Airframes	Processes
Equipping Jig A	1	FC-A LH	Preliminary Tests Equipping
Equipping Jig B	1	FC-A RH	Preliminary Tests Equipping
Equipping Jig C	1	FC-B LH	Preliminary Tests Equipping
Equipping Jig D	1	FC-B RH	Preliminary Tests Equipping
Cutting Machine	1	All	Cutting
Workbench	4	All	Workbench Assembly 1 Workbench Assembly 2
Furnishing Jig LH	2	FC-A LH FC-B LH	Furnishing
Furnishing Jig RH	2	FC-A RH FC-B RH	Furnishing
Soft Cutting	2	All	Soft Cutting
Final Tests	1	All	Final Test
No Machine	4	All	Final Operations

III. PROBLEM STATEMENT

The production scheduling follows several steps. First of all, an aggregated planning is made yearly, to make sure the overall capacity is enough for the demand. Afterwards, a more detailed production plan is generated. At that step, the production rates for each time period are set. For example, if during a year (with an estimated length of 202 working days) 42 units of each product must be delivered, that can be split into 100 days delivering 1 product each 4 days and 102 days delivering 1 product each 6 days. The different production rates can be due to a variation on the demand, supply chain constraints or other factors.

The establishment of the production rates per period is out of the scope of the present work. The objective of this work has been the detailed scheduling for each of the periods. That is: to fix the work that needs to be done, for example, during the first 100 days to ensure that 1 unit per product is delivered each 4 days.

To do so, we have pursued to schedule the lowest possible time horizon and repeat that schedule as many times as necessary. That lowest possible time horizon is calculated as the lowest common multiple (lcm) of the airframes cycle times. For example, if FC-A has a delivery rate of 1 unit/5 days and FC-B has a delivery rate of 1 unit/2 days; the planning period will be 10 days (lcm of 5 and 2) during which we will produce 2 units of FC-A (one each for 5 days) and 5 units of FC-B (one each for 2 days).

To be finished, a FC must go through the nine processes described on the prior section. Therefore, the schedule must include as many repetitions of a process as FC need to be delivered. In the previous example, each process on FC-A must be scheduled twice and each process on FC-B must be scheduled 5 times. Where there are intermediate buffers the processes need not be scheduled in order (process 3 can be performed before process 2 using a FC from the buffer).

The objective is to generate a schedule for the time horizon that minimizes the inventory cost or the number of production operators that are needed. This schedule is divided into time slots and should assign an execution date for each operation, the number of operators and the machine to be used.

Until now this schedule had been calculated manually and relied on experts' knowledge. However, planning without the use of an automated system is time consuming, has a high probability of error and does not consider inventory costs.

IV. LITERATURE REVIEW

To the best of our knowledge, few studies have used real-life cases for scheduling manufacturing processes within the aeronautical industry. In 1994, Scott [8] provided the first approach that considered the primary aspects for modelling an aeronautic assembly line: the sequence of jobs, space constraints and human resource availability. Since this seminal study, most of the subsequent studies have addressed problems that are related to final assembly lines. Heike published a case study regarding the various alternatives for aeronautical mixed model assembly lines and focused on the use of constant or variable cycle times within a flow shop [9]. More recently, Menendez *et al.* [10] focused on the final assembly line balancing decision during the industrialization phase and Borreguero *et al.* [11] proposed a heuristic based methodology for scheduling one of the final assembly line's positions during the production phase. Ziarnetzky *et al.* [12] used discrete-event simulation to analyse the cabin installation process on a final assembly line.

In addition, two studies analysed parts manufacturing. Jensen implemented a MILP model for parts scheduling and considered workforce constraints and limited space availability [13]. Finally, Huag *et al.* [14] used simulation to compare a job shop layout and a cellular manufacturing facility for sheet metal parts production.

Our problem shares certain primary constraints with final assembly lines, e.g., the existence of precedence constraints and limited human capacity. However, the machine allocation problem is specific to airframe manufacturing. In addition, most prior studies used simulation to evaluate the suitability of different strategies, but our objective is to provide a detailed schedule to assure on-time delivery at the lowest possible cost. From this perspective, the problem can be studied as a multimode cyclic Flexible Job Shop scheduling problem with operators, which aligns with widely studied machine scheduling problems.

