OPTIMIZATION OF AUTOCLAVE UTILIZATION IN COMPOSITE MANUFACTURING PROCESS

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ABSTRACT

Composite manufacturing process is often a batch production system due to the long curing times and physical limitations of autoclaves. Although, the literature of manufacturing scheduling is very mature in providing methods and solution for batch production, it often overlooks limitations pertain to an autoclave curing process i.e. dimension and vacuum ports as well as the utilization optimization of autoclaves. In this paper, a linear programming problem is provided which minimizes the total number of runs required for the curing of parts with similar curing times. Additionally, an illustrative example is provided based on real data obtained from industry to shed light on the application of the formulation.

INTRODUCTION

United States is the second largest marketplace for composites worldwide after China in terms of volume consumption. Demand in the U.S. composites market is expected to increase to $12 billion by 2020. Growth in wind energy, automotive, aerospace and construction industries is expected to stimulate the composites market through 2020 and beyond.

While the composite manufacturing growth trajectory is promising, its manufacturing often follow very labor-intensive traditional method of manufacturing. Composite manufacturing typically is divided in three distinct stages: Lay-up process, autoclave curing and assembly. The lay-up process involves manually stacking layers of resin-impregnated roving cloth in an open mold often called “tool”. The cloth covered tool is then compressed to form a solid composite product. The cloth is usually made of fiberglass or carbon weave. To form the exterior profile of composite parts, depending on the component application, different types of tools is used. The tools therefore have different dimensions and shapes. when the specifications require to add extra compression, methods such as vacuum bagging, mated molds, etc. are applied. When the required form is obtained, the composite is placed in a special oven, which is called autoclave, to cure. An autoclave is a pressure chamber required for providing temperature and pressure required as per specification which is different from ambient air pressure. The process performed by an autoclave is typically time-consuming and expensive due to the amount of energy that it used to provide the required temperature and pressure. In composite manufacturing, often the bottle-neck process is the autoclave curing as the capacity of autoclave is limited and curing times are long. As a result, increasing the efficiency and utilization of autoclaves often has a significant impact on the overall manufacturing yields. The capacity of autoclave is limited by its vacuum ports and dimension. Figure 1 shows an image of a typical autoclave currently used in aerospace manufacturing process.

Figure 1 a typical autoclave used in aerospace manufacturing industry

Serval researchers have provided batch production and scheduling solutions in the literature. Demeulemeester and Herroelen [2] developed a general production-scheduling problem (GPSP). Their conceptual formulation seeks to minimize the time to completion of the final activity, which is equal to minimizing the make-span. Constraints are defined to ensure that: a) precedence relationships among the activities are satisfied, to include any finish-start time lags, which may be needed; b) a dummy activity which precedes the first operation of each job is completed at time zero; c) all activities are completed by their due dates; and d) resources required to support scheduled activities in a time period are available. It also addresses the advantage gained by the use of single unit transfer batches. The algorithm constructs finish-start time lags based on the setup and unit processing times involved in processing each batch. Another algorithm created by Lawler [Nahmias, 4] is a powerful technique for solving a variety of constrained scheduling problems. The objective function seeks to minimize the maximum flow time. The algorithm is designed to handle precedence constraints, which occur when one operation in a process sequence must be completed before another operation can begin. Lawler's algorithm first schedules the job to be completed last, then the job to be completed next to last, and so on.

Many researchers have studied scheduling problems for multi-purpose batch plants in chemical processing [1, 3, 5, 6, 7, 8, 9, 10]. Due to the complexity of the batch-scheduling problem, most of the research work in this area is focused on efficient heuristic procedures that yield sub-optimal solutions to the problem. Suhami and Mah [5] develop a heuristic solution procedure based on a linear programming model to minimize the total tardiness for the scheduling of production runs of identical batches. Egli and Rippin [6] develop an enumerative solution procedure for the scheduling of the non-identical batches. Rich and Prokopakis [7] and Patisdou and Kantor [8] formulate the batch-scheduling problem as a mixed-integer non-linear program. The studies assume the number of batches for each product is fixed (a single batch for each product) and the batches do not merge, or split. Musier and Evans [9] argue that the batch size should be variable and needs to be determined by the scheduling system. They argued that assuming a fixed number of batches is not reasonable since most customer orders are either larger or smaller than the batch size of the plant's process unit.

Y.M. Dessouky and C.A Robert [10] developed a heuristic algorithm to schedule the multi-purpose batch plants with junction constraints for chemical process. The algorithm is called BATCH_SCHED. The scheduling problem is similar to an N-job, M-machine job-shop scheduling problem in discrete-parts manufacturing with batch sizing, alternative routing, zero buffering, and batch merging. The objective minimizes the total tardiness, which is the difference between the completion time of the order and the order due date if an order is late. The algorithm schedules the orders based on the orders' slack times. For each order, the algorithm determines the number of batches required to satisfy the order quantity, the size of each batch, and the completion time for each batch on each resource in the selected process plan. Yuan et al. [11] provided a heuristic for the batch scheduling problem with a performance ratio of 2 which also had a polynomial time approximation scheme.

