Analysis of scheduling rules for an FMS

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The application of FMSs in mid-volume manufacturing situations appears to promise substantial cost savings (Cook 1975).

- However, FMSs are quite expensive and efforts must be made to avoid the high investment risk.

- Characteristics of a general-purpose, user-oriented, discrete-event simulator for FMS

- Revealing very few general results.
  - Performance of scheduling rules depends very heavily on the criterion chosen.

- Scheduling rules → Performance measures of in automated system
  - All components of system are tightly interconnected.

**Contribution**

- Effect of scheduling rules in actual FMS and in a criteria chosen
2. Other experiment review

Table 1. Summary of literature for scheduling rules (performance measures classification)

<table>
<thead>
<tr>
<th>Performance</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conway (1965 a, b)1</td>
</tr>
<tr>
<td></td>
<td>Dar-El and Wysk (1982)1</td>
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<tr>
<td></td>
<td>Hershauer and Ebert (1975)1</td>
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<td></td>
<td>McCartney and Hinds (1981)2</td>
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<tr>
<td></td>
<td>Stecke and Solberg (1981)2</td>
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<td></td>
<td>Elmaraghy (1982)2</td>
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<tr>
<td></td>
<td>Blackstone et al. (1982)3</td>
</tr>
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<td></td>
<td>Ballakur and Steudel (1984)3</td>
</tr>
<tr>
<td>Average utilization</td>
<td>—</td>
</tr>
<tr>
<td>Production rate</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>—</td>
</tr>
<tr>
<td>WIP inventory</td>
<td>SIO</td>
</tr>
<tr>
<td>Average flowtime</td>
<td>SIOa</td>
</tr>
<tr>
<td>Average lateness</td>
<td>SIOb</td>
</tr>
<tr>
<td>Average tardiness</td>
<td>SIO</td>
</tr>
<tr>
<td>RMS tardiness</td>
<td>WINQ</td>
</tr>
<tr>
<td>Number of tardy jobs</td>
<td>—</td>
</tr>
<tr>
<td>Due date based criteria</td>
<td>SLACK/ROc</td>
</tr>
<tr>
<td></td>
<td>SLACK/ROe</td>
</tr>
<tr>
<td></td>
<td>SLACK/ROf</td>
</tr>
<tr>
<td></td>
<td>SLACK/ROg</td>
</tr>
</tbody>
</table>

1 In a job shop environment
2 In an FMS environment
3 Environment is not mentioned
a For ‘constant’, ‘random’, ‘total work contents’, and ‘number of operations’ due date assignment
b For ‘constant’ and ‘random’ due date assignment
c When shop has no control over due dates or shop has control over due dates and due dates are tight or shop has control over due dates and due dates are loose and there is a great congestion in the shop
d When due date is loose and machine utilization is moderate
e The rule if the best of the standard due date type of priority rules
f When due dates are loose
g When due dates are tight
— Not tested
3. The modular FMS simulator

Modular FMS simulator’s design concepts
- Modularity
  - Independent control for each activity
  - User can write his own modules and ignore unnecessary modules
- User-friendliness
  - The modular FMS simulator: menu driven package (in a logical order)
  - Diagnostic routine in the input part: detect input errors
- Decision rule consideration
  - A wide range of decision rules: used at each decision point
  - User can write his own decision rule and can add to package
3. The modular FMS simulator

- General-purpose, user-oriented, discrete-event simulator
- Aid in design, operation, and scheduling of manufacturing system
- Wide range of priority rules
- Necessity of user-defined parameters for model initialization
- Major entities: Parts, Pallets, Stations (machines, clamping/unclamping), WIP buffers, Carts
- Written in Fortran 77 & Originally implemented on a VAX 780 mini-computer
- Vax 780 in less than 1min computer time (Run time):
  Typical model (8 stations, 3 carriers, 10 WIP buffer positions for 24hr simulation time)

→ Dependent on the model parameters
3. The modular FMS simulator

Figure 1. Software configuration of the modular FMS simulator

4. Problem Description

- Focusing on an FMS project in a Belgian company.
  - Being carried out by the manufacturing company.
  - Subcontracting to four machine tool builders and two suppliers of material handling systems and computer controls.

