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ORIGINAL ARTICLE

Performance Evaluation of Flexible Manufacturing System Under Different Material Handling Strategies

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Abstract *The current market scenario is such that customers demand a variety of good quality products at a very short notice. The need of manufacturing flexibility in flexible manufacturing system producing these parts is a major challenge in effectively integrating material, information and decision flow in the system. The evolving flexible manufacturing environment requires a judicious combination of manufacturing flexibility, material handling strategies, design, planning and operational strategies, etc. In this paper, a series of simulation experiments are conducted to study the impact of routing flexibility on the make-span and average waiting time of parts in queue as performance measures of flexible manufacturing system under different material handling strategies. The results are further analyzed with the help of ANOVA to measure the effect of input variables on flexible manufacturing system performance. It is seen that for assumed conditions there is an optimal routing flexibility level for a given material handling strategy. This work will help system designers in taking judicious decision in setting manufacturing strategies. The results also show the impact of sequencing and dispatching rules, buffer size and number of parts on the performance of flexible manufacturing system.*

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Keywords Manufacturing flexibility · Make-span · Routing flexibility · Simulation

Introduction

The current market scenario is such that a customer demands a variety of good quality products at a very short notice. The increasing and fast changing product variety has dramatically enhanced the complexity which requires more effective management of the production systems. The traditional systems of product manufacture were unable to satisfy the requirements of variety, quantity and speed at the same time. This has led to the development of flexible manufacturing system (FMS). FMS is a group of numerically-controlled machine tools, interconnected by a central control system that can simultaneously process medium-size volumes of medium variety parts (Browne et al. 1984). The various components of FMS are machining centers, loading and unloading stations and automated storage and retrieval systems. A classification of manufacturing flexibility often cited in literature is that by Browne et al. (1984) which considers eight different types of flexibility. These are machine flexibility, product flexibility, process flexibility, operation flexibility, routing flexibility, volume flexibility, expansion flexibility, and production flexibility. Chang and Yang (2003) studied the combined effect of manufacturing flexibility and business strategy on the performance of small and medium sized firms. Similarly, Wadhwa et al. (2005) studied flexibility-enabled lead-time reduction in flexible system. Also Wadhwa et al. (2008) studied the performance of flexible manufacturing system under planning and control strategies. Anoop et al. (2011) evaluated the performance measure of flexible manufacturing system and showed the effect of uncertainty on make-span time at various levels of routing flexibility. The combined effect of routing and pallet flexibility on system performance was studied by Ali (2012).

The evolving flexible manufacturing environment requires a judicious combination of manufacturing flexibility and material handling strategies. Routing flexibility has been recognized as a fundamental characteristic of a manufacturing system's overall flexibility, as it enhances a system for the easier scheduling of parts by better balancing the machine loads and allows the system to produce a given set of part types or part families without interruption (Sethi and Sethi 1990). Chan (2001) has also considered routing flexibility to evaluate the performance of flexible manufacturing system. Ali and Wadhwa (2005) studied the performance of partial flexible manufacturing system and showed that merely increasing the level of routing flexibility is not beneficial. Yasemin et al. (2010) developed mathematical models for job-shop scheduling problems with routing and process plan flexibility. Ali and Ahmad (2014) studied the impact of routing and part mix flexibility on the performance of FMS. He et al. (2014) points out that machine flexibility and system layout flexibility is not sufficient to respond to changes in the business environment. However, the system performance can be improved by incorporating sequencing flexibility (Khan and Ali 2015).

Tiwari and Dharmaraju (2002) solved machine loading problems in a flexible manufacturing system using a genetic algorithm based heuristic approach. Kumar and Kumar, (2003) developed a fuzzy-based solution approach to address a machine-loading problem of a flexible manufacturing system. The proposed solution methodology effectively deals with all the three main constituents of a machine loading problem, viz. job sequence determination, operation machine allocation, and the reallocation of jobs. Chan and Chan (2004) developed a novel approach for production planning of flexible manufacturing systems using an efficient multi-objective genetic algorithm. Loukil and Makram (2005) solved the multi-objective production scheduling problems using meta-heuristics. There are a number of researchers who have used discrete event simulation for evaluating the performance of flexible manufacturing system. The notable of them are (Sabuncuoglu and Lahmar 2003; Nazzal et al. 2006; Suresh and Sridharan 2007; Singholi et al. 2010; Ali 2012; El-Khalil 2013)

Reeja and Rajendran (2000) studied the impact of different dispatching rules for scheduling in assembly job shop. Mohanasundarama et al. (2003) studied different scheduling rules for dynamic shops that manufacture multi-level jobs. Wadhwa et al. (2008) studied the performance of flexible manufacturing system under planning and control strategies. They considered makespan time as the performance measure to evaluate the performance of the system. Recent trends towards make span time, lead time and WIP reduction have increased interest in the application of process control strategies. Ali and Wadhwa (2010) considered MINQ and MWTQ as the dispatching rules to evaluate the performance of flexible system of integrated manufacturing system. Singholi et al. (2013) also considered MINQ and MWTQ as control rules to evaluate the effect of machine and routing flexibility on flexible system performance. It is seen that the performance of flexible manufacturing system is being evaluated under the impact of number of manufacturing strategies. The selection of parts from the queue based on a sequencing rule can further add to the operational issues in an FMS. But very few works are on the effect of different material handling strategies on the performance of flexible system. Hence the purpose of this work is to present the use of a simulation based decision support tool to evaluate the performance of FMS with different material handling strategies.