Machine scheduling problems have been the subject of continuing research since the early days of operations research. This type of problem includes NP-hard optimization problems and in practice, are among the most intractable and classical problems.

The classical Job Shop Problem (JSP) refers to scheduling a set of jobs, J, (each job is divided into n operations) on a set of m machines with the objective of minimizing a certain criterion and is subject to the constraint that each job has a specified processing order through all machines, which are fixed and known in advance [15]. Blazewicz [16] provided a classification of job scheduling problems and a survey study in 1986.

However, the airframe assembly line in this study incorporates additional features when compared to the classical JSP. First, this study analyses a Flexible Job Shop scheduling as certain jobs may be performed by using more than one machine. In addition, the product demand follows a cyclic pattern that is repeated over time. Finally, human resource requirements must be considered. Each job requires the presence of an operator at each machine and the duration of the job on each machine depends on the number of assigned operators (which may vary within an interval).

In all, the problem that is analysed in this study could be classified as a cyclic Flexible Job Shop problem with operators. Three assignments must be solved concurrently; each job must be assigned to a machine, a time period and order and finally, to a number of operators per profile and active period. To our knowledge, this problem has not been previously addressed; however, its primary features have been separately analysed.

Flexible Job Shop scheduling problems are being used more frequently because they are more effective for providing answers to a more complex and dynamic market. Fattahi *et al.* [17] proposed a mathematical model and a heuristic for these types of problems. Other authors have presented genetic algorithms, [18], ant colony approaches [19] or tabu search metaheuristics [20].

Brucker and Kampmeyer analysed cyclic Job Shop problems. In [21] these scholars presented a survey on the problem formulation and solving methods, including a tabu search algorithm and a benchmark on existing heuristics. Later, they studied the case of a cyclic Job Shop with blocking [22]. In 2011, Jalilvand-Nejad and Fattahi [23] implemented a genetic algorithm.

Operator scheduling has rarely been considered for machine scheduling. Recently, Agnetis *et al.* [24] introduced a Job Shop problem with one type of operator. Sierra *et al.* [25] proposed a new scheduling generation scheme for this problem and used it to solve scenarios that included a maximum of 120 operations, 3 machines and 2 available operators. However, a study has not been conducted that includes the possibility of multiple modes and considers the operators profiles, as is the case in our problem.

To conclude, the scheduling of an aeronautical airframe assembly has not yet been addressed in aeronautical literature. In addition, cyclic Flexible Job Shop scheduling with operators, which is a more general problem, has not been

TABLE 2. Sets.

E	Set of elements e that are produced
P	Set of processes p that must be performed
M	Set of machines m
T	Set of types t of operators
T^P	Subset of types t that belong to a production category
T^{NP}	Subset of types t that belong to a non-production category
S	Set of slots s
CY	Set of cycles cy in which the time is divided
CY_e	Subset of cycles (CY) of each element
$S_{e,cy}$	Subset of slots s that belong to each cycle cy of the element e

TABLE 3. Parameters.

Cycle times per element and scheduling time horizon	CYD_e	Cycle duration of each element e
	LCM	Lowest common multiple (of all CYD_e)
	QCY_e	Number of cycles for each element e in the time frame considered: LCM/CYD_e
	$FS(e,cy)$	First slot of the cycle cy of the element e
Element and processes characteristics	$W_{e,p}$	Workload (hours) to be performed to complete a process p of an element e
	$MXO_{e,p,t}$	Maximum number of operators of the type $t \in T$ for the process $p \in P$ of the element $e \in E$
	$ENM_{e,m,p}$	1 if the process p of element e uses machine m and 0 otherwise
	UP_p	1 if the process p can be interrupted and 0 otherwise
Precedencies between Processes	$PR_{p,p'}$	1 if there is a precedence relationship between p and p' and 0 otherwise
	$IP_{p,p'}$	1 if there is a precedence relationship with zero time lag between p and p' and 0 otherwise
	$SFT_{p,p'}$	1 if there is a precedence relationship with at least a $TSFT_{p,p'}$ hour time lag between p and p' and 0 otherwise
	$TSFT_{p,p'}$	Duration of the minimum time lag between processes p and p' (hours)
Machine Availability	Q_m	Number of machines m that are available
Slot Definition	SD	Slot duration (hours)
	MS_s	1 if slot s belongs to a morning shift and 0 otherwise
	AF_s	1 if slot s belongs to an afternoon shift and 0 otherwise
	QNN	Quantity of non-night slots
	NS_s	1 if slot s belongs to a night shift and0 otherwise
	PS_p	1 if in the slot s it is allowed to work on process p and 0 otherwise
	$PA(s)$	Previous active slot of slot s
	$NA(s)$	Next active slot of slot s
Buffer Definition	$BP_{p,p'}$	1 if there is a buffer between processes p, p' and 0 otherwise
	$WB_{p,p'}$	Weight value of each the buffer $BP_{p,p'}$

