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An Enterprise Decision Model for a Large Scale Assembly Operation

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Abstract: Aircraft manufacturing is typically characterized by large, highly complex end items that require a great deal of human assembly resources. For large scale operations producing complex items at high volumes, management oversight is broken down into discrete areas that operate as internal suppliers/customers to each other. While the scale of the production system lends itself to this decomposition, global efficiency can suffer in such a scenario (based on internal managerial and political dynamics). This paper presents an enterprise model for optimizing a large scale, high volume assembly operation based on the minimization of the variability between labour capacity and labour demand.

Keywords: Enterprise modeling and BPM; Enterprise integration; Business process management systems

1. INTRODUCTION AND LITERATURE REVIEW

At times there can be a disconnect between the problems that are confronted in the realm of academia and those that are encountered in industry. This is certainly the case for aircraft manufacturing where the nature of the product complicates production planning. In aircraft manufacturing, the product being built is large, complex, and requires a large amount of human assembly resources. Liu, Chua and Yeoh (2010) point out that products with these characteristics make aggregate production planning quite difficult. Boysen, Fliedner and Scholl (2007), Abdinnour (2011) and Falkenauer (2005) all juxtapose the extensive coverage of the assembly line balancing problem (ALBP) in academic operations research against the lack of practical application in complex industries such as automotive and aircraft manufacturing.

The complexity of the work being done in aircraft production lends itself to decomposition in a top-down management approach. Major sections of the aerostructure are first built up before being integrated together. These sections are themselves built up from other sub-assemblies and components that move through multiple shops where the assembly work is accomplished.

In determining the amount of labour resources necessary for a particular production rate, the sum total of the labour standards (derived from time studies and/or cost accounting activities) for the work statement is used. As a simple example, consider a demand of 21 fuselages for a particular month and that each fuselage requires 4,000 labour hours to build. If the workforce is on a typical eight hour work day and there are 21 workdays in the month, then the company would need 4,000 hours per day divided by 8 hours per mechanic per day which would equal 500 mechanics.

If there were no variability in manufacturing, production planning would be as simple as the example above. Obviously, however, this is not the case and operations managers must try to account for variability when they plan production. While there are many sources of variability in manufacturing, two major sources affecting high-volume, complex assembly operations like aircraft manufacturing are found in labour capacity and labour demand. Moreover, there are certain characteristics about this type of manufacturing that make managing these factors even more difficult.

This paper proposes that successfully accounting for and managing the variability in labour capacity and labour demand is necessary for production health—though this is not necessarily the primary concern for managers. In large operations such as aircraft manufacturing, it is common for individual shops within the assembly operation to act as discrete business units in customer/supplier relationships. Depending upon performance metrics and incentives, global production health can be sacrificed for local optima in such an arrangement. For this reason, we propose an enterprise model to minimize variability between labour capacity and labour demand in order to assist with production planning.

1.1 Labour Demand

On a basic level, labour demand in any manufacturing environment depends on the demand for the products the company produces. In an assembly operation where the product is physically built by skilled labourers (as opposed to automated production), labour demand generally increases with increasing product demand, thought not necessarily in a linear fashion. Wright (1936) observed that learning occurs as cumulative production rises and it reduces manufacturing costs. This has been a long-held fact—especially in aircraft manufacturing—but Benkard (1999) presented strong data that manufacturing dynamics are too complex to assume smooth learning curves; he pointed out that manufacturers are also subject to organizational forgetting due to employee turnover, and increases in inexperienced workers during rate increases. In any case, labour standards should be closely monitored for accuracy. For the purposes of this paper, they are assumed to be correct.

In terms of product demand in commercial aircraft manufacturing, production rates are usually set reasonably far in advance based on a backlog of orders. In this sense, demand is fairly predictable compared to other industries and for this paper will be considered deterministic.

Once a production rate has been set, however, day to day labour demand can vary a great deal depending on factors such as move rate, line configuration, model mix and labour capacity.

1.2 Move rate and line configuration

Though Lu and Sundaram (2002) discuss simulation of a moving assembly in aircraft production, most of the major work typically takes place in fixed tooling positions and the units are moved into position by overhead cranes. Eventually, multiple major components must come together for integration into a complete fuselage and all of the sections need to be moved before work can begin. Depending upon production volume, size of the subassemblies and crane availability, making all of these moves could take the better part of a shift. Since moving the line for large aero structures takes time, the unit moves usually take place in between shifts to maximize workers' time on the units and minimize idle time. This is what's known as a "fixed move rate," since the line moves at a fixed time. In a one-day line, for instance, an area unloads a unit every day; in a two day line the area unloads a unit every two days, etc.

