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ORIGINAL ARTICLE

Effects of routing flexibility, sequencing flexibility and scheduling decision rules on the performance of a flexible manufacturing system

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Abstract This paper focuses on a simulation-based experimental study of the interaction among routing flexibility, sequencing flexibility and part sequencing rules in a typical flexible manufacturing system (FMS). Two scenarios are considered for experimentation. Three routing flexibility levels, five sequencing flexibility levels and four scheduling rules for part sequencing decision are considered for detailed investigation. The performance of the FMS is evaluated using various measures related to flow time and tardiness of parts. The simulation results are subjected to statistical analysis. The analysis of results reveals that deterioration in system performance can be minimized substantially by incorporating either routing flexibility or sequencing flexibility or both. However, the benefits of either of these flexibilities diminish at higher flexibility levels. Part sequencing rules such as earliest due date and earliest operation due date provide better performance for all the measures at higher flexibility levels.

Keywords Flexible manufacturing system · Routing flexibility · Sequencing flexibility · Part sequencing rules

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1 Introduction

With the globalization of manufacturing, there has been renewed interest in the competitiveness of the manufacturing sector throughout the world. There is an increasing trend towards higher product variety, smaller lot sizes and shorter lead times in the market place. In this environment, manufacturing companies are forced to implement systems that can provide flexibility and efficiency. Emergence of flexible manufacturing systems is an important development in this direction. MacCarthy and Liu [1] state that a flexible manufacturing system (FMS) is a production system in which groups of numerically controlled or computer numerically controlled machine tools and an automated material handling system (MHS) work together under computer control. Stecke [2] identifies four hierarchical levels in which the decision problems in an FMS are partitioned: design, planning, scheduling and control problems. Scheduling decision problems of FMSs continue to attract the interest of both the academic and industrial sectors. This can be attributed to the fact that these problems have fundamental implications on the overall performance of the system. Proper scheduling procedures are essential for the efficient utilization of the expensive resources in FMSs such as machines, MHS etc. and for improving the responsiveness of the system in meeting the changing customer needs.

Flexibility is a term generally used to describe the ability of a system to respond in a cost-effective manner to changes in volume requirements, product-mix requirements, machine status and processing capabilities. The flexibility of an FMS is dependent upon its components (machines, MHS etc.), capabilities, interconnections and the mode of operation and control. Browne et al. [3] describe eight types of flexibility as follows: machine flexibility, process flexibility, product flexibility, routing flexibility, volume flexibility, expansion flexibility, operation flexibility and production flexibility. Gupta and Goyal [4] provide a review of the concepts of flexibility. Sethi and Sethi [5] enhance the types of flexibility to include the flexibility types such as material handling flexibility, program flexibility and market flexibility. Vokurka and O'Leary-Kelly [6] describe four additional flexibility dimensions such as automation flexibility, labour flexibility, new design flexibility and delivery flexibility.

ElMaraghy [7] states that reconfigurable manufacturing system (RMS) is a new manufacturing system paradigm that aims at achieving cost-effective and rapid system changes, as needed and when needed, by incorporating principles of modularity, integrability, flexibility, scalability, convertibility and diagnosability. RMSs promise customized flexibility on demand in a short time, while FMSs provide generalized flexibility designed for the anticipated variations and built-in a priori. Youssef and ElMaraghy [8] review the relevant literature on RMS and highlight the gaps that exist in this area of research. A novel RMS configuration selection approach is introduced. Katz [9] outlines design principles for reconfigurable machines, which may be applied in different fields of manufacturing. Based on these design principles, three types of reconfigurable machines are designed for various types of production operations such as machining, inspection and assembly. Pattanaik et al. [10] present an approach to design machine cells using modular machines to achieve certain characteristics of reconfigurable manufacturing. Deif and ElMaraghy [11] investigate how RMSs can manage their capacity scalability on the system level in a cost-effective manner. Bi et al. [12] summarize a survey on the development of reconfigurable machines. Kumar et al. [13] and Li et al. [14] use Petri Net approach for modelling RMSs. Kannan and Saha [15] propose an approach of generic setup planning for reconfigurable machine tools. Rahimifard and Weston [16] present an approach for modelling RMSs based on the provision of means for explicitly representing and computer executing dynamic producer units. Abbasi and Houshmand [17] focus on the utilization stage of an RMS and introduce a methodology to effectively adjust scalable production capacities and the system functionalities to market demands. Renna [18] proposes a multi-agent architecture for the capacity reconfiguration problem in an RMS. A policy to manage capacity exchange among manufacturing lines based on due-date performance is presented.

Routing flexibility can be regarded as the main contributor to the flexibility of an FMS. It is the ability of a system to provide multiple alternate routes to produce a set of parts economically and efficiently. Sequencing flexibility exists when alternate feasible sequences can be used to process the operations of a part. Sequencing flexibility is also known as operation flexibility [19]. Routing flexibility is a type of hardware flexibility whereas sequencing flexibility is a type of software flexibility since sequencing flexibility is inherent in product structure rather than machine hardware. Most of the studies that consider routing flexibility in FMSs focus on the problem of routing selection prior to production [20]. This approach is not applicable to random-type FMS (also known as non-dedicated FMS) in which no knowledge about incoming part types is available prior to production. Here, part routings can be different, even for parts of the same type. Thus, the control system of a random-type FMS is required to have the capability to adapt to the randomness in arrivals by effectively using operation and routing flexibility in real time. Enhancing the performance of an FMS using routing flexibility and sequencing flexibility in scheduling is the motivating factor for this paper.

The present paper deals with a simulation-based experimental study focused on the analysis of the effects of routing flexibility, sequencing flexibility and scheduling decision rules on FMS performance. The first step has been to establish the FMS configuration and the data regarding the processing requirements of part types to be produced in the system. Then, operational control procedures have been established in terms of how the orders for part types arrive, how the parts are launched into the system, how these launched parts are routed through various machines and how parts are sequenced for processing on a machine. Three routing flexibility levels (RFLs), five sequencing flexibility levels (SFL) and four part sequencing rules (PSR) are considered for detailed investigation. Operations of part types can be processed on alternative machines depending upon the level of routing flexibility present in the system. The sequencing flexibility measure (SFM) proposed by Rachamadugu et al. [21] has been used to model SFL. This measure takes into consideration both the number of operations and the number of feasible operation sequences. The performance of the FMS is evaluated using various measures related to flow time and tardiness of parts. The simulation results are subjected to statistical analysis. The analysis of the performance of an FMS under different RFL and SFL together with the scheduling policies is a significant contribution of the research work presented in this paper. Thus, the objectives of this paper are as follows:

- To investigate the interaction between SFL and PSR in a typical FMS for the situation wherein part types to be produced in the system arrive continuously in a random manner
- To study the effects of RFL, SFL and PSR on the performance of an FMS

The rest of the paper is organized as follows: Section 2 deals with the review of the relevant literature. Section 3 provides the salient aspects of the configuration of the FMS considered in the present research. Section 4 outlines the development of simulation model. This section also includes the modelling aspects of routing flexibility and sequencing flexibility. Section 5 describes the details of the simulation experiments. Section 6 provides the analysis of the simulation results. Section 7 presents conclusions.