TABLE 4. Variables.

Operators assignment per slot and element	$ops_{e,p,s,t}$	Number of operators of type $t \in T$, during slot $s \in S$, in process $p \in P$ for each element $e \in E$
	to	Total number of operators
	tom_t	Total number of operators of type $t \in T$ who work morning shifts
	toa_t	Total numbers of operators of type $t \in T$ who work afternoon shifts
	to_t	Total number of operators of type $t \in T$
	$so_{e,p,s}$	1 if there are operators working on process $p \in P$ of element $e \in E$ in slot $s \in S$ and 0 otherwise
	$opsslot_{s,t}$	Number of operators of type $t \in T$ in slot $s \in S$
Machine assignment	$ma_{e,p,m.s}$	1 if machine m ϵ M is assigned to the process $p \in P$ of the element $e \in E$ in the slot s ϵ S and 0 otherwise
Slot assignment	$st_{e,p,s}$	1 if a process $p \in P$ of an element $e \in E$ starts in the slot $s \in S$ and 0 otherwise
	$fn_{e,p,s}$	1 if a process $p \in P$ of an element $e \in E$ finishes in the slot $s \in S$ and 0 otherwise
	$fnaux_{e,p,s}$	Auxiliary variable used to calculate fne,p,s
WIP measure	$buf_{e,p,p',s}$	The number of elements e in the buffer between processes p and p' during slot s
	$pbuf_{e,p,p'}$	The number of elements e between processes p and p' at the beginning of the time horizon
	$tbuf$	Total amount of work in progress throughout the scheduling time horizon

analysed in prior studies. Therefore, our case study is of interest both from the industrial and academic perspective.

V. FORMULATION

An MILP discrete time formulation has been developed. The sets used are listed in Table 2. The airframes to be produced are denoted as set $\boldsymbol{E}$ and $\boldsymbol{P}$ represents the set of processes into which the assembly of each element is divided. The set $\boldsymbol{T}$ represents the types of operators, divided into production (***TP***) and non-production categories (***TNP***). The machines are defined as set $\boldsymbol{M}$.

The time horizon is divided into slots $\boldsymbol{S}$, which are classified as morning, afternoon or night shift slots. The duration of a slot is one of the input parameters. We used a discrete time approach because the added modelling difficulties do not justify the computational cost [26].

The total scheduling time horizon is defined by the cycle time of the different elements that need to be produced and is calculated as the lowest common multiple (***LCM***) of all the cycle times. Therefore, an integer number for each element is produced within this time horizon. ***CY*** refers to the set of cycles in which the time is divided, ***CYe*** refers to the subsets of cycles of each element and ***Se,cy*** refers to the subset of slots that belong to each cycle ***cy*** of the element ***e***.

Input parameters provide information regarding each element's cycle time, the processes per element (including their workload, precedencies and resource consumption and the use of operators' time), the machines' availability and the existing buffers in the plant. All the parameters are listed in Table 3.

The primary decision variables include $\boldsymbol{so_{e,p,s}}$, which are equal to 1 if operators are working on process $p \in P$ of the element $e \in E$ in the slot $s \in S$ (binary) and $\boldsymbol{ops_{e,p,s,t}}$ that define the number of operators of type $t \in T$, in slot $s \in S$, in process $p\epsilon P$ for each element $e\epsilon E$. Table 4 provides a listing of all the variables.