The amount of time a unit is in an assembly area does not necessarily equal the move rate. A shop might require five days to complete a unit, for example, and still be on a one-day line. In this case, they would need five tool positions to meet the throughput requirement of supplying one unit per day to its internal customer. Little (1992) established this relationship in what's commonly known today as Little's Law; since TH = WIP x CT, to achieve 1 unit/day throughput, there needs to be 5 units in WIP if the cycle time is 1 unit every 5 days.

When production rates are determined in aircraft manufacturing, they are typically given in terms of "airplanes per month" (APM) and are based on an average of 21 manufacturing days per month. Production rates that are multiples of 21 are fairly straight forward since 21 APM can be accomplished by running a single one-day line continuously, 42 APM by running two one-day lines and so on. Any production rate that is not a multiple of 21, however, must be accomplished with some other line configuration. When this happens it is occasionally necessary to "cool off" a line so that it does not produce more than the required demand and create excess inventory. One method of accomplishing this is to introduce "nonscheduled days" into the production schedule. On non-scheduled days, the day is treated as a non-working day and the line neither loads nor unloads. While non-scheduled days allow the factory to achieve the desired production rate without overbuilding, they also increase the variability of labour demand since no work is scheduled on that line for that day. This complicates the task of labour planning.

1.3 Task scheduling and crew cycling

Due to the complex nature of the work being done, it is advantageous to be structured in such a way that the same workers perform the same tasks day in and day out. A one-day line lends itself to this type of specialization of labour and therefore tends to be favored in practice whenever possible. In the realm of operations research, optimal task scheduling across workstations has been covered extensively with the Assembly Line Balancing Problem (ALBP). As mentioned earlier though, applications to aircraft manufacturing have been limited. Several—such as Abdinnour (2011) and Ríos, Mas and Menéndez (2012)—have developed alternative approaches to accommodate aircraft assembly but research is still scarce. Moreover, the ability to balance tasks is a function of line configuration which is itself a function of the production rate—factors that can be subject to relatively quick changes. While it is theoretically possible to achieve optimal task scheduling for different line configurations with 100% cross-training, this assumption is not very realistic in practice and is subject to a number of factors, making the problem extremely computationally intensive. For these reasons, the model presented in this paper will focus primarily on line configuration and labour resources rather than dynamic task balancing across assembly areas.

1.3 Model Mix

If a company produces more than one model variant, this could also lead to increased variability in labour demand since certain models could demand more labour resources than others. In some cases, the difference could be quite large. Obviously, the larger the difference in labour requirements per model, the larger the potential for disruption—assuming the frequency and rhythm of the model variants do not synchronize to provide a smooth labour demand. This would be nearly impossible for a product that has multiple major sections built up in parallel since the increase in labour for one section might be large while another section may have no delta. Lee, Clayton and Taylor (1977) took a goal programming approach to mitigate the impact of model mix on labour cost in aircraft production, but the solution is not an integer one and in this application, the firing order is set by the customer so there is limited flexibility in scheduling. Mixed model assembly line balancing has been covered by researchers such as Thomopoulos (1967) and more recently Lee and Vairaktarakis (1997), but again the nature of aircraft manufacturing renders the applications limited.

1.4 Labour Capacity

Variability in labour capacity is affected by several factors, some of which are in the company's control and some of which are not. Factors outside of the company's (direct) control include things like absenteeism and employee turnover. Factors within the company's control include things like shift duration, workweek structure, and number of shifts. Direct labour employees engaged in non-direct labour activities also affect labour capacity. Examples of this would include mechanics attending mandatory training/certification classes or acting as team leaders who help manage the shop.

In order to cope with variability in production schedules and day-to-day problems that arise, overtime is a commonly employed solution in manufacturing. Overtime provides additional flexibility in labour capacity but it comes at a price premium. A premium wage rate is not the only cost of overtime, however. Dembe, Erickson, Delbos and Banks (2005) found a 61% higher injury hazard rate in jobs with overtime schedules compared to jobs without. Olivia and Sterman (2001) found quality erosion to be related to overtime and gaps between labour capacity and demand. Thomas and Raynar (1997) found that scheduled overtime resulted in productivity losses stemming from an increase in disruptions and an inability to provide resources at an accelerated rate.