2 Literature review

Several researchers have studied scheduling problems of FMSs with the consideration of routing flexibility. Lin and Solberg [22] indicate that flexible processing could reduce mean flow time while increasing system throughput and machine utilization. Barad [23] investigates the relative impact of versatility as a physical characteristic and operating strategies on FMS performance. Lun and Chen [24] develop a simulation-based framework for part routing decision in FMS scheduling using a holonic concept by establishing cooperation among the identical workstations and other resources or information systems. Garavelli [25] reports on a simulation study conducted to analyse the performance of several flexible manufacturing systems, each of which is characterized by a specific degree of routing flexibility. The researcher finds that instead of complete flexibility, a system with limited flexibility performs better in terms of lead time and work in process. Mohamed et al. [26] present a study wherein the relationship between the degree of machine flexibility and the level of system performance is analysed. Shukla and Chen [27] propose a decision support system framework to assist in the control of an FMS through intelligent part launching. The proposed system makes use of a heuristic based on the pull concept and a neural network model. Saygin et al. [20] present a simulation study of an FMS that has routing flexibility. The study demonstrates the effectiveness of the dissimilarity maximization method for real-time control. Chan et al. [28] present a review of scheduling studies of FMS, which employ simulation as an analysis tool.

Haq et al. [29] propose an enumerative heuristic algorithm for scheduling an FMS wherein the production schedule is integrated with the MHS schedule. ElMekkawy and ElMaraghy [30] use flexible routing in order to avoid system deadlock caused by machine breakdowns and downtimes. Chan [31] reports on a simulation study of the effects of dispatching and routing decisions on the performance of an FMS. The effect of changing part mix ratios is investigated under both finite and infinite buffer capacity conditions. Kumar [32] proposes flexibility measures based on the concept of entropy. Four measures and the properties of these measures have been described. These measures have been illustrated in measuring routing flexibility, operations flexibility and loading flexibility in a manufacturing system. Wu [33] develops a measurement of flexibility in manufacturing systems for mass customization. This measurement measures not only the impact of manufacturing technology hardware but also the impact of the product design and process design. It can be used as a guide in manufacturing reengineering for mass customization.

Chan et al. [34] present a simulation study for analysing the impact of variations in physical and operating parameters of an FMS and to identify the level of these variations that do not restrict the advantages of flexibility. The results show that the expected benefits from increasing the levels of flexibility and a superior control strategy may not be achieved if the physical and operating parameters of alternative machines have variations. Turgay [35] presents an agent-based approach for scheduling an FMS with the consideration of capacity and operational constraints and alternative routings. Chan et al. [36] propose a framework to solve the operation allocation problem in an FMS using the concept of multifidelity that reduces the computation time for simulation.

There have been a few attempts to study the scheduling problem in FMS with the consideration of sequencing flexibility. Hutchinson and Pflughoeft [37] use a modified job-shop scheduling problem to test the benefits of sequencing flexibility. The results show that sequencing flexibility increases system performance in a linear relationship. Saygın and Kılıç [38] highlight the importance of integration between process planning and scheduling in FMS. A framework to integrate flexible process plans with offline scheduling is proposed in their paper. Chan [19] analyses the effects of operation flexibility (sequencing flexibility) and various scheduling rules on the performance of an FMS. Mean flow time is used as the only criterion for carrying out the evaluation. Altering the scheduling rules seems to have a more significant effect on the mean flow time performance than changing the level of operation flexibility.

The literature review reveals that there is a need for research focused on the analysis of the combined effects of routing flexibility, sequencing flexibility and scheduling decision rules on FMS performance. The present paper deals with a simulation-based experimental study in this direction.

3 FMS configuration

A typical FMS is considered for investigation in the present study. The FMS consists of six different (non-identical) machines with local input and output buffers, two automatic guided vehicles (AGVs) as the material handling system for part transportation and a load/unload station as shown in Fig. 1.

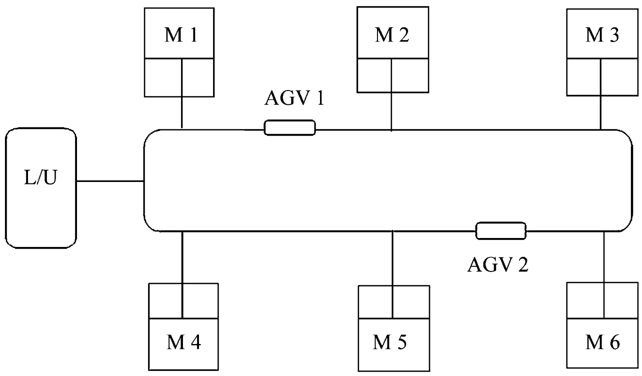

Fig. 1 Physical configuration of the FMS

3.1 Part data

Ten different part types are considered for processing in the FMS. Orders for part types to be produced arrive at the system randomly. Arrival of an order for a part type among the ten part types is equally likely. The details regarding the orders for part types are generated as described below:

- The interarrival time of orders follows an exponential distribution with a mean of 15 min.
- The number of operations for each part type is uniformly distributed in the range 4–6.
- The processing time for an operation on the primary machine is uniformly distributed in the range 10 to 20 min.
- The operation type of an operation is uniformly distributed in the range 1 to 15.
- The due date of each part is determined using the total work content method. Using this method, the due date of each part is set equal to the sum of the part arrival time and a multiple of the total processing time of the part. Thus, due date d_i of a part i is determined as follows: $d_i = a_i + K\sum_{j=1}^{ki} p_{ij}$, where a_i is the arrival time of part i, K is the due-date allowance factor, k_i is the number of operations of part i and p_{ij} is the processing time of operation j of part i. When routing flexibility exists in the system, an operation of a part can be performed on more than one machine. But the processing time on alternative machines is 10% more than that on primary machine. Hence, the total processing time of a part is calculated as the sum of the average processing time of the operations. The due-date allowance factor K is set at 2.0.

3.2 Modelling routing flexibility

The machines in the system perform 15 different operations. An operation can be performed on alternative machines depending upon the level of routing flexibility present in the system. The RFLs have been modelled as a variable. RFL=0 (denoted as RFL0 in the present study) means that there is exactly one machine known as primary machine available in the system for processing an operation on a part, i.e. there are no alternatives. RFL=1 (denoted as RFL1) implies that for each operation there are two possible machines, i.e. there is exactly one alternative machine known as secondary machine (other than the primary machine that is available at RFL0) for any operation on a part. RFL=2 (denoted as RFL2) means that there are three possible machines for processing the same operation, i.e. there are exactly two alternative machines (known as secondary machines) other than the primary machine available at RFL0 for processing any operation on a part. Based on these different RFLs, operation–machine compatibility data are shown in Table 1.

In the present study, it is considered that the processing time on the alternative machines for processing the same operation has been increased by 10% of the processing time on the primary machine. It can be noted that the alternative machines for an operation cannot be more efficient than the primary machine. The increased processing time on alternative machines represents the combined change in the characteristics such as machine efficiency, machine setup time, tool changing time etc.

3.3 Modelling sequencing flexibility

Sequencing flexibility refers to the number of alternative sequences in which the operations of a part can be performed.