Two different models were used. The first model minimizes the number of operators. The second model minimizes the average size of the buffer in the plant.

The complete formulation is as follows:

A. MODEL A: MINIMIZING THE NUMBER OF OPERATORS'

$$min.z = to\,(0\text{ op})$$

$$\sum_{s,t} ops_{e,p,s,t} \cdot SD = W_{e,p} \quad \forall e,p,cy|cy \in CY_e;\; s \in S_{e,cy} \quad (1)$$

$$\sum_{e,p} ma_{e,p,m,s} \le Q_m \quad \forall m,s \quad (2)$$

$$ma_{e,p,m,s} \ge so_{e,p,s} \quad \forall e,p,m,s|ENM_{e,m,p} = 1 \quad (3)$$

$$opsslot_{s,t} = \sum_{e,p} ops_{e,p,s,t} \quad \forall s,\ t|t \in T^P \quad (4)$$

$$tom_t \ge opsslot_{s,t} \quad \forall s,\ t|t \in T^P; MS_s = 1 \quad (5)$$

$$toa_t \ge opsslot_{s,t} \quad \forall s,\ t|t \in T^P; AS_s = 1 \quad (6)$$

$$to = \sum_t tom_t + toa_t \quad (7)$$

$$ops_{e,p,s,t} = 0 \quad \forall e,p,s,t|NS_s = 1 \quad (8)$$

$$\begin{aligned} &if\ s = FS\,(e,cy)\ then\ st_{e,p,s} \ge so_{e,p,s}\\ &else\\ &st_{e,p,s} \ge so_{e,p,s} - so_{e,p,PA(s)}\\ &endif\\ &\forall e,p,p',s,cy|s \in S_{e,tk} \end{aligned} \quad (9)$$

$$\sum_s st_{e,p,s} = QCY_e \quad \forall e,p \quad (10)$$

$$\sum_s fn_{e,p,s} = QCY_e \quad \forall e,p \quad (11)$$

$$ops_{e,p,s,t} \le so_{e,p,s} \cdot MXO_{e,p,t} \quad \forall e,p,s,t \quad (12)$$

$$\sum_t ops_{e,p,s,t} \ge so_{e,p,s} \quad \forall e,p,s \quad (13)$$

$$so_{e,p,s} \le PS_p \quad \forall e,p,s \quad (14)$$

$$so_{e,p,s} \le st_{e,p,s} + so_{e,p,PA(s)} \quad \forall e,p,s,cy|UP_p = 1;\; cy \in CY_e;\quad s \ne FS\,(e,cy)\,;\; s \in S_{e,cy} \quad (15)$$

$$\frac{\sum_s^{\prime} ops_{e,p,s',t} \cdot SD}{LW_{e,p}} + 0.999 \forall e,p,s,cy|s \in S_{e,tk} \quad (16)$$

$$fn_{e,p,s} + 1 \ge fnaux_{e,p,s} + so_{e,p,s} \quad \forall e,p,s \quad (17)$$

$$so_{e,p',FA(s)} = 0 \quad \forall e,cy,p',p,s|PR_{p,p'} = 1 \quad (18)$$

$$\frac{\sum_s^{\prime} ops_{e,p,s',t} \cdot SD}{LW_{e,p}} \ge st_{e,p',s}|FS\,(s) < s' < s \quad \forall e,p,p',s,cy|s \in S_{e,cy};\quad PR_{p,p'} = 1 \quad (19)$$

$$so_{e,p,s} + so_{e,p',s+n} \le 1 \quad \forall e,p,p',s,n|SFT_{p,p'} = 1;\; n = 0,1,\ldots,\frac{TSFT_{p,p'}}{SD} \quad (20)$$

$$so_{e,p,FS(e,tk)} = 0 \quad \forall e,p,p',s,tk|SFT_{p,p'} = 1 \quad (21)$$

$$fn_{e,p,s} = st_{e,p',s+\frac{TSFT}{SD}+1} \quad \forall e,p,p',s|SFT_{p,p'} = 1 \quad (22)$$

$$fn_{e,p,s} \le ma_{e,p',m,s+n} \quad \forall e,p,p',m,s|SFT_{p,p'} = 1;\quad ENM_{e,m,p} = 1;\; n = 0,1,\ldots,\frac{TSFT_{p,p'}}{SD} \quad (23)$$

