PERFORMANCE TRADEOFFS IN FLEXIBLE MANUFACTURING SYSTEMS

Paul J. Schweitzer, Abraham Seidmann, and Paulo Goes
William E. Simon Graduate School of Business Administration, University of Rochester, Rochester, NY 14627, USA

ABSTRACT: This paper discusses some of the performance tradeoffs arising in the operation of FMS, and surveys some of the stochastic models developed by us for analyzing these tradeoffs. Issues addressed include: selecting part routes, setting economic tool speeds, making tool choices, fixing the number of pallets, expanding capacity, and planning multi-period production. Non-linear optimization algorithms developed for dealing with these issues are also presented.

1. INTRODUCTION

Several studies by the authors (Schweitzer and Seidmann (1988, 1989, 1990), Schweitzer et al (1990)) have provided new frameworks for optimizing processing rates in production systems operating subject to throughput constraints. These studies were motivated by the empirical observation that tool costs comprise 20 - 30% of the total operating costs of many FMS's (Ayres (1988), Cummings (1986)). Significant cost savings were demonstrated for repetitive metal-cutting operations by a careful choice of the workcenters' operating parameters. This paper further extends some of these earlier results by analytical and numerical investigation of several key decision options in FMS capacity management.

2. THE FMS MODEL

The FMS operates with \( M \geq 1 \) workcenters labelled \( i = 1, 2, \ldots, M \). Each workcenter either has one server with first-come first-serve (FCFS) service discipline or is an ample server (AS). The ample server case is useful for modeling known delays or modeling transporters such as conveyor belts. We label \( i = 1 \) as the load/unload station (L/UL).

Workcenter \( i \) \((1 \leq i \leq M)\) can perform \( n(i) \geq 1 \) distinct types of operations labelled as \( j = 1, 2, \ldots, n(i) \). We let

\[
\color{red}{s_{ij} = \text{mean processing time for workcenter } i \text{ required to perform the } j\text{-th type of operation, } 1 \leq i \leq M, 1 \leq j \leq n(i), \text{ (at the L/UL, } s_{11} \text{ is the sum of load and unload times).}}
\]

The \( \{s_{ij}\} \) must satisfy

\[
(2.1) \quad 0 < s_{ij}^L \leq s_{ij} \leq s_{ij}^U,
\]

where the limits \( s_{ij}^L \) are chosen to satisfy the tool maker specifications and to provide acceptable surface quality.

Completed parts exit the FMS at the L/UL station and are immediately replaced by new raw parts. The expected number of times that each job visits workcenter \( i \) for the \( j\)-th type of operation is \( V_{ij} \). The \( V \)'s are the so-called visit ratios and \( V_{11} = 1 \) since the load/unload operation is performed only once per job. We also use the notation \( V_i = \sum_{j=1}^{n(i)} V_{ij} \) to denote the expected total number of times that a fresh job will visit workcenter \( i \).

The mean transport delay associated with one type \( j \) operation at work center \( i \) is given by \( D_{ij} \). We assume one part family and let \( TH \) be the desired FMS throughput. Given the total number of pallets \( K \) in the system, the minimum \( \{s_{ij}^L\} \) and maximum \( \{s_{ij}^U\} \) processing times, the transport delays \( \{D_{ij}\} \) and visit ratios \( \{V_{ij}\} \), it is possible to determine the minimum and maximum throughputs (\( TH^- \) and \( TH^+ \), respectively) that the system is capable of. The problem is feasible if and only if the throughput goal \( TH \) satisfies:

\[
(2.2) \quad \color{red}{TH^- \leq TH \leq TH^+.}
\]
We let \( g_{ij}(s_{ij}) \) denote the expected cost of performing one type \( j \) operation at workcenter \( i \), for \( 1 \leq i \leq M, \ 1 \leq j < n(i) \), if the processing time is \( s_{ij} \) (where \( s_{ij} \leq S_{ij} \)). We assume that the tool cost functions \( g_{ij}(s_{ij}) \) are known and satisfy, for \( s_{ij} \leq S_{ij}^+ \):

\[
g_{ij}(s_{ij}) > 0, \ Dg_{ij}(s_{ij}) < 0, \ D^2g_{ij}(s_{ij}) < 0.
\]