Table 1 Operation–machine compatibility data

Operation type	Routing flexibility level		
	RFL0	RFL1	RFL2
O_1	M_1	M_1, M_5	M_1, M_5, M_2
O_2	M_6	M_6, M_5	M_6, M_5, M_3
O_3	M_5	M_5, M_6	M_5, M_6, M_4
O_4	M_4	M_4, M_6	M_4, M_6, M_5
O_5	M_3	M_3, M_2	M_3, M_2, M_4
O_6	M_6	M_6, M_4	M_6, M_4, M_1
O_7	M_6	M_6, M_3	M_6, M_3, M_2
O_8	M_5	M_5, M_2	M_5, M_2, M_3
O_9	M_4	M_4, M_1	M_4, M_1, M_6
O_{10}	M_3	M_3, M_1	M_3, M_1, M_5
O_{11}	M_2	M_2, M_4	M_2, M_4, M_6
O_{12}	M_1	M_1, M_3	M_1, M_3, M_2
O_{13}	M_1	M_1, M_4	M_1, M_4, M_3
O_{14}	M_2	M_2, M_5	M_2, M_5, M_4
O_{15}	M_3	M_3, M_6	M_3, M_6, M_1

RFL routing flexibility level

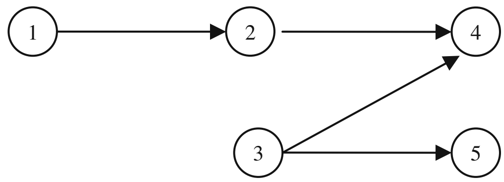

Fig. 2 Operation graph

Sequencing flexibility is inherent in the product structure rather than machine hardware. Sequencing flexibility is modelled as a variable using a sequencing flexibility measure that depends upon the number of options available for an operation and the number of operations required for a part type. In the present research, the number of operations required for part types vary between four and six. Hence, a measure that considers both the number of options available for an operation and the number of operations required for a part type is more appropriate. The SFM proposed by Rachamadugu et al. [21] satisfies this requirement. The SFM is defined as follows:

$$\mathrm{SFM}_i = 1.0 - \frac{2 \times TPA_i}{k_i(k_i - 1)} \quad (1)$$

where k_i is the number of operations of part type i, TPA_i is the number of transitive precedence arcs in the operation graph of part type i and SFM_i is the sequencing flexibility measure for part type i. The term transitive precedence arc is used to represent precedence relations, both explicit and implicit, between all pairs of operations of a part type. For example, consider the operation graph of a part type shown in Fig. 2.

Figure 2 shows four explicit precedence arcs, namely (1, 2), (2, 4), (3, 4) and (3, 5). There exists one implicit precedence arc between operations 1 and 4. Hence, the total number of precedence relationships (both explicit and implicit) known as transitive precedence arcs is 5. The SFM value for the part type whose operation graph is shown in Fig. 2 is therefore 0.5 using the Eq. 1. When there is no sequencing flexibility for a part type, the SFM value is 0. When there is perfect sequencing flexibility for a part type, the SFM value is 1. Generally, SFM value for most practical situations falls between 0 and 1. In the present study, the operation graphs for each of the ten part types are generated and the corresponding SFM values are calculated using Eq. 1. For the purpose of illustration, the operation graphs of part type 1 for the various sequencing flexibility levels are shown in Fig. 3a–e.

The operation graphs of the other part types are not included due to space limitations. In the simulation studies carried out in the present research, the sequencing flexibility of part types has been set at five levels, namely SFL0, SFL1, SFL2, SFL3 and SFL4 as shown in Table 2.

3.4 Operational logic

For the FMS considered, orders for part types arrive randomly and the FMS is run continuously. In the simulation model, the initial status of the system is assumed to be empty and idle with the first order arrival event

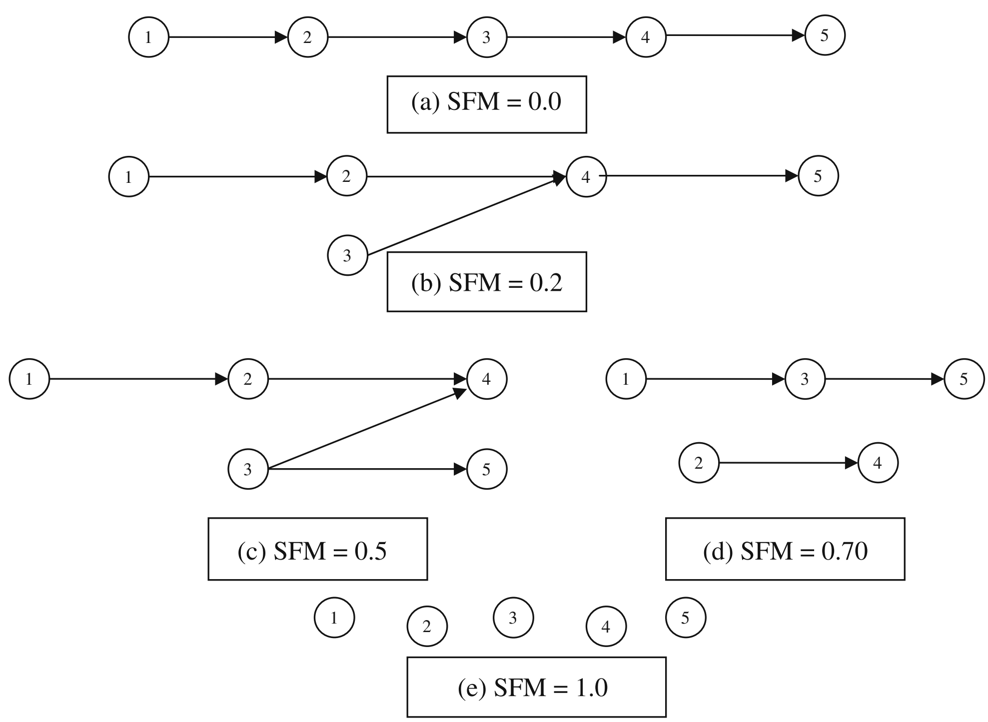

Fig. 3 Operation graphs for part type 1. **a** SFM=0.0. **b** SFM=0.2. **c** SFM=0.5. **d** SFM=0.70. **e** SFM=1.0

Table 2 Sequencing flexibility levels of part types

Part types	Number of operations	SFM values obtained from the operation graphs of part types				
		SFL0	SFL1	SFL2	SFL3	SFL4
2, 6, 9	4	0.0	0.16	0.50	0.67	1.0
1, 3, 4, 8	5	0.0	0.20	0.50	0.70	1.0
5, 7, 10	6	0.0	0.27	0.47	0.73	1.0

scheduled to occur at time zero. The order can belong to any one of the ten part types with the same likelihood. After identifying the part type associated with the order arrived, the attributes associated with the part type such as the number of operations, the operation graph, machines for the operations and processing times for the operation are determined from the part data file. The raw part is loaded onto the pallet for subsequent launching into the system based on *part launching rule*. The parts are then routed to the machines for processing. When there is no routing flexibility, there is only one machine available for processing an operation of a part. When there is no routing flexibility, but sequencing flexibility exists, selection of the operation to be processed is based on the *operation selection rule*. When there is routing flexibility, but no sequencing flexibility exists in the system, *part routing rule* is used to select the machine for performing an operation. When both routing flexibility and sequencing flexibility are present, operation selection rule and part routing rule are used simultaneously to determine the operation to be performed and the associated machine. The parts are then released to the machines as soon as AGVs are available. The parts waiting at the input buffer of a machine are selected for processing based on part sequencing rules. After a machine completes processing an operation of a part, the machine releases the part on the output buffer and places an AGV call to remove the part. If an AGV is available, then it travels to the machine and picks up the part. If all the operations of the part are completed, the finished part will be unloaded at the load/unload station. Else, the next operation to be performed based on the operation graph of the part and the associated machine is determined. Accordingly, the AGV takes the part to the machine. After an AGV unloads a part at the input buffer of a machine, it tries to attend the pending calls. If there are no calls to be met, then an attempt is made to find whether any raw part can be launched into the system.