- Objective
  - To determine the effectiveness of scheduling rules for various system performance criteria.

- Assumptions
  - Raw material for each part type is readily available.
  - An idle machine or the lowest utilized machine have higher priority than other machines.

- Testing 14 scheduling rules.
  - 15~20 scheduling rules were not tested.
  - All parts are completed within the given week.

- Testing with three different sets randomly generated input sequences.
  - Mean value of the three runs is considered.

- All decision points in the system are assigned the same priority rule in every run.
  - Select next part to be processed by the machines.
  - Select next part to be moved in the system.
  - Select next part to be reclamped by the worker.
  - Select next part to be loaded on carrier from a facility.

| 1. SIO | 6. LIO | 11. MRO |
| 2. SPT | 7. LPT |
| 3. SRPT | 8. LRPT |
| 4. SMT (SIO,TP) | 9. LMT (LIO,TP) |
| 5. SDT (SIO,TP) | 10. LDT (LIO,TP) |
| 12. FRO |
| 13. FIFO |
| 14. FASFO |
4. Problem Description (Constraints)

- Machine family: F1 (two machines), F2 (two machines), F3 (one machine)
  - Own dedicated shuttle with three or four positions
- Load/Unload station: L1, L2, L3
- 3 carriers that can transfer parts between stations, machines, WIP buffers
- 11 WIP buffer positions
- Workers assigned to each station to load/unload parts
4. Problem Description (Constraints)

- Weights between 12.5kg ~ 240kg & Size from $\varnothing 300 \times 150\text{mm}^3$ to $\varnothing 600 \times 850\text{mm}^3$

- 11 different part types and 199 parts per week

- 20 pallets of 11 types

- PR 01, 02, 03, 04, 07, 08: 2 pallets

- PR 05, 06, 09, 10: 1 pallet

- PR 11: 4 pallets

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<table>
<thead>
<tr>
<th>Part name</th>
<th>Weekly production</th>
<th>Production mix</th>
<th>Average time per operation (min)</th>
<th>Part routeing</th>
<th>Processing times (min)</th>
</tr>
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<tbody>
<tr>
<td>PROD01</td>
<td>19</td>
<td>9.5%</td>
<td>8.8</td>
<td>L2 F2 L3 F1</td>
<td>2 11 10 20</td>
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<tr>
<td>PROD02</td>
<td>20</td>
<td>10.1%</td>
<td>8.7</td>
<td>L3 F2 L2</td>
<td>3 14 2</td>
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<td>PROD03</td>
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<td>10.1%</td>
<td>11.8</td>
<td>L3 F2 L1</td>
<td>2 15 2 30</td>
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<td>PROD04</td>
<td>24</td>
<td>12.1%</td>
<td>9.7</td>
<td>L3 F2 L1</td>
<td>10 21 3</td>
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<td>PROD05</td>
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<td>5.0%</td>
<td>13.6</td>
<td>L3 F2 L1</td>
<td>2 12 2 26</td>
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<td>PROD06</td>
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<td>17.4</td>
<td>L3 F2 L1</td>
<td>10 13 3</td>
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<td>PROD07</td>
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<tr>
<td>PROD08</td>
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<td>18</td>
<td>L3 F2 L1</td>
<td>5 22 10 24</td>
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<td>PROD09</td>
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<td>22.7</td>
<td>L3 F2 L1</td>
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<td>PROD10</td>
<td>7</td>
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<td>PROD11</td>
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<td>20.1%</td>
<td>27.4</td>
<td>L2 F1 L3 F1</td>
<td>3 34 3 80</td>
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</tbody>
</table>

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4. Problem Description (Notations)

Indices
- $T$: Scheduling horizon (total available production time)
- $t$: Time at which a decision is to be made
- $n$: Number of jobs in the shop
- $i / j$: Job index / Operation index