Although the literature of batch production and scheduling is very mature, it overlooks limitations specific to autoclave curing processes i.e. dimension and vacuum port constraints as well as the utilization optimization of autoclaves after grouping parts based on curing times. In this paper, in the next section, a linear programming problem is proposed which addresses these issues. Then, an illustrative example is provided to depict the application of the proposed method for a real-life autoclave optimization problem. At the end, conclusion and feature works are proposed.

Optimization Formulation

In this section, a linear programming problem is proposed to maximize the space utilization of autoclaves and minimize the number of runs required to meet the demand. Suppose there are m autoclaves with length L_j , $\forall j=1,..,m$. The number of vacuum ports inside each autoclave is given by V_j, $\forall j=1,..,m$. Also, suppose that there are n parts that have approximately similar curing times i.e. they can be batched together for the curing purposes. Each part has a demand d_i, $\forall i=1,..,n$ at the end of the planning horizon (T runs). It is assumed that the length of each part is less than the length of autoclave i.e. $li<= L_j$ $\forall j=1,..,m$. Additionally, The number of vacuum ports required by a single tool is not greater than the total number of vacuum ports existing in an autoclave i.e. $vi<= V_j$ $\forall j=1,..,m$. Furthermore, it is assumed that tools can only be placed in one row (sequential) inside the autoclave. To develop the mathematical programming, the following notations are used:

Variables:

X_{ij} Number of part i allocated to autoclave/run j

Input parameters:

l_i length of tool i (this length also includes the clearance required along the length of tool j)

v_j number of vacuum ports required for part i

d_i demand of part i

L_j Length of autoclave j

V_j Number of vaccum ports in autoclave j

$$\text{Max } z = \sum_{t=1}^{T}\sum_{j=1}^{m}\sum_{i=1}^{n} X_{ijt} \tag{1}$$

$$\sum_{i=1}^{n} l_i X_{ijt} \le L_j \quad \forall\ j \in \{1,..,m\} \text{ and } \forall\ t \in \{1,..,T\} \tag{2}$$

$$\sum_{i=1}^{n} v_i X_{ijt} \le V_j \quad \forall\ j \in \{1,..,m\} \text{ and } \forall\ t \in \{1,..,T\} \tag{3}$$

$$\sum_{t=1}^{T}\sum_{j=1}^{m} X_{ijt} \ge d_i \quad \forall\ i \in \{1,..,n\} \tag{4}$$

$$X_{ij} \ge 0 \text{ and integer} \tag{5}$$

The first term (1) is the objective function which maximizes total number of items produces after T runs of m autoclaves. The constraints (2) enforces that the maximum length of tools allocated to an autoclave do not exceed its Maximum length. The second constraint (3) makes sure the number of vacuum ports used in one run of an autoclave is not more than number of vacuum port available. The third constraint (4) enforces that the total number of parts produced in T runs are least equal to the demand requirements.

Although in this mathematical formulation the number of runs (T) is a known input parameter, application of the same formulation for optimizing the total number of T required to meet the demand is straight forward. To determine T (number of runs), one can start by assuming a lower bound on the number of runs required and start the optimization process. If the problem is feasible with the lower bound found, the optimal solution has obtained. Otherwise, if the problem is not feasible, the number of runs can be incremented by 1 until a feasible solution is achieved. A lower bound on the number of runs (T) required to meet the demand can be found using the following terms:

$$t_l = \left\lfloor \frac{\sum_{i=1}^{n} d_i l_i}{\sum_{j=1}^{m} L_j} \right\rfloor + 1 \tag{7}$$

$$v_l = \left\lfloor \frac{\sum_{i=1}^{n} d_i v_i}{\sum_{j=1}^{m} V_j} \right\rfloor + 1 \tag{8}$$

$$T_{LB} = max\{t_l, v_l\} \tag{9}$$

In equation (7), the number of autoclaves required is calculated by dividing the total length of all required parts by the total length of available autoclaves. However, since the value of this fraction is often fractional we round up this value by first taking the integer portion of the ratio and then adding one unit to it. For example, if the total length of tools is 100 ft and we have two similar autoclaves each of length 30 ft, then the minimum number of runs is going to be 100/30(3) =1.11. This means we need to have at least two runs of autoclave to complete processing of all parts in the autoclave. The same logic can be applied to find the minimum number of runs required to meet the vacuum ports constraints. In the same example, suppose that the total number of ports required for all parts is equal to 85 and each autoclave has 20 ports. In this case, the minimum number of autoclave runs required is 85/20(2)=2.125, which means we need at least 3 runs to meet the vacuum port requirements. Finally, for this problem the minimum number of autoclave runs is equal to 3 (T=3). Consequently, using the min T the optimization process can be started. Figure 2, shows the optimization algorithm which results in optimization of number of runs as well as space utilization of the autoclave.