This work attempts to fulfill the following objectives:

1. To study the impact of routing flexibility on the performance of FMS.
2. To study the impact of material handling strategies on the performance of FMS.
3. To perform ANOVA analysis to establish the relative significance of different parameters of the system performance.

In pursuance of these objectives, different demo models are developed in ARENA simulation package. A series of experiments is conducted to study the impact of routing flexibility on the performance of FMS under different material handling strategies. The results are further analyzed in ANOVA to measure the effect of input variable on flexible system performance. The outline of the paper is as follows. "Introduction" section provides the required introduction which includes the background and objectives related to the proposed work. In "Development of FMS Models" section, the development of FMS models is presented. In "Results and Discussion" section, various results focusing on the effect of routing flexibility and loading and unloading strategies on the system performance are presented. In "Conclusion" section conclusion is discussed.

Development of FMS Models

This section comprises of problem formulation and development of simulation models of FMS. The models are first developed for conventional manufacturing system and then for flexibility focused manufacturing system. The conceptual model of the proposed flexible manufacturing

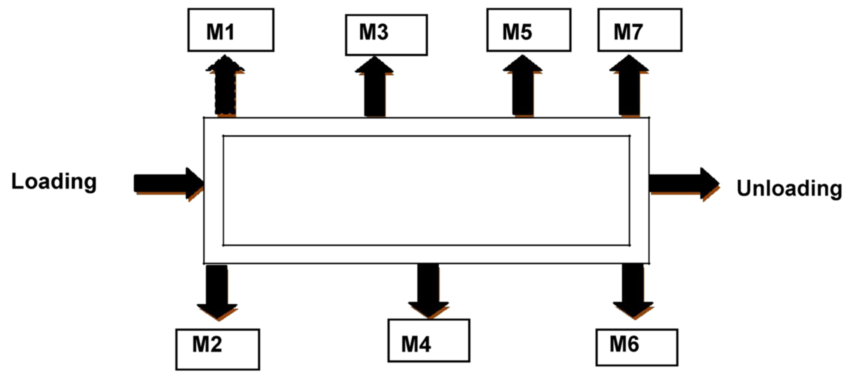

Fig. 1 Conceptual model of the proposed flexible manufacturing system

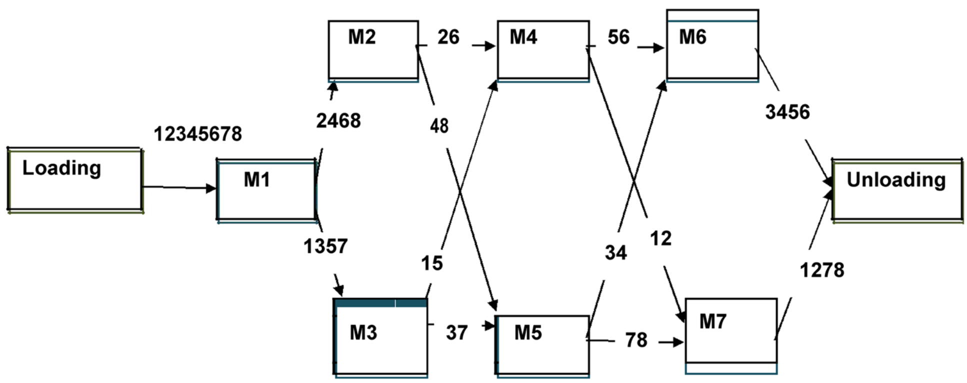

Fig. 2 Routes for Part A

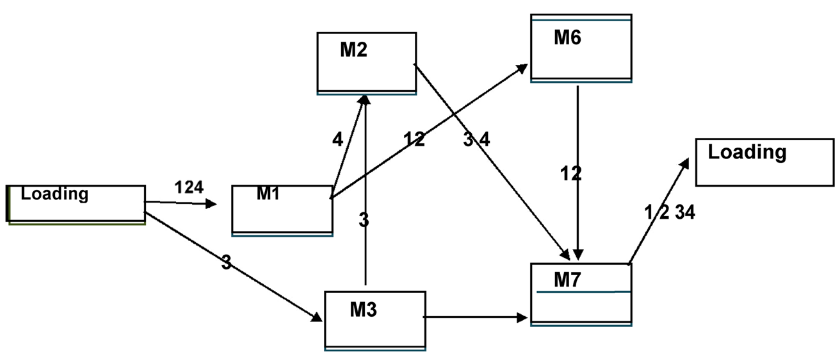

Fig. 3 Routes for Part B

system is shown in Fig. 1. The FMS model considered consists of seven flexible machines (M1, M2, M3, M4, M5, M6 and M7). This dimension is chosen as it can be considered to occur most frequently (Caprihan and Wadhwa 1999; Ali and Wadhwa 2010). Each of these flexible machines is capable of processing up to five different part types (Part A, B, C, D and E). Each of these parts has its own sequence of operation and requires between three to four operations.

There are four basic models based on different material handling strategies. Material handling strategies manifest itself in the form of loading and unloading options of the parts on the machines. Each model is further studied with different levels of routing flexibility. Figures 2, 3, 4, 5 and 6 shows the routes allocation of different types of parts considered in this study. For Part A, Part C and Part D there are eight different routes through which the operations can be performed. Similarly, Part B has four different routes and Part E has only one route. The numerical numbers along the path shows the respective route number. The simulation models are developed for the first route for each part type.