1.5 Mismatches between labour capacity and demand

To visualize the mismatches that can occur between labour capacity and labour demand, let us return to our earlier example of a demand for 21 airplanes per month. First assume a single type of model (no model mix variation) that requires 4,000 labour hours to build and that the work is distributed equally across each day of flow. Let us further assume no variation in the workforce—everyone comes to work every day and there is no direct labour engaged in indirect or non-value added activity. There are 21 workdays per month and production is accomplished by a single 1-day line. A graphical representation of labour capacity vs. labour demand for any given week would look like figure 1—a perfect match between labour capacity and labour demand.

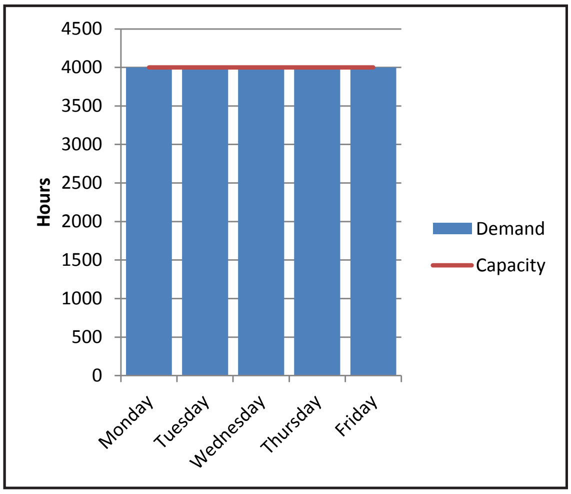

Fig. 1. Labour capacity matches labour demand

For a second example, we will change the production rate to 32 APM and keep all other assumptions the same. Since the rate is greater than 21 APM, an additional line will be needed to handle the additional demand so we will add a second one-day line. If the factory ran two one-day lines a full 21 days a month, however, it would be over producing by 10 units each month. To account for this, each line will incorporate 5 non-scheduled days per month. Assuming the factory maintains a standard 5x8 work week, average labour requirements by day for 32 airplanes per month would be 32 airplanes * 4,000 hours per plane/21 days per month = 6,095.24 hours per day or roughly 762 mechanics. The manner in which the non-scheduled days are distributed will influence the variability between labour capacity and demand. If the non-scheduled days are alternated roughly every other day, labour capacity vs. demand will look something like figure 2:

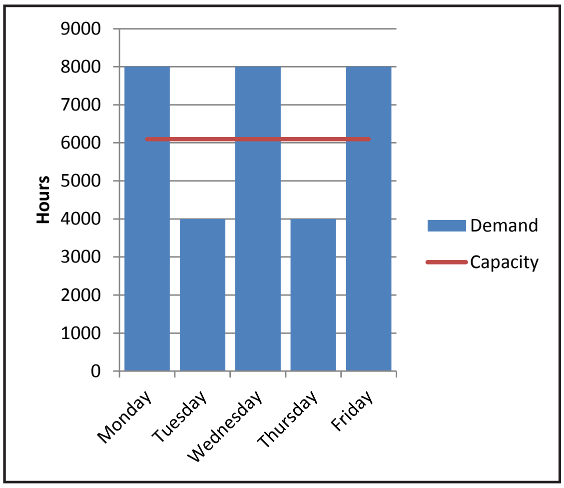

Fig. 2. Mismatch between labour capacity and demand

Obviously there is now a great deal more variability between labour capacity and demand than the first example, despite simplifying assumptions. In this scenario, the shops will fall behind on one day and either work overtime or try to make up for it on the following day. In the meantime, units still move down line to the next assembly station regardless of whether work is still open on them or not (assuming the line is not on a non-scheduled day). If this happens, mechanics must complete out of position work, which takes longer because they have to physically relocate to the unit and bring the necessary tools to accomplish the work. Furthermore, it increases the chance for quality problems since the work is not being completed where it was intended and it could possibly present safety concerns depending upon accessibility. On days that are overscheduled, mechanics could prioritize the unit that will move out the next day and leave the one that will be non-scheduled the following day for the next day's work, but this points out a crew-cycling problem where mechanics are no longer able to do the same tasks day after day—more cross-training would be required. There could also be work precedence issues complicating such a strategy.