$$fn_{e,p,s} = st_{e,p',NA(s)} \quad \forall e,p,p',s|IP_{p,p'} = 1 \quad (24)$$

B. MODEL 2: MINIMIZING THE AVERAGE SIZE OF THE BUFFER IN THE PLANT

All the constraints used in the first model in addition to the following:

$$min.z' = tbuf + 0.001to\,(0\,bf)$$

$$\begin{aligned} &if\ s = FS\,(e,cy)\ then\\ &buf_{e,p,p',s} = pbuf_{e,p,p'}\\ &else\\ &buf_{e,p,p',s} = buf_{e,p,p',s-1} + fn_{e,p,s-1} - st_{e,p',s}\\ &endif\\ &\forall e,p,p',s,cy|s \in S_{e,tk};\quad BP_{p,p'} = 1 \end{aligned} \quad (25)$$

$$pbuf_{e,p,p'} \ge 0 \quad \forall e,p,p'|BP_{p,p'} = 1 \quad (26)$$

$$pbuf_{e,p,p'} \le QCY_e \quad \forall e,p,p'|BP_{p,p'} = 1 \quad (27)$$

$$tbuf = \sum_{e,p,p',s} buf_{e,p,p',s} * WB_{p,p'} \forall e,p,p'|BP_{p,p'} = 1 \quad (28)$$

Where the objective function (0 op) is the minimization of the number of operators and (0 bf) the minimization of the average size of the buffer in the plant. Constraint (1) ensures that the workload that is assigned to process p of element e in all slots s of a cycle that is multiplied by the duration of the slots is at least the total process workload for that element (We,p).

The number of machines m that are assigned during a slot cannot be more than the machine availability (Q_m) per constraint (2). The simultaneous assignment of the machines and operators to the process of an element is guaranteed by constraints (3).

The total number of operators that are needed per type and shift is calculated by (4). Constraints (5) through (7) limit the total number of operators, which is the sum of the morning operators (5) and afternoon operators (6). Operators are not permitted to work during the night shift per constraint (8).

When evaluating the first slot, a process begins ($st_{e,p,s}$) when an operator ($so_{e,p,s}$) begins working in this process.

For the remaining slots, a process begins ($st_{e,p,s}$) when an operator ($so_{e,p,s}$) begins working and no operators were working in the previous active slot ($so_{e,p,PA(s)}$) (9).

The number of times that a process begins/ends ($st_{e,p,s}$) must equal the number of elements to be manufactured (QCY_e) (10/11).

Constraints (12) and (13) refer to the operators that are assigned to a process. The number of operators of type t working on process p for element e in slot $s(ops_{e,p,s,t})$ must be less than its maximum ($MXO_{e,p,t}$) (12) and if operators are working on a process for a slot then an operator type must be assigned ($\sum_t ops_{e,p,s,t} \geq so_{e,p,s}$) (13). Furthermore, per (14) operators only work on a process during a slot if this slot belongs a morning or afternoon shift.

A process cannot be interrupted once it has started if non pre-emption applies to it per (15).

To determine the end of a process, the auxiliary variable ($fnaux_{e,p,s}$) is equal to 1 when the addition of the prior work load is equal to the total amount that is required. To guarantee that only the last slot indicates the end of the process, the primary variable ($fn_{e,p,s}$) is 1 when the previous condition occurs and an operator is working there (16-17).

Precedence relationships are managed with constraints (18) through (24). Constraints (18-19) address general precedence constraints and (20-23) address time lag constraints (processes that must begin precisely n slots after their predecessor). Constraint (23) addresses the machine occupation during the time lag. Constraint (24) refers to a zero time lag precedence.

The following constraints in addition to the prior constraints form the second model. The objective function (0 bf) is a weighted sum of the number of elements in buffers ($tbuf$) and the total number of operators (to), the number of operators has a small weight because we need to minimize the size of the buffer. If we do not use the total number of operators in the objective function then unbounded results are obtained for the number of operators.