Parameters
- $j(t)$: Imminent operation of job $i$, i.e., all operations $1 \leq j < j(t)$ are completed
- $P_{i,j}$: The processing time for the $j$th operation of the $i$th job
- $TO_i$: Total number of operations on the $i$th job ($1 \leq j \leq TO_i$ for all $i$)
- $TP_i$: Total processing time for the $i$th job ($\sum_{j} p_{i,j}$ for $j = 1, TO_i$)
- $RO_i(t)$: Remaining number of operations on the $i$th job
- $RP_i(t)$: Remaining processing time on the $i$th job
- $R_{i,j}$: The time at which the $i$th job becomes ready for its $j$th operation
- $R_{i,1}$: The time at which the $i$th job arrived at the shop
- $C_i$: The time at which the $i$th job is completed and leaves the system
- $d_i$: The due date of the $i$th job
- $L_i$: The lateness of the $i$th job ($L_i = C_i - d_i$)
- $T_i$: The tardiness of the $i$th job ($T_i = \max(0, L_i)$)
- $F_i$: Flowtime (the amount of time that job $i$ spends in the system ($F_i = C_i - R_{i,1}$))
- $S_i(t)$: Slack (difference between due date, the present time and the remaining processing time of the part ($S_i = d_i - R_{i,1} - TP_i$))
- $S_i$: Static slack (difference between due date, the arrival time and the total processing time of the part ($S_i = d_i - R_{i,1} - TP_i$))
- $N_{i,j}(t)$: The set of jobs in the queue corresponding to the $j$th operation of the $i$th job at time $t$
- $Z_i(t)$: The priority of job $i$ at time $t$
4. Problem Description (Scheduling rules)

**Scheduling rules**

1. SIO  Select the job with the shortest imminent operation time, i.e., select minimum $Z_i(t)$ where $Z_i(t) = p_{i,j}(t)$
2. LIO  Select the job with the longest imminent operation time, i.e., select maximum $Z_i(t)$ where $Z_i(t) = p_{i,j}(t)$
3. SPT* Select the job with the shortest processing time, i.e., select minimum $Z_i(t)$ where $Z_i(t) = TP_i$
4. LPT* Select the job with the longest processing time, i.e., select maximum $Z_i(t)$ where $Z_i(t) = TP_i$
5. SRPT Select the job with the shortest remaining processing time, i.e., select minimum $Z_i(t)$ where $Z_i(t) = RP_i(t)$
6. LRPT Select the job with the longest remaining processing time, i.e., select maximum $Z_i(t)$ where $Z_i(t) = RP_i(t)$
7. SDT  Select the job with the smallest ratio obtained by dividing the processing time of the imminent operation by the total processing time for the part, i.e., select minimum $Z_i(t)$ where $Z_i(t) = p_{i,j}(t)/TP_i$
8. SMT  Select the job with the smallest value obtained by multiplying the processing time of the imminent operation by the total processing time for the part, i.e., select minimum $Z_i(t)$ where $Z_i(t) = p_{i,j}(t)TP_i$
9. LDT  Select the job with the largest ratio obtained by dividing the processing time of the imminent operation by the total processing time for the part, i.e., select maximum $Z_i(t)$ where $Z_i(t) = p_{i,j}(t)/TP_i$
10. LMT Select the job with the largest value obtained by multiplying the processing time of the imminent operation by the total processing time for the part, i.e., select maximum $Z_i(t)$ where $Z_i(t) = p_{i,j}(t)TP_i$
11. FRO  Select the job with the fewest number of remaining operations, i.e., select minimum $Z_i(t)$ where $Z_i(t) = RO_i(t)$
12. MRO  Select the job with the largest number of remaining operations, i.e., select maximum $Z_i(t)$ where $Z_i(t) = RO_i(t)$
13. FIFO Select the job according to first in, first out, i.e., select minimum $Z_i(t)$ where $Z_i(t) = R_{i,j}$ for $i \in N_{i,j}(t)$
14. FASFO* Select the job according to first at shop, first out, i.e., select minimum $Z_i(t)$ where $Z_i(t) = R_{i,j}$ for $i \in N_{i,j}(t)$
### 4. Problem Description (Scheduling rules)

