An Analytical and Simulation Approach for Modeling Flexible Manufacturing System

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Abstract. Varying needs of customer causes fluctuation in existing market condition. So, it’s a challenge for manufacturing firms to protect their existence under every unpredicted situation. For this, there is a need of system that can handle changes smoothly. Flexible manufacturing system (FMS) is one of the solutions that enable any system to withstand the changing requirements of market. But due to high installation and capital cost of FMS, a method that can easily depicts its performance measures before its implementation is needed. In literature, there are various mathematical programming approaches for prior calculation of FMS performance. But due to their difficulty in solving complex problem, simulation technique is used for FMS analysis. Selection of performance parameters followed by system modeling using simulation technique is usually performed to see the results under varying conditions. In present work, process simulator is used for analyzing FMS performance. Later, a mathematical technique is used for comparing and verifying the results obtained by simulation. Results showed it is easier to analyse the performance of complex and large FMS problems by simulation techniques in comparison to mathematical one.

Keywords. Flexible manufacturing system, modeling, process simulator, mathematical technique, performance parameter.

1. Introduction
A flexible manufacturing system comprises of certain numbers of operating workstations, that are interconnected mechanically by a material handling system along with a storage system and electronically by a distributed computer system. Flexible automated manufacturing system is one of the most felicitous terms one can give to FMS. The word “automated” is use to differentiate FMS from those manufacturing systems which inherit the property of flexibility but are not automated, like a manned group technology machine cell. While, the word “flexible” would distinguish it from those manufacturing systems that are highly automated but are not flexible, like a conventional transfer line. Due to the capability of being flexible along with the concept of automation, it has been an area of interest for researchers from many years. Till date, there are lot of works in the literature that are concerned with design, planning, operational and implementation related issues of FMS. Various case studies, analytical methods, simulation techniques along with optimization techniques are discussed in the work of past researchers. In this paper, simulation experiments on given FMS is performed, for predicting its behaviour in real time with an advantage of no loss of money and resources. Also, mathematical modeling is performed for the same problem.

2. Literature Review
There are various works in literature that were done for analysing the behaviour of different parameters of FMS. Some of the works that are related with mathematical techniques are discussed here. Stecke (1983) calculated minimum number of machines for providing tools on the machining centers, by using an optimization formula. If number of machines exceeded the number of formed groups, then additional machines were tooled identical to few of the ones that were grouped. Major constraint of that model was its tool magazine capacity for each machine tool. Sujono and Lashkari (2007) used integer programming method for developing a model that can select machines, assign operations on them followed by selection of material handling system for transferring of parts from one machine to another. Selection was done based on material handling equipment and parts compatibility. Objective of the whole work was minimization of cost related with operating machine, material handling system, machine setups along with maximizing the compatibility of part equipment. Tiwari and Vidyarthi (2000) used Genetic
Algorithm (GA) based heuristic for solving machine loading problem in case of random FMS, with an objective of minimizing the unbalancing of system and maximizing the throughput. Constraints imposed were availability of machining time and tool slots during operation. Prakash et al. (2006) solved FMS loading problem by extending simple genetic algorithm into constraints based genetic algorithm for handling of variables that were complex in nature. It was done by introducing three new genetic operator’s constraint that were based on initialization, crossover and mutation. Singholi et al. (2010) had taken case study of a firm for improving its performance. It involved mathematical models that were illustrated in literature for estimating certain performance parameters like production rate, overall utilization of the system etc. An effort was also done for presenting an improved design for the existing FMS. Erdin and Atmaca (2014) proposed that analysis of manufacturing systems should be done carefully to protect them from failure at any level. It was done by using physical, analytical or simulation methods. In that work, comparison was done between conventional, FMS and ideal system based on necessary number of servers required at each workstation by using bottleneck technique.