Finally, constraints (25) through (28) refer to the buffer occupation during the time horizon. The buffer that corresponds to the first slot is equal to the quantity that the system uses to begin the production. The buffer of the subsequent slots ($buf_{e,p,p',s}$) is equal to the number of the previous slot ($buf_{e,p,p',s-1}$) and a balance of the income and output of this buffer ($fn_{e,p,s-1} - st_{e,p',s}$) (25).

The initial value of the buffers of elements ($pbuf_{e,p,p'}$) must be greater than or equal to 0 (26) and less than or equal to the number of elements that must be produced (QCY_e) (27). The total number of elements through all the slots ($tbuf$) is equal to the weight sum of each buffer ($\sum_{e,p,p',s} buf^*_{e,p,p',s} WB_{p,p'}$) (28).

VI. COMPUTATIONAL RESULTS

Tests were performed using real-life data and considered real-life production times and the product mix from prior years. Because of confidentiality constraints, process workloads have been modified for the experimentation we will present.

TABLE 5. Number of working hours per process and airframe.

Part	Preliminary Test	Cutting	Workbench Assembly 1	Workbench Assembly 2	Equipping	Furnishing	Soft Cutting	Final Tests	Final Operations
FC-A LH	4	8	16	8	60	48	12	8	12
FC-ARH	4	8	20	8	52	32	8	8	12
FC-B LH	8	12	16	8	56	40	12	8	12
FC-B RH	8	12	20	8	48	48	8	8	12

The workload per process and airframe are common in all the instances and is provided in Table 5. They vary from 4 to 60 man-hours per process. On the assembly line, work is assigned each 4 hours and therefore, the slot duration has been set to this length. In consequence, production times are also rounded to multiples of 4. For example, the average time for the cutting process of the FC-A-LH is 6.7 hours and it will be rounded to 8 hours. We round up instead of round down because processing time is more frequently exceeded than reduced.

The nine processes that were explained in Section 2 must be performed in order for each airframe. (Preliminary Tests, Cutting, Workbench Assembly 1, Workbench Assembly 2, Equipping, Furnishing, Soft Cutting, Final Tests and Final Operations). Furthermore, there is an immediate precedence between Final Tests and Final Operations.

Preliminary Tests, Cutting, Workbench Assembly 2 and Final Tests have no pre-emption. The time lag (*TSFTp,p'*) between Workbench Assembly 1 and Workbench Assembly 2 should be at least 8 hours.

All machines are available during morning and afternoon shifts, with the exception of the Final Tests machine, which is only available in the afternoon.

The experimentation of this study is divided into three steps. In a first step, we solved an instance with the production times on Table 5 and all possible combinations of cycle times for a time horizon that lasted a maximum of 12 days, minimizing the total number of operators. In the second step we repeated the experimentation minimizing the buffer. Finally, in the third step, for the first three instances (time horizon of 4, 5 and 6 days), we experimented with several numbers of operators to obtain the optimal solution in terms of buffer. That is, we obtained the Pareto Front for the two objective functions.

From the used instances, the most common on the workshop are those of 4, 5 and 6 working days. The maximum time horizon is 12 days because a production pattern of more than 15 calendar days is rarely used in practice. Conversely, a time horizon of less than 4 days is not possible because of FC-A's total workload.

The prior models were solved using an Intel Core i7 pro with 8 GB of RAM running AIMMS with CPLEX under Windows 10.