There can be two categories of tasks (parts) waiting for loading on AGVs: (1) raw parts waiting at the load/unload station and (2) semi-finished/finished parts waiting at the output buffer of a machine. In both the cases, the dispatching policy used is first come first served (FCFS). When an AGV has more than one call for the removal of a part from the output buffer of different machines, the call to be attended is selected using FCFS policy.

The following are the assumptions made regarding the operational aspects of the FMS for developing the simulation model:

- Processing times of operation of part types include setup times and tool changing times and are independent of the sequence followed.
- The transportation time for the AGVs is proportional to the distance travelled.
- After completing the task assigned, the AGVs can remain near the machines or at the load/unload station as the case may be.
- After completing any material transfer, an AGV tries to attend the pending calls. The calls for AGVs can be of two types: (a) providing an input to a machine and (b) removing the processed part from the output buffer of a machine.
- Upon part completion at any machine, if more than one AGV is available to transfer the part to the next machine or the load/unload station, the one closest to the current machine is selected.
- The machines and AGVs are continuously available.

4 Structure of the simulation model

In the present study, a discrete-event simulation model that can capture the logic of the different levels of routing flexibility, sequencing flexibility and the operational decisions of the FMS has been developed using the C programming language. The discrete-event model views the FMS as consisting of entities, their associated attributes and files which contain entities with common characteristics. The entities in the FMS are parts, machines and AGVs. The operation of the FMS is conceptualized as a succession of events centring on the parts to be processed. The appropriate events are suitably generated for capturing the dynamics that are taking place in the system. The simulation model is structured in a modular way consisting of a number of modules each of which performing a specific role as shown in Fig. 4. The simulation model has been subjected to a multilevel verification and validation exercise.

4.1 Scheduling decision rules

The scheduling rules incorporated in the simulation model are described below.

4.1.1 Part launching rule

The part launching decisions involves selecting a part for processing from the load/unload station. In the present study, FCFS rule is used, i.e. parts are launched into the system in the order in which they arrive.

4.1.2 Operation selection rule

Operation selection decision is required when sequencing flexibility exists. The scheduling rule used for this purpose is earliest finishing time (EFT). This rule is implemented as per the logic described below.

At first, the operations that are available for processing based on the operation graph are identified. Then, the finishing time of each of these operations is determined. The operation that will be completed earliest is chosen for processing. The finishing time consists of the following components:

- Sum of the processing time of the operations of parts waiting in the queue of the machine that is capable of processing the operation (work load of the machine)
- Remaining processing time of the machine for completing its current operation
- Processing time of the operation of the part that is considered for assignment
- Transportation time involved in moving the part from current location to the machine

Thus, EFT denotes the earliest time at which the operation (to be selected) will be completed on the machine if the operation is assigned to the machine.

4.1.3 Part routing rule

When routing flexibility is present in the system, part routing decision is required for selecting the machine for

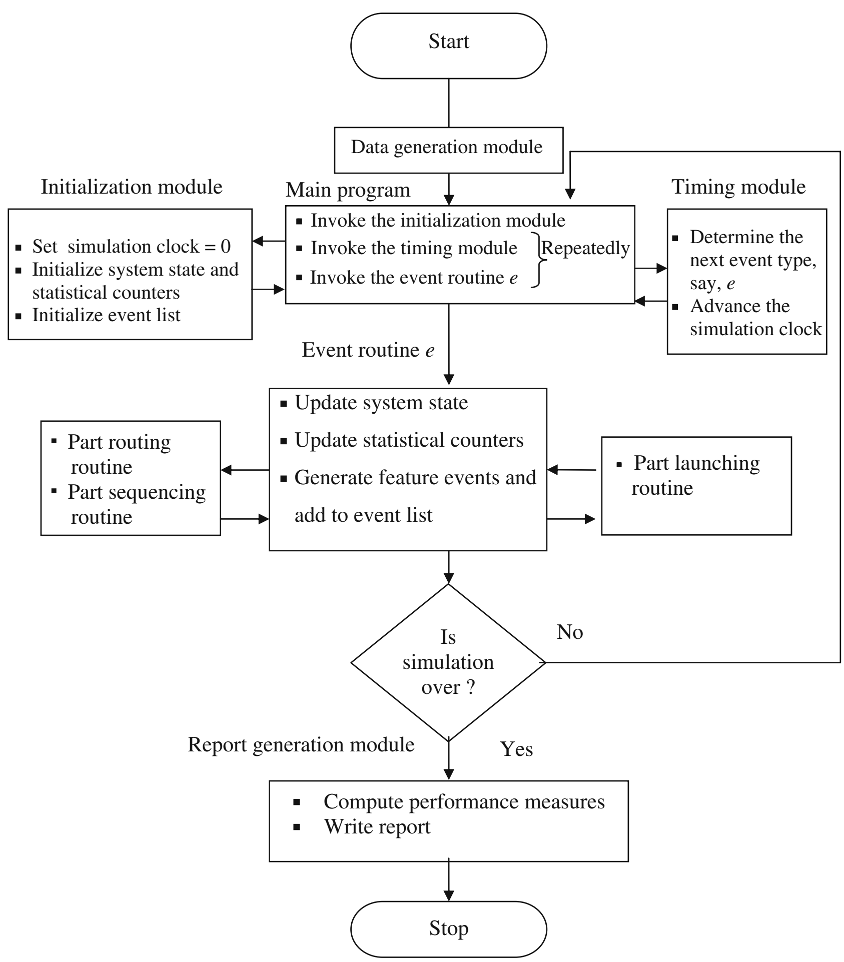

Fig. 4 Structure of the simulation model

processing an operation of a part. The part routing rule used in the present study is earliest finishing time with alternatives (EFTA). This rule is a modification of the EFT rule. Here, in the computation of the finishing time of the operation, the alternative machines are also considered. The machine on which the operation will be completed earliest is chosen. It can be noted that when both routing flexibility and sequencing flexibility are present, operation selection rule and part routing rule are used simultaneously to determine the operation to be performed and the associated machine.

4.1.4 Part sequencing rule

The part sequencing decision is required for selecting a part to be processed on a machine from among the parts waiting at the input buffer of the machine. For making this decision, a scheduling rule is used to assign to each of the waiting parts, a priority value. The part having the highest priority, which is defined by the smallest priority value, is selected for processing next. The following are the scheduling rules used for part sequencing decision:

- First in first out (FIFO): The part that has arrived first at the machine is selected for processing. FIFO is also known as FCFS.
- Shortest imminent operation (SIO): The part with the shortest processing time for the imminent operation is selected.
- Earliest due date (EDD): The part with the smallest due date is selected.
- Earliest operation due date (EODD): The part with the smallest operation due date (ODD) is selected. The operation due dates of operations of a part are determined by allocating the original flow allowance of the part among the operations of the part. ODD of operation j of part i, ODD_{ij}, is computed as follows:

$$\mathrm{ODD}_{ij} = \mathrm{ODD}_{ij-1} + Kp_{ij} \text{ where} \mathrm{ODD}_{i0} = a_i$$

4.2 Performance measures

The performance measures evaluated for analysis are described below.