The input parameters are routing flexibility (RF), number of pallets (NP), production volume (PV) and buffer capacity (BC), process control strategies being sequencing

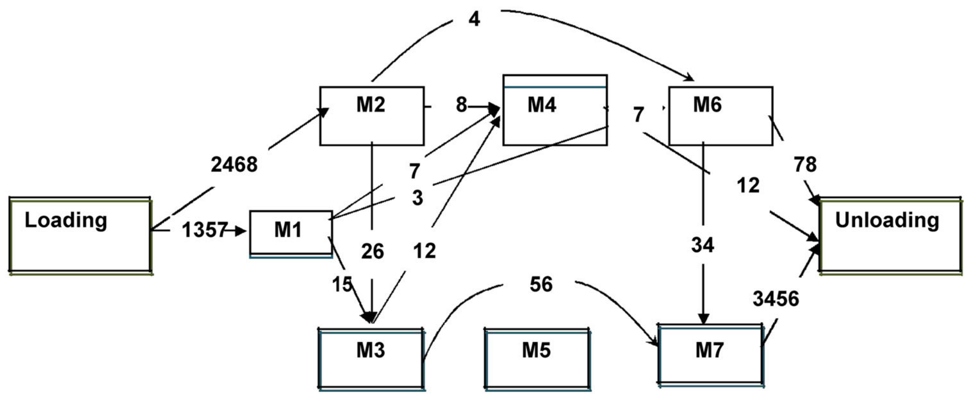

Fig. 4 Routes for Part C

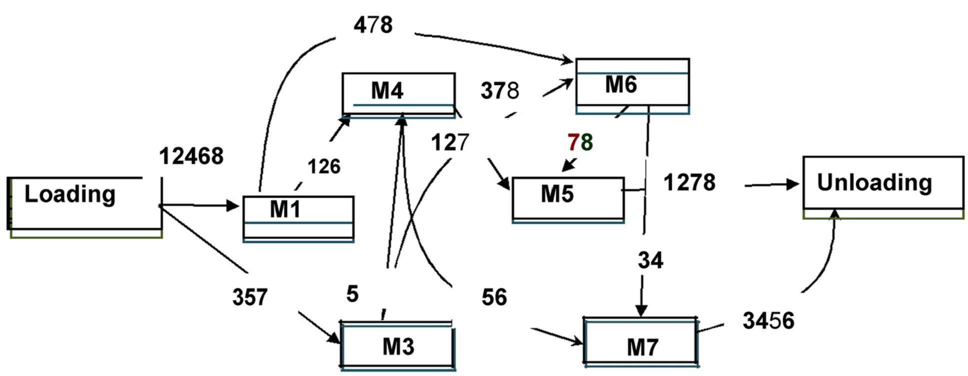

Fig. 5 Routes for Part D

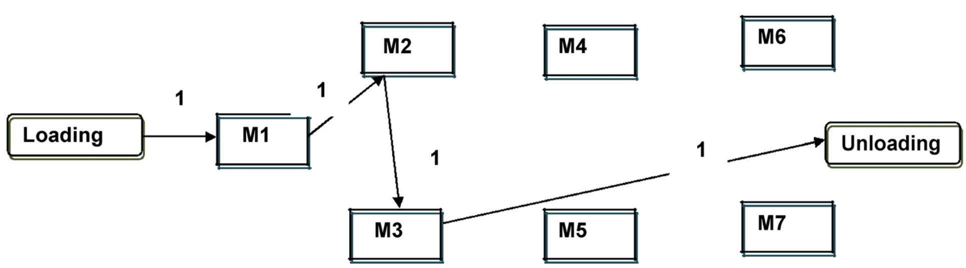

Fig. 6 Routes for Part E

rules (SR) and dispatching rule (DR). The system is evaluated under make-span time (MST) and average waiting time (AWT) in queue. MST is defined as the total time between the first operation of the first part and the last operation of the last part. In this work, we have determined the MST for total of 500 parts and average waiting time in queue is defined as the total time spent in processing all the parts present in the queue at a particular machine. The concept of routing flexibility is similar to the one taken by Wadhwa and Rao (2002). It is described as follows: RF = 0, means that there is exactly one machine for an operation on a given part, i.e., there are no (zero) alternatives; R = 1, implies that there are two possible machines for processing the same operation, i.e., there is exactly one more alternative machine (other than the machine which is available at RF = 0) for any operation on any part; RF = 2, implies that there are three possible machines for processing the same operation, i.e., there are exactly two more machines available for processing the same operation (other than the machine which is available at RF = 0) and RF = Full, implies that there are seven possible machines for processing the same operation, i.e., there are exactly six

Table 1 Processing time for Parts at RF = 0

PARTS	OPT1	OPT2	OPT3	OPT4	OPT5	OPT6
A	L_A(3)	M1(10)	M3(20)	M4(18)	M7(6)	UL_A(3)
B	L_B(5)	M3(20)	M6(10)	M7(15)	–	UL_B(5)
C	L_C(2)	M1(13)	M3(20)	M4(18)	–	UL_C(2)
D	L_D(3)	M3(20)	M4(30)	M5(12)	–	UL_D(3)
E	L_E(4)	M1(20)	M2(12)	M3(20)	–	UL_E(4)

Table 2 Processing time for Parts at RF = 1

Parts	OPT1	OPT2	OPT3	OPT4	OPT5	OPT6
A	L_A(3)	M1M2(10)	M3M5(20)	M4M1(18)	M7M4(6)	UL_A(3)
B	L_B(5)	M3M2(20)	M6M4(10)	M7M4(15)	–	UL_B(5)
C	L_C(2)	M1M2(13)	M3M4(20)	M4M6(18)	–	UL_C(2)
D	L_D(3)	M3M1(20)	M4M6(30)	M5M4(12)	–	UL_D(3)
E	L_E(4)	M1M2(20)	M2M5(12)	M3M4(20)	–	UL_E(4)