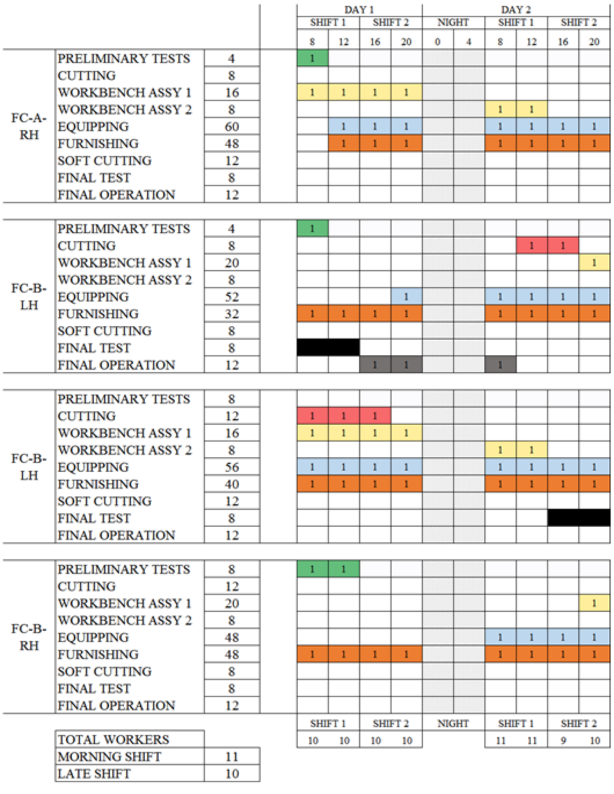

FIGURE 2. Solution bar chart of the first two days of the instance Op/4/4.

The scheduling output includes a bar chart where each process has an allocated time slot and a number of operators that have been assigned for that operation. Figure 2 provides the results for the first two days for the example Op/4/4. The different processes are listed on rows. There is one column per time period (half a shift = 4 hours). The coloured cells are the ones when a process is being done and the number inside the cell is the number of operators assigned to that execution of the process. For example, on the first half shift there are two FC-A-LH being processed: one is going through the Preliminary Test process and another one through the Workbench assembly 1 process. They are using one operator each. In all, 10 operators are needed during that half shift.

Table 6 provides the results of the first step of the experimentation when we solved the first model for solely minimizing the number of workers, then we calculated the average buffer in the plant for those solutions. In Table 7 we provide the results for the average size of the buffer minimization and the corresponding number of workers.

Both tables have the following structure: The first column provides the name of the instance. Instances are named with

TABLE 6. Results for the minimization of the number of operators.

Instance	Time Horizon (days)	Var (Int)	Constr.	Solving time (sec)	**Num Op***	Average buffer in the plant.
Op/4/4	4	4622 (4583)	11252	15	**21**	32.75
Op/5/5	5	5774 (5727)	15716	36	**16**	28.65
Op/6/6	6	6926 (6871)	20852	33	**14**	18.13
Op/4/6	12	13838 (13735)	37610	2,783	**18**	49.29
Op/6/4	12	13838 (13735)	29617	1,300	**17**	48.81

All instances achieve the optimal outcomes. * is the objective function

TABLE 7. Results for the minimization of the average buffer.

Instance	Time Horizon (days)	Var (Int)	Constr	Solving time (sec)	Num Op	**Average buffer in the plant.***
Bf/4/4	4	5122 (5084)	11773	16 sec	27	**14.94**
Bf/5/5	5	6394 (6348)	16357	39 sec	20	**9.85**
Bf/6/6	6	7666 (7612)	21613	400 sec	16	**4.71**
Bf/4/6	12	15298 (15196)	39091	7,537 sec	21	**6.73**
Bf/6/4	12	15298 (15196)	39091	9,178 sec	21	**7.60**

*All instances achieve the optimal outcomes. * is the objective function*

a two letter code that depends on the objective function that used to solve it ("op" represents the number of operators objective function and "bf" represents the average number of elements in the buffer objective function) followed by the FC-A's cycle time and FC-B's cycle time. *Time Horizon* refers to the scheduling time horizon. *Var* and*constraint* refer to the number of variables and constraints in the model, respectively. Solving times are measured in seconds. All instances have been solved to obtain the optimal outcome. *Num Op* refers to the total number of operators in the solution and *Average buffer in the plant* refers to the average number of elements in the buffers during the scheduling horizon.

As expected, minimizing one criterion has a negative impact on the other criterion. For example, for instance Op/4/4, we obtain 21 workers and 34.75 elements, but for instance Bf/4/4 we obtain 27 workers and 14.95 elements on average in the buffer. A typical solution to the combine two objectives would have been to transform everything to cost, and then minimize the cost. However, this traditional approach limits the decision maker to only one option. Based on the specific situation of the week, the decision maker could make a decision that prioritizes the number or workers or the size of the buffer, or something else in the middle. Therefore, in our third experimentation step we studied the entire range of possible solutions for instances 4-4, 5-5 and 6-6.