A second alternative would be to schedule non-scheduled days for both lines on the same day and rearrange shifts to a 4x10 setup. In this configuration, average daily labour requirements would be the same as before but the 762 mechanics would be working 4 10-hour days instead of a 5 8-hour days so that their day off would match up with the majority of non-scheduled days (there would still be one non-scheduled day per line to account for some other time during the month). Figure 3 displays this scenario.

Clearly, the labour capacity fits very well with labour demand with this combination.

3. THE MODEL

The objective of the model was to find the line configuration and workweek structure combination that minimized labour

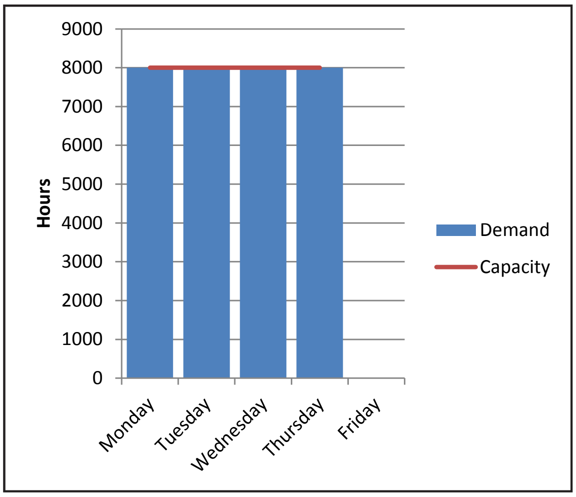

Fig. 3. Realignment between capacity and demand under an alternate work week.

costs for a given production rate. To simulate the assembly environment, 11 hypothetical aircraft assembly areas were used. Each of these areas had different labour requirements and different distributions of work across their respective flow days (see tables 1 and 2). Figure 4 shows the relationship of these assembly areas to each other.

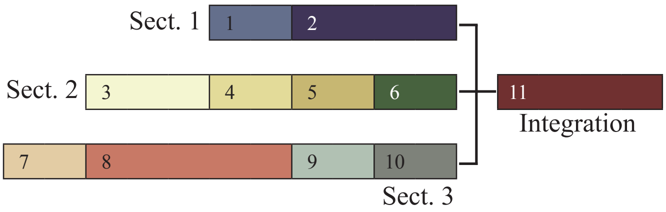

Fig. 4. Workstation overview

Two product options—a regular version and an extended range version—were considered in order to simulate the effects of model mix on aggregate planning. Extended range units composed about 15% of the firing order depending upon the production rate. Some assembly areas reflected additional labour demands for the extended range model while other assembly areas did not.

Since out of position work typically correlates with quality degradation, a constraint was placed on the model to ensure labour capacity met labour demand every day. Labour capacity was composed of regular time and/or overtime. Labour demand in excess of regular labour capacity was made up by overtime. Excess regular capacity was counted as a sunk cost. Daily overtime was constrained to 1 hour per employee. A 4x10 hour workweek was available as an option in addition to the traditional 5x8 hour workweek; in the case of a 4x10 workweek, the overtime constraint was relaxed on Fridays to allow 5 hours of overtime per worker.

Table 1. Hours by flow day by assembly area, base model

Station	Day 1	Day 2	Day 3	Day 4	Day 5	Total days
1	74	76				2
2	43	87	51	17.5		4
3	38	90	27			3
4	63	0				2
5	18	31.5				2
6	36	56				2
7	63	74				2
8	44.5	36	50	22.5	7	5
9	49	55.5				2
10	32.5	42				2
11	64	280.5	101.5	94.5		4

Table 2. Hours by flow day by assembly area, ext. range model

Station	Day 1	Day 2	Day 3	Day 4	Day 5	Total days
1	64	86				2
2	43	87	51	17.5		4
3	38	89.5	27			3
4	63	0				2
5	18	31.5				2
6	36	56				2
7	75	110.5				2
8	56	58	65	58.5	106	5
9	54	63.5				2
10	65.5	128.8				2
11	75	220	88	113		4

A month of production was simulated across four different production rates: 38, 42, 46 and 52 APM. For each production rate, three combinations of line configuration and workweek structure were considered and the model determined the optimal number of assembly workers and overtime that minimized labour costs for each combination. Labour costs are represented in hours, not dollars. Whenever overtime was used, it was counted as 1.5 hours in the cost function since the company pays for overtime at rate of 1.5x the hourly rate. If desired, the results can be multiplied by an average wage rate.