Certain simulation techniques were also used for FMS modeling, for studying the effect of various parameters associated with FMS performance. Caprihan and Wadhwa (2005) studied the influence of delay in information on decisions, related with selecting the best levels of routing flexibility for FMS problem. Result of simulation model indicated a tolerance limit below which if operation was carried then the objective of obtaining performance minimization was not possible. Cheng and Chan (2011) optimized part input sequence by using simulation model for production planning. Developed model simulated the FMS, which was used for producing different components. A custom-built user interface was used for inputting production and demand data from an excel spreadsheet into the developed model. Singholi (2015) evaluated routing and machine flexibility effects in different configuration of FMS by using a Taguchi method. Number of pallets and different scheduling rules were also used for finding the effects on buffer delay in the FMS considered. Simulation results indicated that number of pallets and routing flexibility are the two factors influencing average delay at buffers the most. Dosdoğru et al. (2015) analysed the effect of routing flexibility by taking number of parts, number of jobs, operation number and flexibility levels as important factors. They used genetic algorithm integrated with Monte Carlo method for analysing routing flexibility. Results showed make-span was best when number of machines were at high level. Jain and Raj (2016) studied the effect of different flexibility measures on FMS performance. They used structural equation modeling, graph theory and matrix approach. Fifteen variables were identified form literature and then intensity of these variables on the quality, productivity and flexibility of FMS was studied. Arshad et al. (2016) studied effect of different scheduling rules and FMS layout on the performance of FMS. ARENA software was used for developing different models, results showed that shortest processing time scheduling rules performs best. Rybicka et al. (2016) showed how discrete event simulation software can be used in any manufacturing system for studying its performance parameter. WITNESS simulation software was used for developing model of an actual production line and studying the effect of sequence change, number of machines and number of pallets on system performance. Florescu et al. (2017) developed a methodology for studying how performance of FMS involved in processing of cylindrical parts gets affected. Reduction of waiting time of parts was the major concern. ARENA simulation software was used for analysing the existing model and validating the proposed solution. Mahmood et al. (2017) analysed FMS performance by integrated definition modeling technique. The study focused on operational study of FMS by performing simulation analysis, various performance changes were suggested in the existing model by eliminating formed bottleneck condition. Use of an efficient cutting tool was suggested for increasing the production rate of FMS. Yadav and Jayswal (2017) provided an insight on previous work in the area of FMS modeling by investigating works that are accomplished by using different modelling techniques in FMS like mathematical, artificial intelligence, hierarchical, multi criteria decision-making method, Petri Nets and simulation.

For performance evaluation of any FMS there are number of techniques which are available in literature like mathematical, artificial intelligence, hierarchical, heuristic, petri nets, MCDM method and simulation model, they have enriched the work concerned with modeling of FMS. For analysing different system performance measures of FMS and seeing how they behave with constraints in particular condition, one can consider the process of mathematical modeling and simulation as the best one. In this paper mathematical and simulation techniques are evaluated with help of an example.

3. Proposed approach
A mathematical modeling technique discussed in the work of Curry and Feldman (2009) is used for FMS modeling. Cycle time along with utilization rate of each workstation of FMS are taken as performance parameter. Simulation technique is also used later for FMS modeling. Process simulator is the simulation software which is used in the paper, due to its ability of modeling probability conditions easily. The proposed approach is explained in detail with the help of a case study one by one.

3.1. System Description
An FMS consisting of four machines on which production of two components is required (Part A and B). The first part uses four distinct machining processes while second uses only first three workstations used by part first. Process routing of both the parts is as shown in Figure 1 and 2 respectively.

3.2. Mathematical modeling
From given process routing one can write system of equations that will define workstations total arrival rates.