Results from the third step are plotted on Figure 3. A curve for the different solutions of each of the instances is provided. The first point is the minimum number of

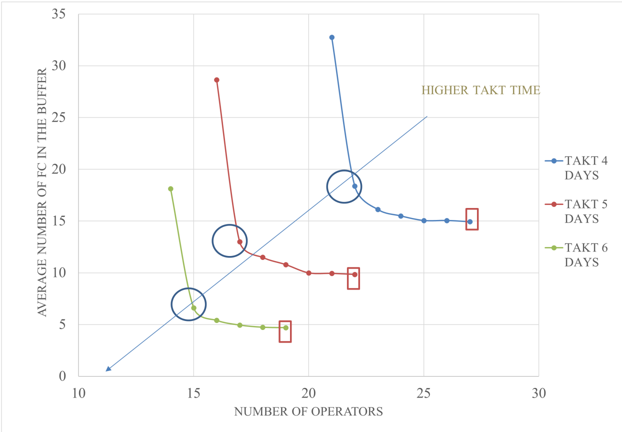

FIGURE 3. **Solutions obtained from the different scenarios. The red squares highlight the dominated solutions.**

operators as calculated on Step 1 (see Table 5). Then, we fixed the number of operators, adding an operator at a time and solving the resulting problem minimizing the average buffer. We stopped the experimentation for each instance when adding an extra worker did not provide a further improvement in the solution. The red squares highlight the dominated solutions. The circles point out the better solutions. Each point in the graph has a bar chart associated as the one that we can see in Figure 2.

Solutions are provided within an adequate computational time. In the worst case scenario, a solution was provided in less than 4 hours, whereas a planner spends approximately 40 hours to manually calculate a solution without using any computational methods. Real-life examples were solved using two objectives: minimizing human resource costs and minimizing the work in progress. Although academia generally uses a common approach that translates everything to cost, in real life problems, scholars agree that a translation is complicated and depending on their perspective and external factors, different costs could be applied to the same item.

VII. CONCLUSION

This study describes a MILP model for the scheduling of a cyclic Flexible Job Shop problem with operators. The problem was solved for instances of up to 11 machines, 45 different processes and 30 operators. The model was used with real-life examples and tests were performed with scheduling horizons from 4 to 12 working days. To the authors' knowledge, this problem has not been addressed in prior studies.

Furthermore, this study is relevant for direct applications in the aeronautic industry where reducing the costs that are incurred for human resources or work in progress is an important source of competitiveness. A reduction in the number of workers on an assembly line directly decreases the costs related to human resources. Additionally, a decrease in the intermediate stock is greatly appreciated by managers because this not only results in financial savings but also reduces the possibility of damaging the products and incurring reparation costs.

Flexibility is one of the major assets of Industry 4.0 [27] Schuh proposed flexibility as part of Industry 4.0 as a mechanism to increase productivity. As the factories are living things, we cannot ask the decision support tool to decide which one is the best production plan, but we have designed the decision support tool to easily provide different solution to the decision maker.

We believe that the optimal solution enables schedulers to select different weight combinations of work in progress and human resource costs and adapt the final decision to the current state of the factory, such as capacity to allocate spare workers, the amount of inventory, the price of the inventory and the risks. This approach is possible because the time needed to solve the problem has been greatly reduced. The time needed to solve the problem is in fact, one of the primary advantages of the model that is presented in this study. The resulting schedule is a non-typical linear process with resources that could be configured, elements that visit a workstation more than once, compulsory waiting times, and workers that only work certain shifts. Commercial ERP software, such as SAP, is unable to solve and optimize this type of production process.

In summary, we solved a real-life problem using real-life data and performed experimentation using a dual approach. This type of problem is not exclusive to the aeronautical industry and could be used in other labour intensive industries such as ship manufacturing. The results of this study are also relevant in terms of research because it addresses the simultaneous assignment of machines, time slots and operators to a task.

A. FUTURE WORK

Future studies could improve the model's performance. Although all the instances in this study have been solved to optimality, future studies could solve larger problems such as including operators who are shared by different mixed model assembly lines. To solve these larger problems, parallel computing could be tested. Future studies could also use decomposition approaches, constraint programming or other hybrid and metaheuristic techniques.

Finally, another interesting topic for future research is managing stochastic process times and machine failures.

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