- Performance measure 1 (PM1)—Mean flow time ($\overline{F}$) It is the average time a part spends in the system.

$$\overline{F} = \frac{1}{n}\left[\sum_{i-1}^{n} F_i\right]$$

- Performance measure 2 (PM2)—Standard deviation of flow time (SDFT)

$$\mathrm{SDFT} = \sqrt{\frac{\sum_{i=1}^{n}\left(F_i - \overline{F}\right)^2}{n-1}}$$

- Performance measure 3 (PM3) Mean tardiness ($\overline{T}$): It is the average tardiness of a part.

$$\overline{T} = \frac{1}{n}\left[\sum_{i=1}^{n} T_i\right]$$

- Performance measure 4 (PM4)—Standard deviation of tardiness (SDT)

$$\mathrm{SDT} = \sqrt{\frac{\sum_{i=1}^{n}\left(T_i - \overline{T}\right)^2}{n-1}}$$

- Performance measure 5 (PM5)—Percentage of tardy parts (PT)

$$\mathrm{PT} = \frac{n_{\mathrm{T}}}{n} \times 100$$

Here, C_i=completion time of part i, a_i=arrival time of part i, d_i=due date of part i, n=number of parts completed during the time interval from steady-state period to simulation ending time, n_{T}=number of tardy parts, F_i= flow time of part i, $F_i = C_i - a_i$, T_i=tardiness of part i, T_i= max $\{0, L_i\}$, L_i=lateness of part i and $L_i = C_i - d_i$.

5 Experimentation

Using the simulation model as a test-bed for experimentation, a number of experiments have been conducted. The experimental settings for the two scenarios investigated in the present research are summarized in Table 3.

The first stage in the simulation experimentation involves determining the end of the initial transient period (identification of the steady state). For this purpose, Welch's procedure described in Law and Kelton [39] is used. In a pilot simulation study conducted for the FMS considered in the present research, it was found that the system reached steady state when 200 parts were completed. Hence, in the simulation experiments for the scenarios, ten replications are performed for each scenario. The simulation for each replication is run for the completion of 1,200 parts. Parts are numbered on arrival at the system and the simulation outputs from parts numbering 1 to 200 are discarded. The outputs for the remaining 1,000 parts (parts numbering 201 to 1,200) are used for the computation of the performance measures.

Table 3 Experimental settings

Scenario	Experimental setting			Purpose of investigation
	RFL	SFL	PSR	
1	RFL0 (no routing flexibility)	SFL0, SFL1 SFL2, SFL3 SFL4	FIFO, SIO EDD, EODD	Base case: analyse the effects of SFL and PSR
2	RFL0 RFL1 RFL2	SFL0, SFL1 SFL2, SFL3 SFL4	FIFO, SIO EDD, EODD	Analyse the effects of RFL, SFL and PSR

In the literature, O'Keefe and Kasirajan [40] use the scheduling rules such as least work in queue (WINQ), minimum number in queue (NINQ) and least utilized machine (LUM) for part routing decision. WINQ rule is found to provide better performance for mean flow time. Chan [19] applies NINQ rule for operation selection. Chan et al. [37] use NINQ rule for part routing decision. These rules are described as follows:

- WINQ—select the machine whose input buffer contains the smallest total amount of work, i.e. sum of the processing time of the operations of parts waiting in the queue of the machine
- NINQ—select the machine with the fewest number of parts in the queue
- LUM—select the machine with the smallest total utilization

In the present research, preliminary simulation experiments have been conducted with the scheduling rules WINQ, NINQ, LUM and EFT for scenario 1 and WINQ, NINQ, LUM and EFTA for scenario 2 for operation selection/part routing decision. Figure 5 shows the simulation results obtained (using the simulation output after steady state averaged over ten replications) for mean flow time for scenario 2 (RFL2–SFL2 combination). Due to space limitations, simulation results for all the performance measures for both the scenarios are not presented here.

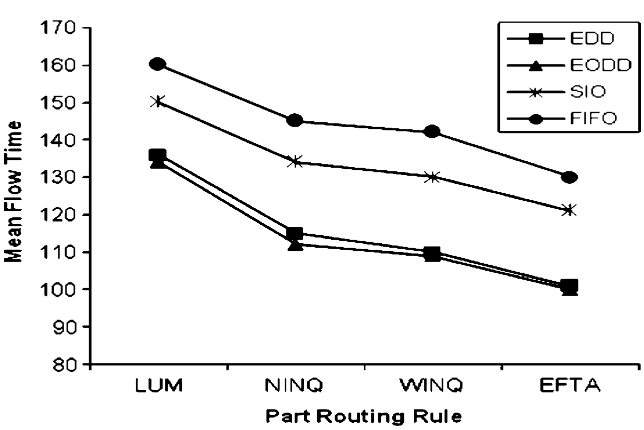

Fig. 5 Mean flow time for scenario 2 (RFL2–SFL2 combination)

It is evident that EFTA for scenario 2 outperforms the scheduling rules such as WINQ, NINQ and LUM. Similar inferences are made for the other performance measures for both the scenarios. Since EFT and EFTA consider work in queue of machines, processing time of the operation to be assigned and transportation time, they are more comprehensive compared with WINQ, NINQ and LUM. Thus, with the use of EFT for scenario 1 and EFTA for scenario 2, the waiting times of parts in the system are reduced. This leads to better performance of EFT and EFTA. Hence, the scheduling rules EFT and EFTA are considered for operation selection/part routing decisions in the further simulation experimentation carried out in the present study.

6 Results and discussion

For each scenario, the simulation results are subjected to statistical analysis using the analysis of variance (ANOVA) procedure in order to study the effect of experimental factors on the performance measures. In scenario 1, the factors considered for analysis are SFL and PSR. Hence, two-factor ANOVA has been carried out. In scenario 2, the factors considered for analysis are RFL, SFL and PSR. Hence, three-factor ANOVA has been carried out. The null hypothesis and the alternative hypothesis for the ANOVA *F* tests for scenario 1 are provided in Table 4.

The least significant difference (LSD) method is used for performing pair-wise comparisons in order to determine the means that differ from other means. All the tests are conducted at 5% level of significance. Values that are not significantly different are grouped. The results obtained and their analysis is presented in the sub-sections below.

6.1 Results and discussion for scenario 1

Scenario 1 represents the base case wherein the purpose of analysis is to investigate the effect of SFL and PSR on the

Table 4 Tests of hypothesis of differences between levels for two-factor model

Factor	Null hypothesis	Alternative hypothesis
A: SFL	H_o: $\tau_1=\tau_2=\tau_3=\ldots\ldots=\tau_a=0$	H_1: $\tau_i\neq 0$ for at least one i
B: PSR	H_o: $\beta_1=\beta_2=\beta_3=\ldots..=\beta_b=0$	H_1: $\beta_j\neq 0$ for at least one j
Interaction: *AB*	H_o: all $(\tau\,\beta)_{ij}=0$	H_1: at least one $(\tau\,\beta)_{ij}\neq 0$

τ_i is the effect of the i-th level of factor A; β_j is the effect of the j-th level of factor B; $(\tau\,\beta)_{ij}$ is the effect of the interaction between τ_i and β_j

performance of the system. Ten replications are made for each of the 20 simulation experiments arising out of the combinations of five SFLs and four PSRs. The routing flexibility is set at RFL0 (i.e. no routing flexibility in the system). The result of the two-factor ANOVA *F* test is shown in Table 5.

The main effects (SFL, PSR) and interaction effects are significant for all the performance measures. The interaction plots are shown in Fig. 6a–e for the performance measures such as mean flow time, standard deviation of flow time, mean tardiness, standard deviation of tardiness and percentage of tardy parts, respectively.