Equation (1) represents the objective function for the model:

$$\min \sum_{i=1}^{11} \sum_{t=1}^{21} (l_{ti} + (1.5 * OT_{ti})) \tag{1}$$

Where:

t is a day in the 21 day work month
i is the index of one of the 11 assembly stations
l_{ti} is regular labour capacity of assembly station i in time t
OT_{ti} is overtime required in assembly station i in time t
d_{ti} is labour demand at assembly station i in time t
h_i is the headcount for assembly station i

with constraints:

$$l_{ti} + OT_{ti} \geq d_{ti}$$

$$l_{ti} = \begin{cases} 8 * h_i,\ for\ t = 1, 2 \ldots 21,\ 5x8\ workweek \\ 10 * h_i,\ for\ t = 1, 2 \ldots 17,\ 4x10\ workweek \\ 0\ otherwise \end{cases}$$

$OT_{ti} \leq h_i$ for daily overtime constraint

$OT_{ti} \leq 5h_i$ for Fridays in a 4x10 workweek.

4. RESULTS

Table 3 summarizes the results of the model.

4.1 38 APM

Line configurations chosen for 38 APM were 2x1-day lines and a 4-day line with 4 non-scheduled days a month each and 2x1-day lines with 2 non-scheduled days each. The 1-1-4 configuration was tested under a 5x8 workweek and a 4x10 workweek. The 4x10 variant of the 1-1-4 configuration resulted in the most cost efficient labour force, but the 1-1 configuration was only 0.2% more costly in terms of labour hours so the cost is negligible. Other benefits of the 1-1 configuration should be considered, such as tooling savings and crew cycling as well as training for the next rate increase.

4.2 42 APM

Line configurations simulated for 42 APM included 2x1-day lines on a 5x8 workweek with no non-scheduled days; 2x1-day lines and a 4-day line with 2 non-scheduled days on each of the 1-day lines and 4 non-scheduled days on the 4-day line (5x8 workweek); and 2x1-day lines and a 2-day line, all with 4 non-scheduled days (4x10 hour workweek). The 1-1 setup offered the most efficient line configuration, representing 3.72% better performance than the next best option.

4.3 46 APM

The 46 APM rate was simulated with two 1-day lines (2 non-scheduled days each) and a 2-day line with four non-scheduled days. This configuration was tested under 5x8 and 4x10 workweeks. A 1-1-4 configuration was also tested. The two 1-day lines had no non-scheduled days and the 4-day line had four non-scheduled days. It was simulated in a 5x8 workweek. The most efficient configuration was the 1-1-2 setup under a 4x10 work week.

4.4 52 APM

Line configurations simulated for 52 APM included two 1-day lines and a single 2-day line with no non-scheduled days (5x8 workweek); and three 1-day lines with four non-scheduled days on two of the lines and three non-scheduled days on the other. The 1-1-1 configuration was tested under 5x8 and 4x10 workweeks. The 1-1-1 configuration with a 4x10 workweek offered the most cost-efficient line configuration.

4.5 Performance comparisons

To compare the results of the model against a simplified, yet not uncommon, method of aggregate planning, labour requirements for 52 APM were totalled and averaged out over the 21 day work month and divided by an 8 hour shift to get headcount numbers for each assembly station. These labour resources were then applied to the line configuration that offered the most non-scheduled days per month, since these days can be mistakenly perceived as "catch-up" days and therefore desirable. The same constraint of meeting daily demand was maintained, but the daily overtime restriction was relaxed so that it could freely adjust. The cost of this approach was then compared to the best results of the model. Not surprisingly, the simpler method of aggregate planning resulted in much higher amounts of daily overtime in order to meet daily demand. The large disparity between daily capacity and demand coupled with infeasible daily overtime requirements means that more and more work would continue to travel to the next assembly station. This would render non-scheduled days ineffective as catch up days since out of position work takes longer to complete. Additionally, it would cause undue safety and quality deterioration as stated earlier. Table 4 summarizes the comparison of headcount, average overtime per employee per month, and labour costs between the model and the simplified heuristic. The savings of the model over the simplified heuristic are striking, amounting to an 11.3% savings is labour costs and an 85.5% reduction in average hours of overtime per employee per month.