Table 3 Processing time for Parts at RF = 2

Parts	OPT1	OPT2	OPT3	OPT4	OPT5	OPT6
A	L_A(3)	M1M2 M3(10)	M3M5 M6(20)	M4M1 M7(18)	M7M4 M5(6)	UL_A(3)
B	L_B(5)	M3M2 M4(20)	M6M4 M7(10)	M7M4 M3(15)	–	UL_B(5)
C	L_C(2)	M1M2 M3(13)	M3M4 M7(20)	M4M6 M2(18)	–	UL_C(2)
D	L_D(3)	M3M1 M4(20)	M4M6 M7(30)	M5M4 M6(12)	–	UL_D(3)
E	L_E(4)	M1M2 M3(20)	M2M5 M6(12)	M3M4 M1(20)	–	UL_E(4)

Table 4 Processing time for Parts at RF = Full

PARTS	OPT1	OPT2	OPT3	OPT4	OPT5	OPT6
A	L_A(3)	M1(10)M2M3 M4M5M6M7	M3(20)M1M2 M4M5M6M7	M4(18)M1M2 M3M5M6M7	M7(6)M1M2 M3M4M5M6 M	UL_A(3)
B	L_B(5)	M3(20)M1M2 M4M5M6M7	M6(10)M1M2 M3M4M5M7	M7(15)M1M2 M3M4M5M6		UL_B(5)
C	L_C(2)	M1(13) M2M3 M4M5M6M7	M3(20) M1M2 M4M5M6M7	M4(18) M1M2 M3M5M6M7		UL_C(2)
D	L_D(3)	M3(20) M1M2 M4M5M6M7	M4(30) M1M2 M3M5M6M7	M5(12)M1M2 M3M4M6M7		UL_D(3)
E	L_E(4)	M1(20) M2M3 M4M5M6M7	M2(12)M1M3 M4M5M6M7	M3(20) M1M2 M4M5M6M7		UL_E(4)