Figure 6a shows the simulation results for mean flow time for the various combinations of SFL and PSR. At SFL0 and SFL1, SIO provides the minimum value for mean flow time. At SFL1, due date-based rules such as EDD and EODD provide values close to SIO. At higher SFLs, EDD and EODD provide the best performance. It can be noted that the SIO rule does not outperform the due date-based rules such as EDD and EODD for mean flow time measure when sequencing flexibility is present in the system. EFT rule is used to select the operation to be performed. As described in Section 4.1.2, EFT rule considers the attributes such as work load of the machine including the remaining processing time of the current part on the machine, the processing time of the operation of the part to be assigned and the transportation time. Consequently, this leads to a reduction in the waiting time of parts. Hence, if a part with early due date is considered, it is more likely to finish sooner.

The beneficial effects of sequencing flexibility are clearly evident here. All the PSRs included in the present study improve their flow time performance as SFL increases. When sequencing flexibility increases beyond SFL2, there is not much improvement in performance. It is also clear that even at SFL1, there is a considerable improvement in the mean flow time values as compared to SFL0. Also the difference in performance between EDD and EODD diminishes significantly when sequencing flexibility exists in production. From Fig. 6c, e, similar inferences can be made for the mean tardiness and percentage of tardy parts, respectively.

Figure 6b compares the standard deviation of flow time for the PSRs at different SFLs. At SFL0, FIFO provides the minimum value for this measure. SIO provides the maximum value at all SFLs. At SFL2, due date-based scheduling rules dominate over SIO and this trend continues for SFL3 and SFL4. The beneficial effects of sequencing flexibility are observed for this measure also. Figure 6d compares the standard deviation of tardiness for the PSRs at different SFLs. For this performance measure, FIFO provides the maximum value. EODD leads to minimum value at all SFLs.

For each PSR, the relative percentage improvement (RPI) in performance at each SFL (SFL1, SFL2, SFL3 and SFL4) is calculated relative to SFL0. For example, the RPI for mean flow time (MFT) for the FIFO rule at SFL1 is calculated as follows:

$$\text{RPI for MFT} = \frac{(\text{MFT\_SFL0} - \text{MFT\_SFL1})}{\text{MFT\_SFL0}} \times 100 \qquad (2)$$

The RPI values thus obtained are shown in Table 6.

Table 6 reveals that when sequencing flexibility increases beyond SFL2, there is not much improvement in performance for the FMS considered in the present study. SFL2 denotes medium level of sequencing flexibility. The simulation results presented in the paper correspond to the mean interarrival time of parts set at 15 min. It is found that the system shows convergence and remains stable beyond SFL2 for the system load specified by the mean interarrival

Table 5 ANOVA results for scenario 1

Source of variation	*F* ratio for performance measures				
	PM1	PM2	PM3	PM4	PM5
Main effects					
A: SFL	258.11[a]	70.96[a]	146.44[a]	48.99[a]	220.38[a]
B: PSR	136.87[a]	61.95[a]	67.91[a]	61.53[a]	96.53[a]
Interaction effect: *AB*	15.82[a]	8.38[a]	6.88[a]	3.46[a]	18.92[a]

[a] Denotes *F* ratio significant at 5% significance level

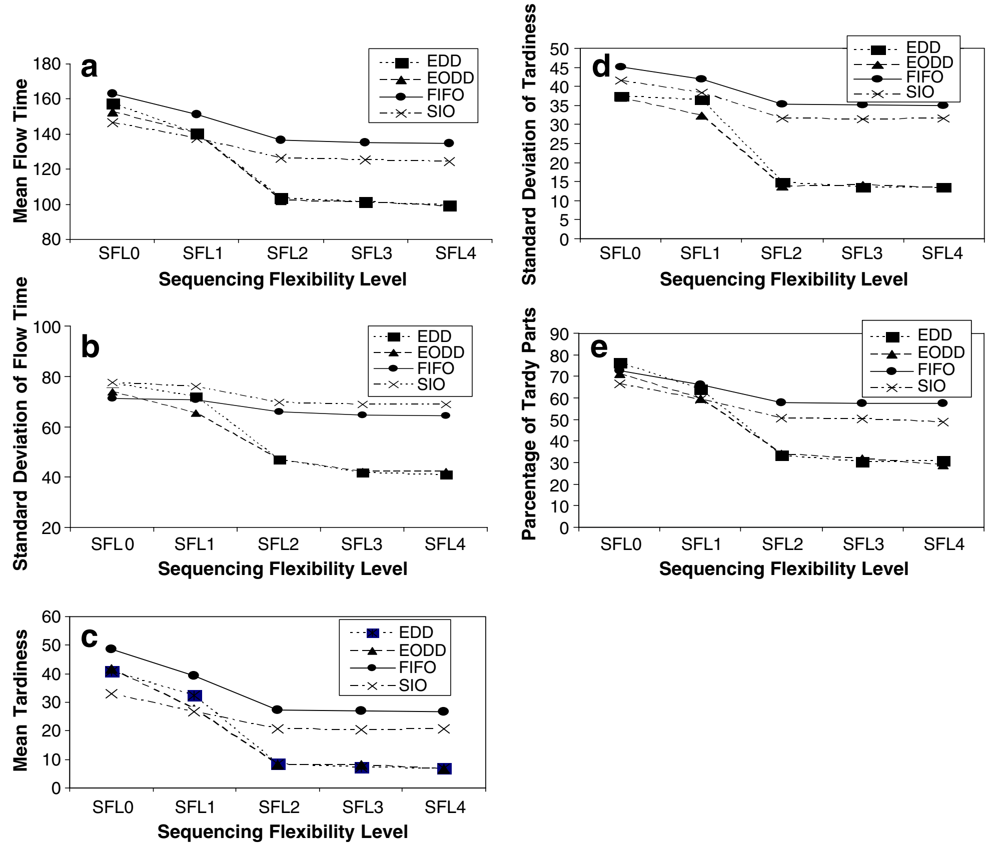

Fig. 6 **a** Interaction plot for scenario 1—mean flow time. **b** Interaction plot for scenario 1—standard deviation of flow time. **c** Interaction plot for scenario 1—mean tardiness. **d** Interaction plot for scenario 1—standard deviation of tardiness. **e** Interaction plot for scenario 1—percentage of tardy parts

Table 6 RPI in performance for scenario 1

PSR	Performance measure	Relative percentage increase			
		SFL1	SFL2	SFL3	SFL4
FIFO	PM1	7.32	16.44	17.04	17.47
	PM2	0.80	7.18	11.82	11.74
	PM3	19.24	44.11	45.32	45.29
	PM4	7.09	21.86	22.00	22.43
	PM5	9.07	20.53	20.90	21.08
SIO	PM1	6.13	13.89	14.47	15.05
	PM2	1.91	10.30	14.95	14.27
	PM3	19.12	33.67	37.80	37.62
	PM4	7.90	24.16	24.36	24.38
	PM5	11.10	24.35	25.78	26.60
EDD	PM1	10.83	34.23	35.66	36.79
	PM2	6.78	39.30	46.19	47.15
	PM3	21.08	79.29	82.22	83.05
	PM4	2.18	60.17	63.51	63.80
	PM5	16.49	56.62	60.30	60.99
EODD	PM1	8.20	33.06	33.74	35.17
	PM2	11.34	36.41	42.96	43.07
	PM3	33.72	80.40	82.62	84.39
	PM4	12.33	63.06	63.64	64.12
	PM5	16.49	52.12	55.53	59.55

time of parts. This results in no further improvement in the performance measures beyond SFL2.