For part A:
\[
\lambda_1 = 4 + 0.3 \lambda_2 + 0.25 \lambda_3 + 0.166 \lambda_4
\]
\[
\lambda_2 = 0 + 0.8 \lambda_1
\]
\[
\lambda_3 = 0 + 0.2 \lambda_1 + 0.5 \lambda_2
\]
\[
\lambda_4 = 0 + 0.2 \lambda_2 + 0.75 \lambda_3
\]

Now, rearrange the formed equations as,
\[
\lambda_1 - 0.3 \lambda_2 - 0.25 \lambda_3 - 0.166 \lambda_4 = 4
\]
\[
-0.8 \lambda_1 - \lambda_2 = 0
\]
\[
-0.2 \lambda_1 - 0.5 \lambda_2 + \lambda_3 = 0
\]
\[
-0.2 \lambda_2 - 0.75 \lambda_3 + \lambda_4 = 0
\]

One can write above equations in matrix form as:
\[
\begin{bmatrix}
\lambda_1 \\
\lambda_2 \\
\lambda_3 \\
\lambda_4
\end{bmatrix} =
\begin{bmatrix}
+1.0 & -0.3 & -0.25 & -0.16 \\
-0.8 & 1.0 & 0 & 0 \\
-0.2 & -0.5 & 0 & 0 \\
0 & -0.2 & -0.75 & 1
\end{bmatrix}
\begin{bmatrix}
4 \\
0 \\
0 \\
0
\end{bmatrix}
\]

On solving the matrix, arrival rate for part A is obtained as:
\[
(\lambda_1, \lambda_2, \lambda_3, \lambda_4) = (7.689, 6.295, 4.721, 4.800) /hr
\]

Similarly, for part B one can write following system of equations that will lead to the given solutions:
\[
\lambda_1 = 3 + 0.6 \lambda_3
\]
\[
\lambda_2 = 0 + 0.8 \lambda_1 + 0.3 \lambda_3
\]
\[
\lambda_3 = 0 + 0.2 \lambda_1 + 0.9 \lambda_2
\]
\[
(\lambda_1, \lambda_2, \lambda_3) = (3.433, 4.044, 4.326) /hr
\]
Now, total arrival rates for given system consisting of both parts is denoted as summation of the entire parts arrival rate at a station, as shown in equation (1).

\[
\lambda_k = \sum_{i=1}^{m} \lambda_{i,k}
\]  

(1)

Where,

- \(k\) is workstation.
- \(m\) is total number of parts.
- \(\lambda_i\) is mean arrival rate of part \(i\).

Using equation (1) values of workstations loads are,

\[(\lambda_1, \lambda_2, \lambda_3, \lambda_4) = (11.301, 10.339, 9.047, 4.800) /hr\]

Now, workstation workload is calculated by using service time value. Further, service time (dependent on the part type) is decomposed into two elements, mean and squared coefficient of variations of the processing time of part \(i\) at workstation \(k\) and are denoted as \(E[T_s(i, k)]\) and \(C_s^2(i, k)\), respectively.

Workstations workload is calculated using equation (2).

\[
WL_k = \sum_{i=1}^{m} \lambda_{i,k} E[T_s(i, k)]
\]  

(2)

Processing time for both parts on different workstation are given in Table 1.

**Table 1. Processing time for parts**

| Workstation | Mean (Part A) E [T_s(A, k)] | SCV (Part A) C_s^2(A, k) | Mean (Part B) E [T_s(B, k)] | SCV (Part B) C_s^2(B, k) |
|-------------|----------------------------|--------------------------|----------------------------|--------------------------|
| 1           | 7.2 min or 0.12 hr         | 1.0                      | 6.0 min or 0.1 hr          | 0.8                      |
| 2           | 6 min or 0.1 hr            | 0.9                      | 2.1 min or 0.03 hr         | 0.9                      |
| 3           | 6 min or 0.1 hr            | 0.8                      | 3.6 min or 0.06 hr         | 1.0                      |
| 4           | 9 min or 0.15 hr           | 0.7                      | -                          | -                        |

By using equation (2) and given values of processing time of both parts (Table 1), workload for all the four workstations are as follows:

\[WL_1 = 7.689 (0.12) + 3.433 (0.10) = 1.2659\]
\[WL_2 = 6.295 (0.10) + 4.044 (0.03) = 0.77104\]
\[WL_3 = 4.721 (0.10) + 4.326 (0.06) = 0.73166\]
\[WL_4 = 4.800 (0.15) = 0.72\]