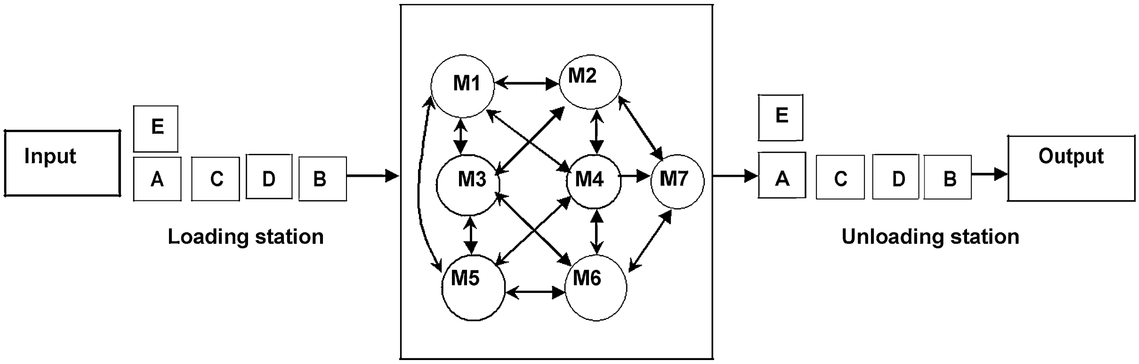

Fig. 7 Conceptual models for L1UL1

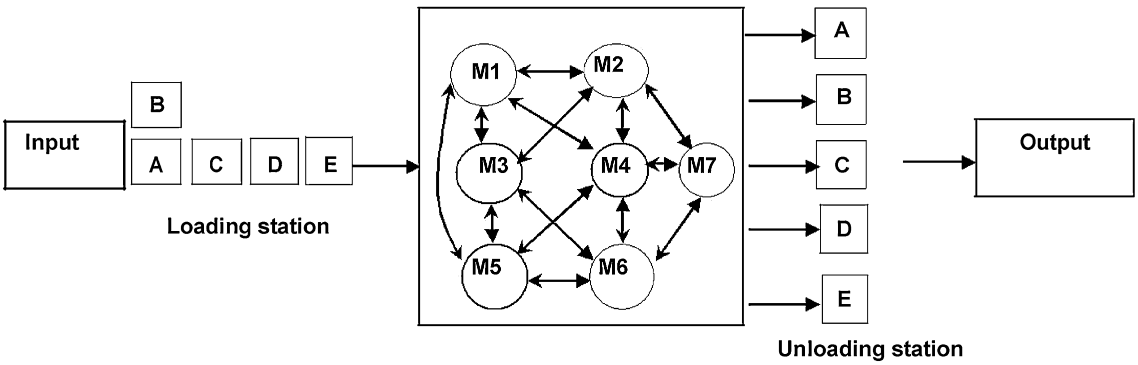

Fig. 8 Conceptual model for L1UL5

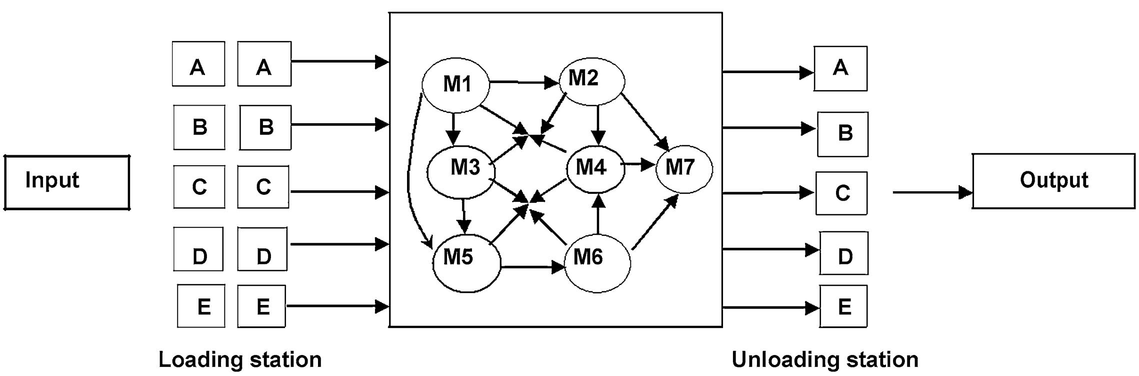

Fig. 9 Conceptual model for L5UL5

more machines available for processing the same operation (other than the machine which is available at RF = 0). Tables 1, 2, 3 and 4 show the details of processing times, alternative machines available at different routing flexibility levels.

Parts are routed to different machines according to the level of routing flexibility that the system is following. Pallet is a work holding device. Each pallet is assumed to accommodate a single part. Number of pallets is varied to change the loading capacity of the system. In this work, we study the impact of number of pallets (5, 10, 15, and 20) on the system performance. We have assumed that there is a dedicated input buffer at every machine. Each machine can accommodate maximum number of parts according to their buffer capacity. The control strategies are modelled as a combination of a sequencing rule and a dispatching rule. The priority of the parts in the queue of the machines is selected on the basis of the sequencing rules (SR). The sequencing rules modelled are as follows: first come first serve (FIFO)., part which arrives first in the buffer queue

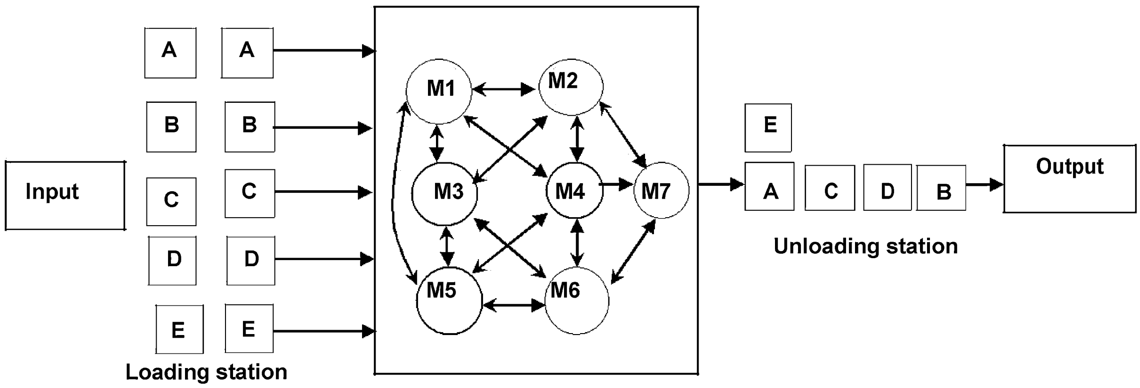

Fig. 10 Conceptual model for L5UL1

has highest priority and is served first; shortest processing time (SPT), part which has the minimum operation time has the highest priority and is served first. The selection of the alternative machine is based on the dispatching decision (DR). The dispatching rule used is minimum number of part in the queue (MINQ), the machine which has the minimum number of parts in the queue is selected to process the next operation. In all we have developed the conceptual model for four different types of FMS based on loading and unloading strategies. These models are designated as:

1. L1UL1: one loading station and one unloading station (see Fig. 7).
2. L1UL5: one loading station and five unloading stations (see Fig. 8).
3. L5UL5: five loading stations and five unloading stations (see Fig. 9).
4. L5UL1: five loading stations and one unloading station (see Fig. 10).

Based on the conceptual models, simulation models are developed in ARENA simulation software. Figure 11 shows the flowchart of material and information flow in the system. Figures 12, 13, 14 and 15 show the simulation models in ARENA for L1UL1 at different levels of routing flexibility.

Firstly, various parts arrive and held at the loading area waiting for the required information in order to proceed into the system. Initially control entities are created to run the simulation model. After sending the signal to release the required number of parts, the control entities are disposed off. Once the parts are released from loading area, they are sent to the decision point where part types are identified. Based on the part type, they are sent to respective stations where various attributes are assigned to the parts. After this the parts are sent to decision point where dispatching rule is invoked in order to select the prospective machines. The machine is selected based on the dispatching rule and availability of space in the dedicated buffer at each machine. The parts are made to wait in the input buffer of the machine till the machine becomes idle. After being processed by the machines, the parts are sent to the decision point where, the status of the part with respect to remaining operations is checked. If another operation is not required on the part, the part is disposed off. Before being disposed, the part sends the signal to the loading area to release the next part. In this way a constant number of parts in the system is maintained. If any operation is left on the part, it is once again sent to the respective stations where attributes and variables are updated. This cycle will repeat until all the parts have been processed. In the proposed models, a list of assumptions has been made, which are as follows. Each machine is continuously available for processing; that is, machines never break down, the same operation processes by the same machine have the same operation time, all the parts are already at the start of the simulation, when RF = 1, all the decisions are made dynamically, i.e., the choice of the machine for the part's next operation is based on dispatching rule immediately after it has finished the current operation, the set-up times are included in the operation times, operation processing times are deterministic and simulation stops when all the parts finish all their operations. Based on this flowchart the simulation models for various system configurations are developed.