5. CONCLUSION

Without taking an enterprise view of how production is scheduled and accomplished, aggregate planning can be

Table 3. Labour cost in hours

	38 APM			42 APM			46 APM			52 APM		
	5x8	4x10	5x8	5x8	4x10	5x8	5x8	4x10	5x8	5x8	4x10	5x8
	1-1-4	1-1-4	1-1	1-1-4	1-1-2	1-1	1-1-4	1-1-2	1-1-2	1-1-2	1-1-1	1-1-1
1	7815.8	6484.8	6347.4	7811.3	6505.0	6396.0	7818.0	7404.4	7921.5	7966.5	7982.0	9495.8
2	9862.8	8072.8	8354.4	9862.8	8473.0	8383.2	9862.8	9646.4	10421.7	10488.0	10460.2	12513.6
3	8151.0	6681.0	6511.5	8151.0	6732.0	6541.5	8151.0	7659.0	8238.0	8281.5	8141.0	9744.0
4	3894.0	3230.0	2673.0	3894.0	3230.0	2688.0	3894.0	3608.0	3924.0	3939.0	3324.5	3991.5
5	2703.0	2213.0	2092.5	2703.0	2216.0	2110.5	2583.0	2513.0	2718.0	2677.5	2624.3	3138.8
6	4915.5	4080.0	3864.0	4915.5	4080.0	3864.0	4915.5	4630.5	4959.0	4980.8	4861.5	5794.9
7	7787.0	6340.0	6304.2	7787.0	6356.6	6348.3	7787.0	7252.0	7812.6	7864.4	7870.4	9351.6
8	9947.7	8177.6	8942.6	9958.7	9027.3	8959.1	9958.7	10035.7	10952.3	10952.3	10469.8	12513.6
9	5583.2	4595.7	4483.2	5576.6	4595.7	4496.7	5576.6	5240.3	5603.1	5630.9	5613.0	6722.1
10	5728.1	4612.1	4891.5	5728.1	4612.1	4901.3	5728.1	6235.7	5728.1	6066.8	5740.7	6909.9
11	27711.8	22575.8	22757.6	27887.3	24551.7	22803.0	27447.6	27718.2	30103.7	30207.5	28332.2	33809.4
Total:	94099.6	77062.6	77221.8	94275.0	80379.2	77491.6	93722.1	91943.0	98381.9	99054.9	95419.3	113985.1

Table 4. Model results vs. simplified heuristic at 52 APM

	Simplified heuristic			Model results		
	# workers	OT/employee	labour cost	# workers	OT/employee	labour cost
1	46	28.6	9045.7	45	4.9	7982.0
2	61	29.9	12070.4	59	4.9	10460.2
3	48	28.2	9415.5	46	4.7	8141.0
4	20	24.7	3853	19	3.3	3324.5
5	15	32.3	3004.5	15	3.3	2624.3
6	28	31.1	5575.3	27	6.7	4861.5
7	45	28	8820.1	45	3.3	7870.4
8	56	30.6	11122.3	60	3	10469.8
9	33	28.2	6473.4	32	3.6	5613.0
10	29	28.5	5697.3	33	2.6	5740.7
11	165	28.8	32469.1	159	5.5	28332.2
Total:	546	29	107546.6	540	4.2	95419.3

reduced to dangerously simplified calculations. Simply averaging out labour requirements for a given planning period and dividing it by a standard shift time can lead to infeasible schedules, high amounts of out of position work, quality degradation, overtime budget overruns and unnecessary worker fatigue.

While this model represents a large improvement over simplified production planning methods, additional research could be done to improve and further validate the model. The model was given predefined line configuration scenarios to optimize; developing an algorithm to come up with line configurations on its own would make the model more robust, though this would increase the computational requirements a great deal. Enhancing the model by including tooling costs and inventory holding costs into the cost function would make the model more comprehensive. Finally, if the model could address task balancing across workstations dynamically, this would provide a benefit to shop managers; though, as alluded to earlier, the benefits may be marginal compared to the effort and complexity required to handle such a problem.

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