For a steady state to exist, number of machines at each workstation must be strictly greater than the workload at that station. So, number of machine for workstation 1, 2, 3 and 4 is two, one, one and one respectively. Service time for an arbitrary job, independent of job type, is a random variable and is denoted by \(T_s(k)\). Mean and coefficient of variation for service time at workstation \(k\) are given by equation (3) and (4) respectively.

\[
E[T_s(k)] = E(S_i) = \sum_{i=1}^{m} \frac{\lambda_{i,k}}{\lambda_k} E[T_s(i, k)] = \frac{WL_k}{\lambda_k}
\]  

(3)

\[
C_s^2(k) = \frac{\sum_{i=1}^{m} (\lambda_{i,k}/\lambda_k) E[T_s(i,k)]^2 (1 + C_s^2(i,k))}{(\sum_{i=1}^{m} (\lambda_{i,k}/\lambda_k) E[T_s(i,k)])^2} - 1
\]  

(4)

Using equation (3) and (4), values of service time characteristics in terms of their mean and SCV values are calculated as:

\[E(S_1) = 1.2659 / 11.301 = 0.11201 \text{ hr}\]
\[E(S_2) = 0.77104 / 10.339 = 4.475 \text{ hr}\]
\[E(S_3) = 0.73166 / 9.047 = 4.85 \text{ hr}\]
\[E(S_4) = 0.72 / 4.800 = 9 \text{ hr}\]
\[ C_s^2(1) = \frac{(7.689)^2}{(11.301)} (0.12)^2 (1 + 1) + \frac{(3.433)^2}{(11.301)} (0.1)^2 (1 + 0.8) }{0.11201^2} - 1 = 0.997 \]

\[ C_s^2(2) = \frac{6.295}{10.339} (0.1)^2 (1 + 0.9) + \frac{4.044}{10.339} (0.035)^2 (1 + 0.9) }{0.074^2} - 1 = 1.279 \]

\[ C_s^2(3) = \frac{4.721}{9.047} (0.1)^2 (1 + 0.8) + \frac{4.326}{9.047} (0.06)^2 (1 + 1) }{0.0808^2} - 1 = 0.964 \]

\[ C_s^2(4) = \frac{4.800}{4.800} (0.15)^2 (1 + 0.7) }{(0.15)^2} - 1 = 0.700 \]

**Table 2. Calculated parameters**

| Workstation | 1 | 2 | 3 | 4 |
|-------------|---|---|---|---|
| Total arrival rate, \( \lambda \) | 11.301/ hr | 10.339/ hr | 9.047/ hr | 4.800/ hr |
| Workload, WL | 1.2659 | 0.77104 | 0.73166 | 0.722 |
| Minimum machine | 2 | 1 | 1 | 1 |
| Service mean, E[S] | 6.72 min | 4.475 min | 4.85 min | 9 min |
| Service SCV, C2[S] | 0.997 | 1.279 | 0.964 | 0.7 |

Till now, parameters (Table 2) which are not subjected to any downtime or repair conditions are calculated. Now, same parameters are calculated when times are adjusted for breakdowns and repairs. Availabilities and repair time characteristics of each workstation are given in Table 3.

**Table 3. Machines availability and repair time characteristics**

| Workstation | 1 | 2 | 3 | 4 |
|-------------|---|---|---|---|
| Availability | 0.90 | 0.95 | 0.93 | 0.95 |
| E[R] | 1 hr | 1 hr | 1 hr | 1 hr |
| C2[R] | 1.75 | 2.00 | 1.50 | 5/3 |

In case of breakdowns and repairs, value of service time characteristics is calculated by using equation (5) and (6) respectively.

\[ E[S_i] = \frac{E[T_s(i)]}{a_i} \]

\[ C^2[S_i] = C^2_s(i) + \frac{[1 + C^2(R_i)]a_i (1-a_i) E[R_i]}{E[T_s(i)]} \]  \hspace{1cm} (5)