Results and Discussion

On the basis of the conceptual and simulation models discussed in the previous sections, in this section we have generated results by executing the models in ARENA simulation software. As discussed in previous sections, there are four configurations of flexible systems based on

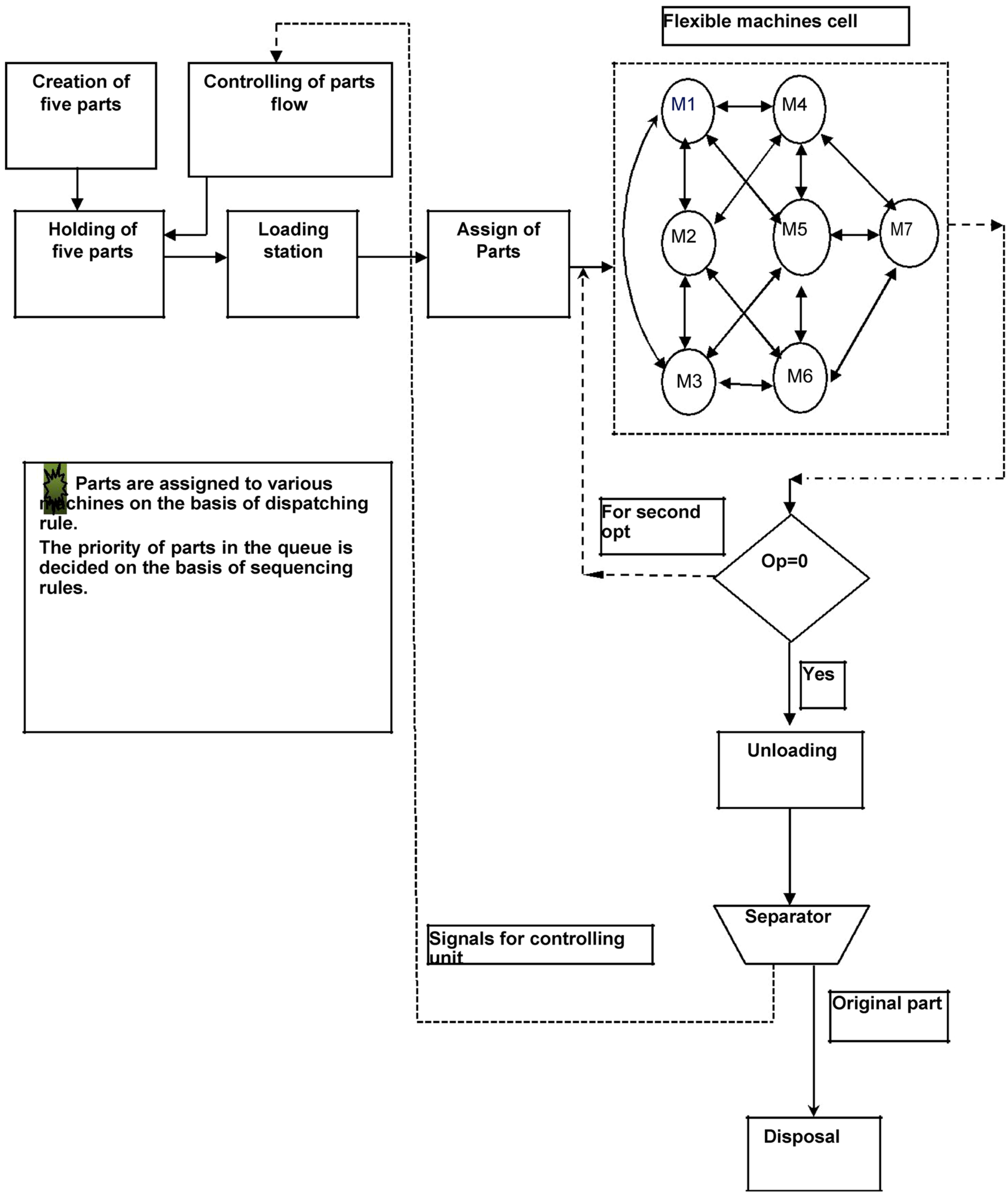

Fig. 11 Flowchart showing material and information flow in the developed system

loading and unloading strategies. These are L1UL1, L1UL5, L5UL5, and L5UL1. These systems are run at four level of routing flexibility i.e., RF = 0, RF = 1, RF = 2, and RF = FULL. In addition, the systems are run at MINQ/FCFS and MINQ/SPT as the combination of dispatching and sequencing rules. Further study is done on the system which gives the best performance with respect to different performance measures.

Impact of Routing Flexibility on MST for All System Configurations

In this section we present the results of experiment carried out to observe the impact of routing flexibility on system configurations based on loading and unloading strategies. The performance measure considered being makespan time. Figure 16 shows the relationship between MST and