6.2 Results and discussion for scenario 2

Scenario 2 represents the experimental settings wherein the purpose of analysis is to investigate the effects of routing flexibility, sequencing flexibility and part sequencing decision rules on the performance of the system. The results for the three-factor ANOVA F tests are shown in Table 7 for the performance measures such as mean flow time, standard deviation of flow time, mean tardiness, standard deviation of tardiness and percentage of tardy parts.

The main effects, namely routing flexibility, sequencing flexibility and part sequencing decision rules, are found to be statistically significant at the 5% significance level for all the performance measures since the probability value (P value) of the F test is less than 0.05. The interaction effects are also statistically significant for all the performance measures.

6.2.1 The main effects of routing flexibility

The LSD method of pair-wise multiple comparisons is used to determine which of the routing flexibility levels are statistically significant. The LSD test results are shown in Table 8.

Table 7 ANOVA results for scenario 2

Source of variation	*F* ratio for performance measures				
	PM1	PM2	PM3	PM4	PM5
Main effects					
A: RFL	3,125.12[a]	1,316.55[a]	1,865.65[a]	1,128.62[a]	2,259.17[a]
B: SFL	331.56[a]	89.31[a]	175.75[a]	55.97[a]	182.62[a]
C: PSR	213.99[a]	87.51[a]	83.15[a]	72.20[a]	68.91[a]
Interaction effects					
AB	100.54[a]	42.91[a]	107.24[a]	28.34[a]	41.17[a]
AC	43.91[a]	33.73[a]	48.88[a]	33.50[a]	18.55[a]
BC	20.62[a]	9.78[a]	7.10[a]	3.21[a]	10.61[a]
ABC	6.15[a]	5.38[a]	5.51[a]	2.31[a]	5.10[a]

[a] Denotes *F* ratio significant at 5% significance level

For each performance measure, the entry in Table 8 corresponding to each routing flexibility level represents the mean value of the performance measure obtained as an average of 20 simulation experiments (5 sequencing flexibility levels × 4 part sequencing rules) over ten replications. The LSD test groups the results into three significantly different groups labelled "*a*", "*b*" and "*c*" for each of the performance measures. As expected, when there is no routing flexibility present in the system, the performance measures have higher values when compared with that obtained for the routing flexibility levels 1 and 2.

6.2.2 The main effects of sequencing flexibility

Table 9 shows the main effect of sequencing flexibility on the performance of the system. For the mean flow time measure, the SFL4 forms a unique group labelled "*a*" providing the smallest value. SFL4 indicates full sequencing flexibility wherein operations of a part can be carried out in any order. Further, EFTA rule used for machine selection aids in choosing machines where operations can be completed earlier. There is no significant difference between SFL2 and SFL3, and hence, these two levels form a unique group labelled "*b*". The SFL0 and SFL1 form unique groups labelled "*c*" and "*d*", respectively. The beneficial effects of sequencing flexibility are clearly evident here. When there is no sequencing flexibility, mean flow time has the highest value.

For the performance measures such as standard deviation of flow time, mean tardiness and standard deviation of tardiness, the sequencing flexibility levels SFL2, SFL3 and SFL4 form a unique group labelled "*a*". SFL0 and SFL1 form unique groups labelled "*b*" and "*c*", respectively, for these three measures. Each SFL forms a unique group for percentage of tardy parts with SFL4 that provide the smallest value. The results show that even this minimum sequencing flexibility (SFL1) provides considerable improvement in the performance of the system for all the measures.

6.2.3 Main effect of part sequencing rule

The LSD results for the main effect of PSRs are shown in Table 10. For all the performance measures, the scheduling rules such as EODD and EDD form a unique group labelled "*a*". The other two scheduling rules, namely SIO and FIFO, form separate unique groups labelled "*b*" and "*c*", respectively. It is interesting to note that the SIO rule does not outperform the due date-based rules such as EDD and EODD for mean flow time measure when sequencing flexibility is present in the system. EFTA rule is used to select a suitable machine to perform an operation of a part. As described in Section 4.1.3, EFTA rule considers the attributes such as work load of a machine including the remaining processing time of the current part on the machine, the processing time

Table 8 Multiple comparison test results for scenario 2 (main effect—RFL)

RFL	PM1	PM2	PM3	PM4	PM5
RFL0	129.17[c]	62.11[c]	23.87[c]	29.72[c]	52.53[c]
RFL1	98.31[b]	41.21[b]	5.24[b]	11.13[b]	25.38[b]
RFL3	89.02[a]	38.81[a]	2.35[a]	6.97[a]	13.97[a]

In each column, values with the same letter are not significantly different from each other by statistical test

Table 9 Multiple comparison test results for scenario 2 (main effect—SFL)

SFL	PM1	PM2	PM3	PM4	PM5
SFL0	118.70[d]	53.24[c]	17.54[c]	20.94[c]	41.79[e]
SFL1	110.49[c]	50.72[b]	12.89[b]	18.13[b]	33.84[d]
SFL2	100.42[b]	44.96[a]	7.65[a]	14.03[a]	27.78[c]
SFL3	99.75[b]	44.12[a]	7.40[a]	13.45[a]	25.80[b]
SFL4	98.12[a]	43.85[a]	6.94[a]	13.04[a]	23.92[a]

In each column, values with the same letter are not significantly different from each other by statistical test

Table 10 Multiple comparison test results for scenario 2 (main effect—PSR)

PSR	PM1	PM2	PM3	PM4	PM5
FIFO	112.99[c]	49.84[b]	14.43[c]	19.71[c]	35.25[c]
SIO	108.52[b]	51.41[c]	10.71[b]	18.20[b]	32.65[b]
EDD	100.60[a]	44.56[a]	8.51[a]	13.06[a]	27.62[a]
EODD	99.87[a]	43.71[a]	8.30[a]	12.78[a]	26.98[a]

In each column, values with the same letter are not significantly different from each other by statistical test

of the operation of the part to be assigned and the transportation time. Consequently, this leads to a reduction in the waiting time of parts. Hence, if a part with early due date is considered for processing on a machine, it is more likely to finish sooner. Among the scheduling rules considered in the present study, EDD and EODD provide better performance for all the performance measures. FIFO provides worst performance for all the measures.

6.2.4 The interaction effects

The ANOVA results presented in Table 7 reveal that the two-factor interaction effects are significant for all the performance measures. For each two-factor combination, interaction plots are obtained for all the measures. The plots for mean flow time are shown in Fig. 7a–c, respectively, for the two-factor combinations such as RFL–SFL, RFL–PSR and SFL–PSR, respectively. Due to space limitations, the interaction plots for the other performance measures are not included here.

RFL–SFL interaction effects It is evident from Fig. 7a that with an increase in RFL, there is an improvement (reduction) in the performance measure values when SFL is increased. However, the improvement is larger at RFL1 when compared to that at RFL2. Even when there is no routing flexibility present in the system, sequencing flexibility leads to a reduction in mean flow time values. However, the combinations such as RFL0–SFL2, RFL0–SFL3 and RFL0–SFL4 provide a larger reduction in the mean flow time when compared with RFL0–SFL1 combination. When there is no sequencing flexibility, the existence of routing flexibility in the system provides a substantial reduction in mean flow time. Hence, appropriate flexibility levels in terms of routing flexibility (manufacturing system design aspect) and sequencing flexibility (product design aspect) can be decided based on the analysis of the interaction effects.

RFL–PSR interaction effects The interaction plot for mean flow time for RFL–PSR combinations is shown in Fig. 7b.