These conditions are based on previous studies (Hax and Candea (1984), Johnson and Montgomery (1974)). When Taylor's law relates tool life to tool speed (Drozda and Wick (1983), Olberg et al (1976), Taylor (1907)), Schweitzer and Seidmann (1988) have shown that \( g_{ij}(s_{ij}) \) has the power form

\[
g_{ij}(s_{ij}) = c_{ij}s_{ij}^{\theta_{ij}},
\]

where \( c_{ij}, \theta_{ij} > 0 \). The power function (2.3) is the one used in this study.

When the \( s_{ij} \) values have been determined for a given TH goal, we also get the following output parameters, for \( 1 \leq i \leq M \) and \( 1 < j < n(i) \):

\[
\lambda_{ij} = \text{throughput at workcenter } i, \text{ measured in number of type } j \text{ operations per unit of time},
\]

\[
w_{ij} = \text{mean sojourn time of parts at workcenter } i, \text{ either on queue or in service, for one type } j \text{ operation},
\]

\[
N_{ij} = \text{mean number of parts at workcenter } i, \text{ either on queue or in service, for type } j \text{ operation},
\]

\[
\text{COSTMIN} = \sum_{i=1}^{M} \sum_{j=1}^{n(i)} \lambda_{ij} g_{ij}(s_{ij})
\]

\[
\tilde{c} = \text{cost per unit time of operating the system}.
\]

\[
\text{COSTMIN}/\text{TH} = \text{cost per part produced}
\]

The optimization problem, minimizing the tool cost for a given throughput goal, is formulated in Schweitzer et al (1990).

3. THE BASE CASE

The set of decision parameters used in managing the FMS performance will be illustrated using the base case data set defined in this section. This data set represents a metal cutting FMS with one L/UL station \( (i = 1) \), six machining centers \( (i = 2, \ldots, 7) \), one contour measurement machine \( (i = 9) \) and two part cleaning and washing stations \( (i = 8, 10) \). Only the processing rates at the six machining centers can be altered. The FMS operates with 27 (= K) pallets, and the required throughput target is 0.055 parts/min (= TH). Table 3.1 depicts the visit ratios, the transporter speeds, the processing time ranges and the parameters of the tool cost function for the base case used throughout this paper. The processing rates at centers \( i = 1, 8, 9, 10 \) are constant since these centers do not involve machining operations. For this reason the cost of operating these centers is omitted from COSTMIN.

4. PERFORMANCE TUNING

- Tool Speed Selection

Nominal values of \( s_{ij} \) are in practice chosen by handbook, tool manufacturer recommendation, historical precedent or by a one-machine economic model (Drozda and Wick (1983)) which balances direct machine operating cost per hour against tool cost (assuming 100% utilization, no starvation, etc.). The nominal values of \( s_{ij} \) were chosen by using a one-machine minimum cost cutting speed model for iron base alloy with carbide tools as in Drozda and Wick (1983). Inserting the nominal \( s_{ij} \) values into the closed queuing network model leads to a nominal throughput of \( \text{TH} = 0.055 \) parts/min. In the next step, the processing times were optimized subject to achieving the same throughput goal \( \text{TH} = 0.055 \) parts/min.

Considerable cost saving was demonstrated here (factor of 3 savings in tool cost implies 5-10% reduction in the total FMS operating costs). The key to achieving these cost savings is the fact that the bottleneck machine (6) was speeded up while all the other workcenters were slowed down. One-machine models are unsatisfactory because they ignore starvation and throughput goals (so stations cannot be operated at speed with lowest cost per operation), and they lead to unbalanced systems.

- Selection of Tool Types

In practice, tool type selection is done for one machine at a time during the "Process Planning" phase (Drozda and Wick (1983), Gray et al (1988), Trucks (1987)). This practice ignores the impact of such early tool choices on the overall FMS performance. This is an important factor since selecting a tool type affects the feasible range of processing rates for that particular task (\( (s_{ij}^-, s_{ij}^+) \)).
Consequently, tool type selection in one machine tends to have an immediate effect on the performance of other machines.