After using equation (5) and (6), values of service time are:

\[ E[S_1] = 6.72/0.90 = 7.47 \text{ min} \]
\[ E[S_2] = 4.47/0.95 = 4.74 \text{ min} \]
\[ E[S_3] = 4.85/0.93 = 5.22 \text{ min} \]
\[ E[S_4] = 9.00/0.95 = 9.48 \text{ min} \]

\[ C^2[S_1] = 0.997 + \frac{[1 + 1.75]0.90 (1-0.90) 60}{6.72} = 3.207 \]
\[ C^2[S_2] = 1.279 + \frac{[1+2.00][0.95 (1-0.95) 60}{4.47} = 3.189 \]
\[ C^2[S_3] = 0.964 + \frac{[1+1.50][0.93 (1-0.93) 60}{4.85} = 2.977 \]
\[ C^2[S_4] = 0.700 + \frac{[1+0.5][0.95 (1-0.95) 60}{9.00} = 1.544 \]

After this, utilization rate of each workstation using equation (7) is calculated.
\[ U_i = \frac{E[S_i]}{C_i} \]  

(7)

Where, \( C_i \) is the number of server at each workstation.

\begin{align*}
U_1 &= \left( \frac{7.47}{60} \right) \left( \frac{11.301}{2} \right) = 0.703 \\
U_2 &= \left( \frac{4.74}{60} \right) \left( \frac{10.339}{1} \right) = 0.816 \\
U_3 &= \left( \frac{5.22}{60} \right) \left( \frac{9.047}{1} \right) = 0.787 \\
U_4 &= \left( \frac{9.48}{60} \right) \left( \frac{4.800}{1} \right) = 0.758
\end{align*}

Squared coefficient of variation for the arrival stream, into each workstation is calculated by using equation (9) and is shown in Table 4.

\[ C^2_a(i) = \frac{\lambda_i C^2_a(0, i) + \sum_{k=1}^{n} \frac{\lambda_k P_{k,i}}{\lambda_i} [P_{k,i}(1 - U_k^2)C^2_a(k) + P_{k,i}U_k^2 \left( \frac{C^2(k) + \sqrt{C^2(k)-1}}{C_k} \right) + 1 - P_{k,i}] }{C_i} \tag{8} \]

Table 4. Squared coefficient of variation for the arrival stream

| Workstation | 1   | 2   | 3   | 4   |
|-------------|-----|-----|-----|-----|
| \( C^2_a(i) \) | 1.56 | 1.602 | 1.841 | 1.497 |

Further, calculation of queue time for single server system is done by using equation (9) and for two servers system it is calculated by using equation (10).

\[ CTQ(i) = \frac{[C^2(i)+C^2(0)]}{2} \left( \frac{U_i}{1-U_i} \right) E[T_s(i)] \tag{9} \]
\[ CTQ(i) = \frac{[C^2(i)+C^2(0)]}{2} \left( \frac{U_i}{1-U_i} \right) E[T_s(i)] \tag{10} \]

After this, mean cycle time and work in process is calculated by using equation (11) and (12) respectively.

\[ CT(i) = \frac{[C^2(i)+C^2(0)]}{2} \left( \frac{U_i}{1-U_i} \right) E[T_s(i)] + E[T_s(i)] = CTQ(i) + E[T_s(i)] \tag{11} \]
\[ WIP(i) = CT(i)\lambda_i \tag{12} \]

Using equation (10), value of queue time for workstation one is calculated, as it has two servers at that station. For rest of the workstations (having one server), equation (9) is used for calculating queue time.

\[ CTQ(1) = \left( \frac{1.561 + 3.207}{2} \right) \left( \frac{0.703}{1-0.703} \right) = 7.47 \text{ min} \]
\[ CTQ(2) = \left( \frac{1.602 + 3.189}{2} \right) \left( \frac{0.816}{1-0.816} \right) = 48.90 \text{ min} \]
Value for cycle time and work in process for each workstation is calculated by using equation (11) and (12) respectively.