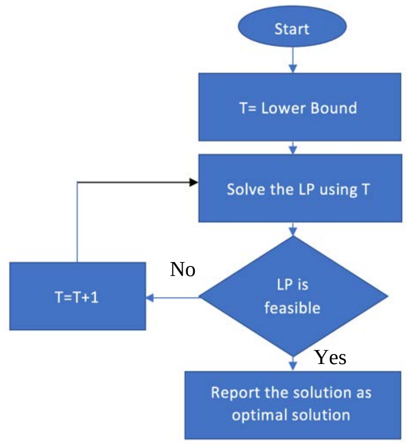

Figure 2 Optimization process for the number of runs required to meet the demand i.e. T

In the following section an illustrative example provided to shed lights on the application of the optimization formulation provided in this section.

Illustrative example:

To illustrate the application of Linear Programming provided in the previous section, a real-life example is provided in this section. The input parameter for this problem are provided by a composite manufacturing company in southern California. However, due to confidentiality, components' names are replaced by letters. Table 1 shows the components' names along with their length, demand, and number of ports. The length of each tool also includes the required clearance in either sides of it. Also, the number of vacuum ports required for each component's tool is provided in the table. In this example, parts A through F are required to go through a 10-hour autoclave curing process. The company has one autoclave which has a length of 264 inches. Also, there are 20 ports inside the autoclave. To have the final assembly, one unit of each part is required except part B which is required by two units.

Table 1 input data regarding tools

	Component	Length(inches)	Demand (also BOM)	port
1	A	104.6875	1	3
2	B	86	2	4
3	C	81.0625	1	4
4	D	41.95	1	3
5	E	39.625	1	2
6	F	34.375	1	4
7	G	31.125	1	3

Assume that there is no specific number of runs determined for the scheduling and optimization. therefore, optimization of T to meet the demand is also required. The first step, is to calculate the minimum number of runs required based on the autoclave length and vacuum port limitations. Using equations 7 through 9 we have:

$t_l = \left\lceil \frac{104.6875\times 1+86\times 2+\cdots+31.125\times 1}{1\times 264} \right\rceil + 1 = 2$

$v_l = \left\lceil \frac{3\times 1+4\times 2+\cdots+3\times 1}{1\times 20} \right\rceil + 1 = 2$

$T_{LB} = max\{2,2\} = 2$

Therefore, at least 2 runs of autoclave is needed to meet the demand requirements. Given T=2 and other input parameters the expansion of mathematical formulation provided in the previous section is as follows:

Max= $X_{111}+X_{112}+X_{211}+X_{212}+X_{311}+X_{312}+X_{411}+X_{412}+X_{511}+X_{512}+X_{611}+X_{612}+X_{711}+X_{712}$

subject to:

$104.6875X_{111}+86X_{211}+81.0625X_{311}+41.95X_{411}+39.625X_{511}+34.375X_{611}+31.125X_{711} \leq 264$

$104.6875X_{112}+86X_{212}+81.0625X_{312}+41.95X_{412}+39.625X_{512}+34.375X_{612}+31.125X_{712} \leq 264$

$3X_{111}+4X_{211}+4X_{311}+3X_{411}+2X_{511}+4X_{611}+3X_{711} \leq 20$

$3X_{112}+4X_{212}+4X_{312}+3X_{412}+2X_{512}+4X_{612}+3X_{712} \leq 20$

$X_{111}+X_{112} \geq 1$

$X_{211}+X_{212} \geq 2$

$X_{311}+X_{312} \geq 1$

$X_{411}+X_{412} \geq 1$

$X_{511}+X_{512} \geq 1$

$X_{611}+X_{612} \geq 1$

$X_{711}+X_{712} \geq 1$

The problem was formulated and solved in LINGO 16.0 and the following results were obtained:

$X_{111} = X_{311} = X_{412} = X_{511} = X_{612} = X_{711} = 1$ and $X_{212} = 2$

According to the result, in the first run, components A, C, E and G are cured. The second run consists of B, D and F. Given the optimization result, all components can be cured with the least unutilized space. It is worth mentioning that the company previously used three runs instead of the two runs suggested by this optimization model. The results save the company 10 hours of autoclave and the associated labor cost which has a significant impact on the production yield of the company.

Conclusion and Recommendations

This paper provided a linear programming problem to maximize the utilization of an autoclave in order to achieve the maximum production yield possible. Currently, the batching of items for autoclave process is often based on similarity of curing time regardless of optimization of space used inside the autoclave. The proposed optimization method maximizes the space utilization within autoclaves and reduced the total number of autoclave runs given production requirements. One possible feature work could be synchronized scheduling of lay-up and autoclave optimization to avoid lay-up of items that need to wait before the curing time more than their out of shelf time.

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