We explore the sensitivity of operating costs to tool choice, and examine the dependence of tool choices among machines. Two tool options are available at machines 2, 4 and 6. Hence, eight tool combinations are possible. We found that it is very hard to predict beforehand the nature of the tool replacements that will take place. The overall change from the base case to the optimal tool combination is comprised of the change of tool at machine 2, followed by the change of tool at machine 6. The first change reduces costs by replacing a tool by a slower-but-cheaper tool. (This in fact is responsible for most of the overall benefits.) The second change slightly reduces costs further by replacing a given tool by a faster one.

- Capacity Expansion Decisions

We found that incrementing the original number of machines leads to significant (but diminishing) operational savings. The benefits of machine duplication consist of lower unit costs, and higher capacity. These benefits may be greater when incrementing the workcenter with the highest utilization rather than the one with the highest contribution to the total cost. This may appear counter-intuitive, and cannot be always correct since it ignores both operating costs and procurement costs. It was observed here because the cost contribution per machine \( \sum_{j=1}^{n} \left( \frac{Vij}{qij(sij)} \right) \) was not a good surrogate for ranking marginal costs and/or marginal benefits.

- Adjusting the Number of Pallets

The "conventional wisdom" is to minimize the WIP (number of parts or pallets) in the system (Buzacott and Yao (1986)). WIP leads to inventory carrying costs and greater system lead-times. The latter both reduces flexibility to respond to schedule changes and increases the time to detect degradation in quality. These adverse consequences of WIP are present, but are not the whole story. We show that increasing WIP has the advantages of increasing system capacity \( TH^+ \) and of reducing the unit operating cost \( \tilde{C} \). Both of these beneficial consequences are due, we believe, to the reduction in machine starvation when pallets are added, and this alleviates the bursty behavior where a machine is alternately starved and working very fast on a part: less starvation permits us to slow down most non-bottleneck machines and thus increase the useful tool lives.

- Multiperiod Production Planning

Here we are concerned with planning production over a future interval of time, called the planning horizon. During this planning horizon, the rate of demand for the products can vary. The purpose of the multiperiod production planning effort discussed here is to map out a program of outputs to meet future customer demands under given constraints, thus utilizing the available manufacturing resources so as to attain high levels of performance criteria. We investigated the following three production policies.

The first policy examined here follows a "chase strategy": each week's production equals the week's demand \( TH_t - D_t \). This is the most flexible approach, and is used where one cannot forecast future demands. The second policy aims at reducing production irregularities. It assumes that we can forecast demand only one period into the future. We then produce at the average demand level for two weeks, after first attempting to meet demand from inventory. The throughput target for week \( t \) is given by \( TH_t = (D_t + D_{t+1} - D_{t+2})/2 \) parts per week, assuming this is feasible. Here \( I_{t-1} \) denotes the inventory at the end of week \( t-1 \). The third policy uses level production at rate \( TH_t = \bar{D} \) where

\[
\bar{D} = \left[ \sum^{T}_{t=1} D_t - I_0 \right] / T.
\]

It assumes that we can forecast the mean net weekly demand rate \( \bar{D} \) for the next \( T \) weeks. Schweitzer et al (1990) show that if the inventory holding costs are negligible and the tool cost function is the same for all periods, this policy is optimal.

Our numerical investigations showed that the optimal total cost is only modestly better than under the second policy which requires forecasting only one period into the future. Our examples show that considerable cost savings are possible by production smoothing. They also show that even a modest amount of myopic demand smoothing can have major benefits.
5. CONCLUSIONS

This study has dealt with several decision problems associated with performance management in FMS's. Two salient features of the problems discussed are that the processing rates of the machining centers can be revised and that the system has to meet a given throughput goal per unit time. The interaction effects between a large set of managerial decision options and the system performance are studied using both analytical and numerical results. The decision options studied include the WIP levels, capacity expansions, tool type selections and multiperiod production planning.