**Scheduling rules**

15. **SLACK**
   Select the job with the least amount of slack, i.e., select minimum $Z_i(t)$ where $Z_i(t) = S_i(t)$

16. **SLACK/RO**
   Select the job with the smallest ratio of slack time to the number of remaining operations (slack-per-operation), i.e., select minimum $Z_i(t)$ where $Z_i(t) = S_i(t)/RO_i(t)$

17. **SSLACK***
   Select the job with the least amount of static slack, i.e., select minimum $Z_i(t)$ where $Z_i(t) = S_i$

18. **SSLACK/RO**
   Select the job with the smallest ratio of static slack time to the number of remaining operations, i.e., select minimum $Z_i(t)$ where $Z_i(t) = S_i/RO_i(t)$

19. **SLACK/TP**
   Select the job with the smallest ratio of the job slack time to the total processing time, i.e., select minimum $Z_i(t)$ where $Z_i(t) = S_i(t)/TP_i$

20. **SLACK/RP**
   Select the job with the smallest ratio of the job slack time to the remaining processing time, i.e., select minimum $Z_i(t)$ where $Z_i(t) = S_i(t)/RP_i(t)$

*Static scheduling rule

✓ No need to be exhaustive
5. Computational results

Figure 3. Average waiting time per part.

Figure 4. Variance of waiting time per part.

- Smaller processing time based rules: minimize average waiting times
- Longest processing time based rules or FIFO: perform poorly in average waiting times
- Priority based rules: leading larger variances in waiting time versus FIFO or FASFO
- MRO: minimize variance by making all parts wait for a fairly long time
- FRO: Doing reasonably well on both
5. Computational results

- Scheduling rules have a large impact in automated systems
  - Interdependencies between the various components and in the small buffers with which it usually operates
- Average machine utilization ranges from 72.9\%(LDT) to 84.8\%(SDT)
- SDT, LMT, LPT, LRPT, MRO: above 83\% in average machine utilization
- SPT, LIO, LDT: The lowest variance of machine utilization → perform badly for average machine utilization
- The large variance of machine utilization for some of the rules → Bottlenecks
  - Machine utilization is not balanced & some are highly utilized while others are often idle
5. Computational results

Figure 7. Average buffer utilization

Figure 8. Average shuttle utilization

Figure 9. Average carrier utilization
5. Computational results

Average buffer, shuttle and carrier utilization (Figs 7, 8, 9)

✓ Direct relation between average waiting time and these criteria

✓ SPT (Short processing time) rule
  → Smallest value for average buffer and shuttle utilization
  → Small value for average carrier utilization

✓ LPT (Long processing time) rule
  → Largest value for average buffer and shuttle utilization
  Small parts (short processing time) have to wait for their turn in buffers
  → Large value for average carrier utilization
  Sending more parts to buffers
5. Computational results

Figure 10. Makespan

- Sharp difference among the scheduling rules
- Long makespan: SPT, LDT, LIO
- Short makespan: LPT, SDT
- Direct relation between makespan and average machine utilization
  - All scheduling rules produce the same number of parts
  - Small makespan → High machine utilization
- SPT (minimize average waiting times) tend to push larger parts to the end of the schedule
  → Large makespan & small average machine utilizations (long tails on a few machines)
6. Conclusions

- No single scheduling rule is generally found to produce excellent results for both average and variance of waiting times. (Except for FRO)
- Small value for average machine utilization (SDT) → Large value for variance of utilization
  - Facility bottleneck in the system
- SPT minimize average waiting times and LPT maximize machine utilization
  - Hard to score well on both criteria
- SIO, SMT, SPT*(Lowest), SRPT: Low value for the average buffer and shuttle utilization
  - LMT: Opposite result
- LDT, SPT: The lowest value for average carrier utilization
  - LMT: Opposite result
- SDT: The lowest makespan
  - LDT: Opposite result
  - SIO: Unlike Table 1, the performance was worse than average
- No scheduling rule is the winner on all performance measures

- Results are system dependant → Can’t generalize results
- Advantage: Easy-configured, Prompt-repeated
- Useful tool in helping the user select the appropriate rules for the system at hand