\[\begin{align*}
CT(1) &= CT_q(1) + E[T_s(1)] = 17.40 + 7.47 = 24.87 \text{ min} \\
CT(2) &= CT_q(2) + E[T_s(2)] = 48.90 + 4.74 = 53.64 \text{ min} \\
CT(3) &= CT_q(3) + E[T_s(3)] = 43.60 + 5.22 = 48.82 \text{ min} \\
CT(4) &= CT_q(4) + E[T_s(4)] = 44.98 + 9.48 = 54.46 \text{ min}
\end{align*}\]

\[\begin{align*}
WIP(1) &= CT(1) \lambda_1 = \left(\frac{24.87}{60}\right)(11.301) = 4.68 \\
WIP(2) &= CT(2) \lambda_2 = \left(\frac{53.64}{60}\right)(10.339) = 9.24 \\
WIP(3) &= CT(3) \lambda_3 = \left(\frac{48.82}{60}\right)(9.047) = 7.36 \\
WIP(4) &= CT(4) \lambda_4 = \left(\frac{54.46}{60}\right)(4.800) = 4.36
\end{align*}\]

After calculating above parameters, values of factory system performance measures in terms of cycle time \(CT_s\), work in process \(WIP_s\) and throughput \(\text{t}h_s\) is calculated. The value of factory throughput is given in terms of factory's inflow rate. From routing diagram, one can calculate total inflow rate as \((4+3=7)/\text{hr}\).

\[WIP_s = \sum_{i=1}^{n} WIP_s(i) = 4.68 + 9.24 + 7.36 + 4.36 = 25.64\]

And according to little's law, if a system satisfies steady state condition than the value of work in process is the product of arrival rate and cycle time, as shown in equation (13).

\[WIP = \lambda \times CT \quad (13)\]

By using equation (13) cycle time of both the parts is found to be 219.77 min.

\[CT_s = \frac{WIP_s}{\text{t}h_s} = \frac{25.64}{7} = 3.66 \text{ hr} = 219.77 \text{ min}\]

3.3. Process Simulator

Given system is now modeled in process simulator software of Promodel corporation with file version of 9.3.0.2701, for evaluating system performance. Network for both the parts along with their obtained cycle time is shown in Figure (3). System involves various activity states that represent the machine type. Arrows were used for connecting different activities for representing the flow of process. Part A and B arrive at machine 1 according to given arrival rate and are processed further with the defined process plans. Developed model is run till production of seven parts from the system is done. One can also see the state of each entity within the system, with the help of model as shown in Figure (4).
4. Results
On application of mathematical and simulation technique for performance evaluation of given FMS, the value of parameters obtained are as follows:

| Modeling Technique | Cycle Time   |
|--------------------|--------------|
| Mathematical       | 219.77 min   |
| Process Simulator  | 206.47 min   |

| Modeling Technique | Utilization  |
|--------------------|--------------|
|                    | Workstation 1 | Workstation 2 | Workstation 3 | Workstation 4 |
| Mathematical       | 70.3%        | 81.6%         | 78.7%         | 75.8%         |
| Process Simulator  | 71.0%        | 76%           | 90%           | 75.0%         |
From obtained values, it can be seen that both techniques gave approximately same values for cycle time and workstation utilizations. The only advantage associated with simulation technique is its ease in use and less time consumption capability.

5. Conclusions
At last it can be concluded that:
1) Mathematical modeling techniques were the commonly used method for modeling purpose. Drawbacks associated with them are stated assumptions in the models, as they may not be valid in real world. Also, the process of computation becomes large with increase in the size of problem.
2) Simulation model simulate given problem in model form, so that one can study the effects of different conditions on the developed model without any loss of money and resources.
3) Results concluded that the obtained performance of given FMS by both the methods are close to each other.
4) It is also seen that mathematical modeling of complex system requires lot of time and effort, so it is better to use simulation for saving a lot of time and resources.

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