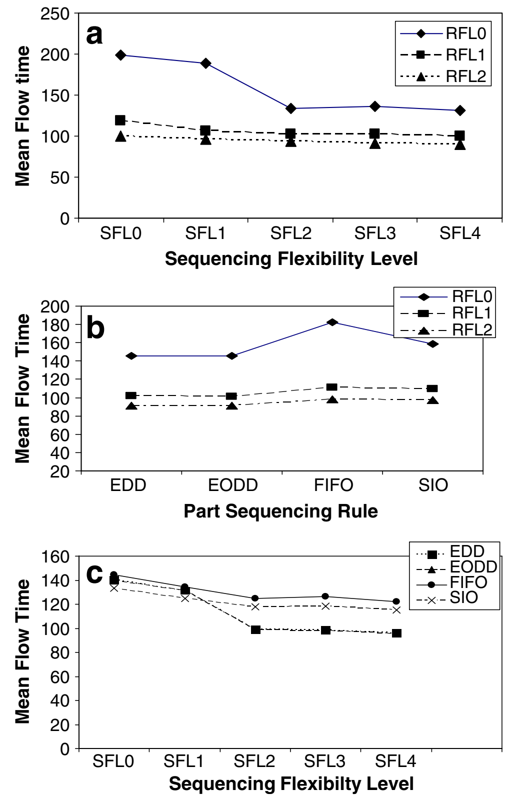

Fig. 7 **a** Interaction plot for scenario 2—RFL and SFL. **b** Interaction plot for scenario 2—RFL and PSR. **c** Interaction plot for scenario 2—SFL and PSR

The part sequencing rules such as EDD and EODD provides similar values for mean flow time for all routing flexibility levels. However, there is a substantial reduction in mean flow time values when either of these scheduling rules are used for part sequencing decision at RFL1 and RFL2 when compared with RFL0. FIFO and SIO rules provide almost similar values at RFL1 and RFL2. However, as expected, SIO performs better than FIFO when there is no routing flexibility in the system. Similar inferences are obtained from the interaction plots for the other performance measures.

SFL–PSR interaction effects Figure 7c shows the interaction plot for mean flow time for SFL–PSR combinations. When there is no sequencing flexibility, SIO leads to minimum mean flow time. But the scheduling rules such as EDD and EODD provide lesser values of mean flow time as the SFL is increased. There is a considerable difference in mean flow time between SIO and due date-based rules at higher SFLs such as SFL2, SFL3 and SFL4. The scheduling rule FIFO provides the worst performance at all the SFLs.

All the PSRs included in the present study improve their flow time performance as SFL increases. It can be noted that the SIO rule does not outperform the due date-based rules such as EDD and EODD for mean flow time measure when higher level of sequencing flexibility is present in the system. EFTA rule is used to select the operation and the associated machine for processing. There are more options available for operations and machines at higher flexibility levels. As described in Section 4.1.3, EFTA rule considers the attributes such as work load of the machine including the remaining processing time of the current part on the machine, the processing time of the operation of the part to be assigned and the transportation time. Thus, with the use of EFTA rule, the waiting times of parts in the system are reduced. Further, the part sequencing rules such as EDD and EODD make use of due dates of parts/operations. SIO considers processing time of imminent operation only, whereas FIFO considers neither processing time nor due date. Therefore, EFTA in combination with EDD/EODD considers processing time and due-date information. This helps in faster completion of parts.

6.3 Desirable operational policies

Based on the analysis of the results presented in the preceding sub-sections, the PSRs that perform better for the various performance measures under each RFL and SFL are shown in Table 11. It is evident that the due date-based rules such as EDD and EODD dominate the other rules in most of the experiments. Specifically, at higher flexibility levels (SFL2, SFL3 and SFL4), EDD and EODD emerge as the best performing PSRs.

7 Conclusion

In this research study, the effects of routing flexibility, sequencing flexibility and part sequencing rules on the performance of an FMS have been analysed using a discrete-event simulation model. The statistical analysis of the simulation results reveals that there is a significant interaction among RFL, SFL and PSR for all the performance measures. In essence, the results can be summarized as follows:

- Even when there is no routing flexibility present in the system, sequencing flexibility leads to an improvement in all the performance measures.
- With an increase in RFL, there is an improvement in the performance measure values when SFL is increased. However, the improvement is larger at RFL1 when compared to that at RFL2.
- Due date-based part sequencing rules such as EDD and EODD provide better performance for all the measures. Since there is no significant difference in performance between these two rules, EDD being a simpler scheduling rule can be used for part sequencing decision.
- The deterioration in system performance can be minimized substantially by incorporating either routing flexibility or sequencing flexibility or both. However, the benefits of either of these flexibilities diminish at higher flexibility levels.
- This study has implications for the design of production planning and control systems, manufacturing system

Table 11 Desirable operational policies

RFL	Performance measure	Sequencing flexibility levels				
		SFL0	SFL1	SFL2	SFL3	SFL4
RFL0	PM1	SIO	SIO, EDD, EODD	EDD, EODD	EDD, EODD	EDD, EODD
	PM2	FIFO	EODD	EODD	EDD, EODD	EDD, EODD
	PM3	SIO	SIO, EODD	SIO, EODD	EDD, EODD	EDD, EODD
	PM4	EDD, EODD	EODD	EODD	EDD, EODD	EDD, EODD
	PM5	SIO	SIO	SIO	EDD, EODD	EDD, EODD
RFL1	PM1	SIO	SIO, EDD, EODD	EDD, EODD	EDD, EODD	EDD, EODD
	PM2	FIFO	EODD	EODD	EDD, EODD	EDD, EODD
	PM3	SIO	SIO, EODD	SIO, EODD	EDD, EODD	EDD, EODD
	PM4	EDD, EODD	EODD	EODD	EDD, EODD	EDD, EODD
	PM5	SIO	SIO	SIO	EDD, EODD	EDD, EODD
RFL2	PM1	SIO	SIO, EDD, EODD	EDD, EODD	EDD, EODD	EDD, EODD
	PM2	FIFO	EODD	EODD	EDD, EODD	EDD, EODD
	PM3	SIO	SIO, EODD	SIO, EODD	EDD, EODD	EDD, EODD
	PM4	EDD, EODD	EODD	EODD	EDD, EODD	EDD, EODD
	PM5	SIO	SIO	SIO	EDD, EODD	EDD, EODD

design and product design. A clear understanding of the dynamics in the system indicated by the interaction effects provided in the simulation analysis helps to determine the appropriate flexibility levels in terms of routing flexibility (manufacturing system design aspect), sequencing flexibility (product design aspect) and scheduling decision rules (operational control policies).

Flow time is a critical indicator of the manufacturing lead time, and it also provides important information that can be used for setting the due dates or due-date allowances. Moreover, it is proportional to the work-in-process levels. Tardiness-based measures are related to customer service. In order to use routing flexibility and sequencing flexibility, it is necessary to have a real-time manufacturing information system that is capable of assessing machines, part status, and to make choices among alternatives. The present study indicates that using routing flexibility and sequencing flexibility results in flow time reduction and improved customer service through decrease in tardiness and the percentage of tardy parts. These benefits can be quantified and used in the economic justification of investments in manufacturing information systems.

The RFLs chosen for experimentation in the present research include a maximum of two alternative machines for an operation. Further experimentation is required for analysing situations involving more options for operations and for varying penalty levels for processing of operations on alternative machines. There is a need for further research to evaluate the effects of different flexibility levels and scheduling decision rules for the experimental conditions that consider system disruptions such as breakdowns of machines and AGVs.

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