For the case studies conducted (Schweitzer et al (1990b)) we found that the major cost savings in order of decreasing importance are:

(I) Tool speed selection
(II) Capacity expansion
(III) Tool type selection
(IV) Setting multiperiod throughput goals, and
(V) Adjusting the number of pallets.

<table>
<thead>
<tr>
<th>Machine</th>
<th>Service Discipline</th>
<th>Operation</th>
<th>V_ij</th>
<th>D_ij (min)</th>
<th>s^-_ij (min)</th>
<th>s^+_ij (min)</th>
<th>C_ij</th>
<th>e_ij</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FCFS</td>
<td>1</td>
<td>1.0</td>
<td>14.3</td>
<td>6.0</td>
<td>6.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>FCFS</td>
<td>1</td>
<td>1.0</td>
<td>7.0</td>
<td>1.5</td>
<td>4.2</td>
<td>791</td>
<td>1.76</td>
</tr>
<tr>
<td>3</td>
<td>FCFS</td>
<td>1</td>
<td>0.50</td>
<td>6.0</td>
<td>3.8</td>
<td>6.1</td>
<td>2471</td>
<td>2.739</td>
</tr>
<tr>
<td>3</td>
<td>FCFS</td>
<td>2</td>
<td>0.70</td>
<td>6.0</td>
<td>7.2</td>
<td>8.4</td>
<td>1577</td>
<td>2.17</td>
</tr>
<tr>
<td>3</td>
<td>FCFS</td>
<td>3</td>
<td>0.40</td>
<td>10.0</td>
<td>1.6</td>
<td>4.0</td>
<td>2018</td>
<td>1.68</td>
</tr>
<tr>
<td>4</td>
<td>FCFS</td>
<td>1</td>
<td>0.50</td>
<td>6.0</td>
<td>3.8</td>
<td>6.1</td>
<td>2471</td>
<td>2.739</td>
</tr>
<tr>
<td>5</td>
<td>FCFS</td>
<td>1</td>
<td>1.0</td>
<td>9.0</td>
<td>5.5</td>
<td>8.5</td>
<td>3720</td>
<td>2.80</td>
</tr>
<tr>
<td>5</td>
<td>FCFS</td>
<td>2</td>
<td>0.50</td>
<td>2.0</td>
<td>7.0</td>
<td>12.9</td>
<td>2431</td>
<td>2.80</td>
</tr>
<tr>
<td>6</td>
<td>FCFS</td>
<td>1</td>
<td>0.70</td>
<td>5.0</td>
<td>17.0</td>
<td>29.0</td>
<td>5198</td>
<td>2.02</td>
</tr>
<tr>
<td>7</td>
<td>FCFS</td>
<td>1</td>
<td>0.70</td>
<td>5.0</td>
<td>4.5</td>
<td>11.0</td>
<td>5198</td>
<td>2.02</td>
</tr>
<tr>
<td>7</td>
<td>FCFS</td>
<td>2</td>
<td>0.30</td>
<td>5.0</td>
<td>13.0</td>
<td>23.1</td>
<td>4741</td>
<td>3.21</td>
</tr>
<tr>
<td>8</td>
<td>AS</td>
<td>1</td>
<td>3.0</td>
<td>12.0</td>
<td>5.4</td>
<td>5.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>FCFS</td>
<td>1</td>
<td>0.15</td>
<td>4.9</td>
<td>27.0</td>
<td>27.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>AS</td>
<td>1</td>
<td>1.0</td>
<td>10.0</td>
<td>5.4</td>
<td>5.4</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3.1-Process Requirements and Tool Cost Functions for the Base Case

(V_ij = Visit Ratio; D_ij = Transporter Time (min); s^-_ij and s^+_ij = longest (shortest) feasible processing times (min); C_ij and e_ij denote the cost proportionality constant and the exponent, respectively. Here: K = 27 pallets, TH = 0.055 parts/min, TH^- = 0.048 parts/min, TH^+ = 0.080 parts/min)
REFERENCES