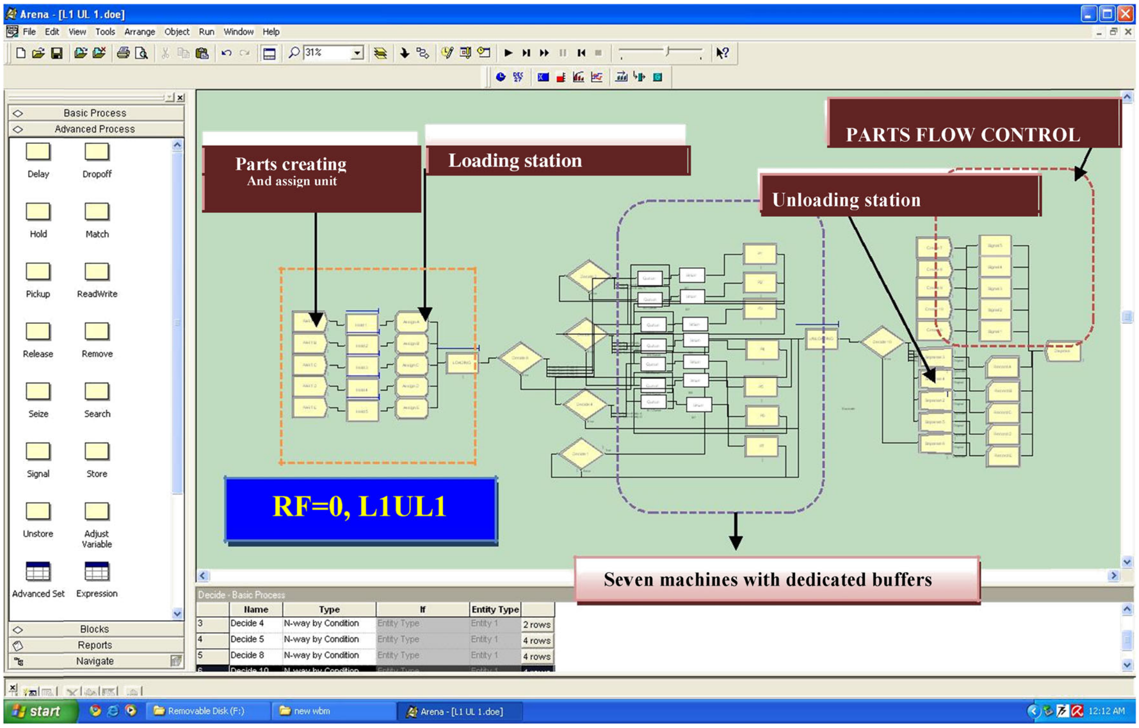

Fig. 12 Simulation model for L1ULI and RF = 0

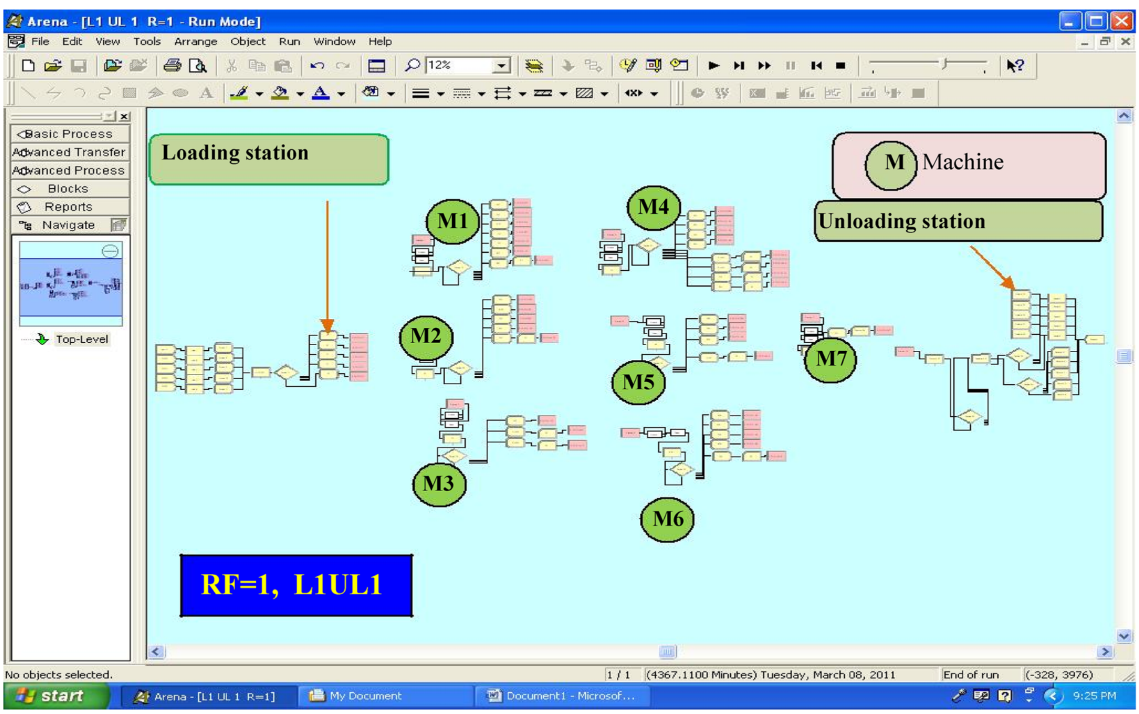

Fig. 13 Simulation model for L1ULI and RF = 1

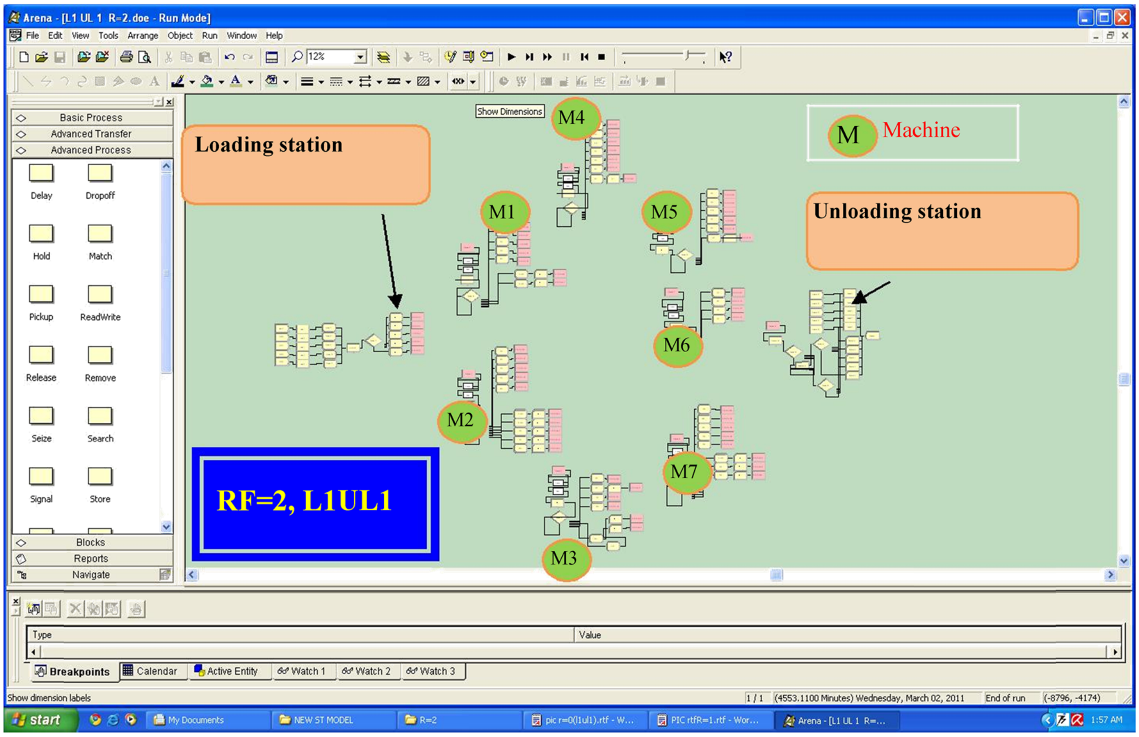

Fig. 14 Simulation model for L1ULI and RF = 2

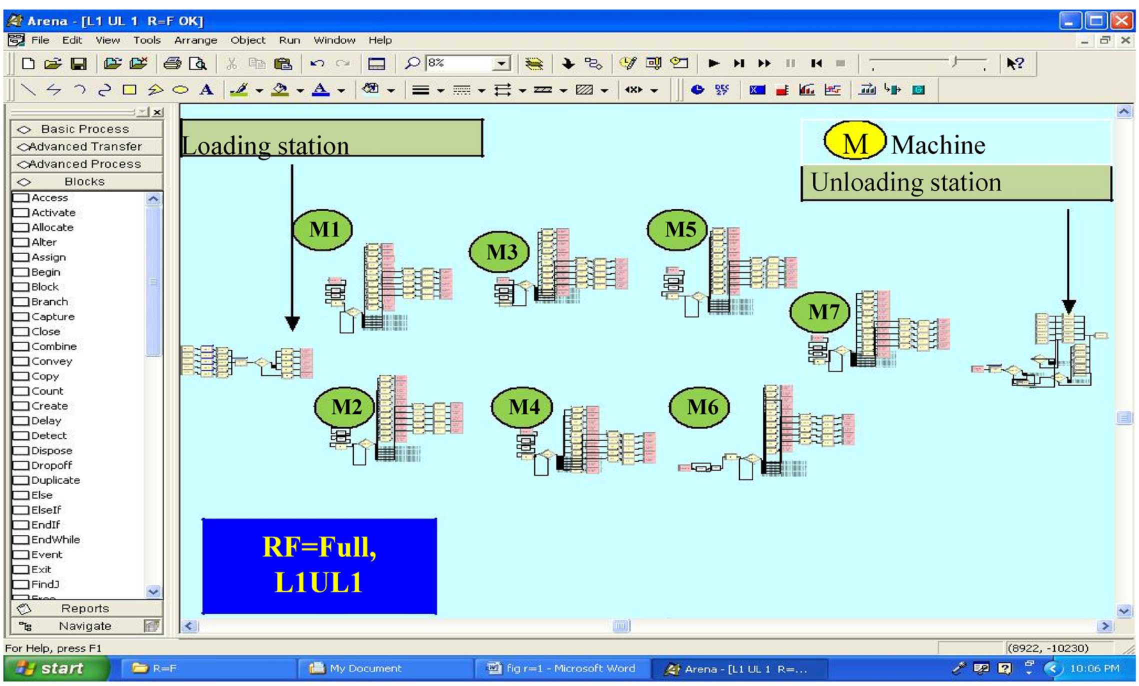

Fig. 15 Simulation model for L1ULI and RF = Full

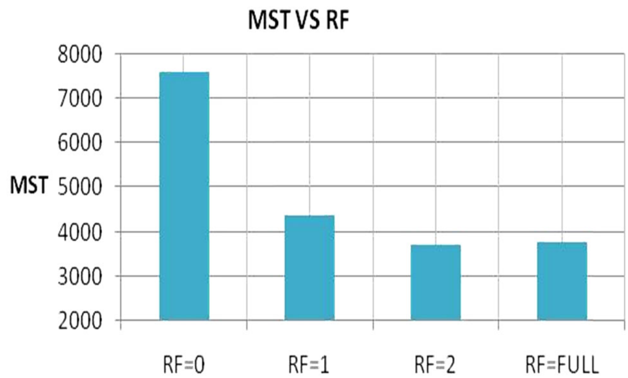

Fig. 16 Impact of RF on MST for L1UL1

Table 5 Percentage reduction in MST with increase in RF for L1UL1

RF	MST	% Reduction from RF = 0 level
RF = 0	7596	
RF = 1	4367	42.50
RF = 2	3728	50.90
RF = FULL	3647	51.98

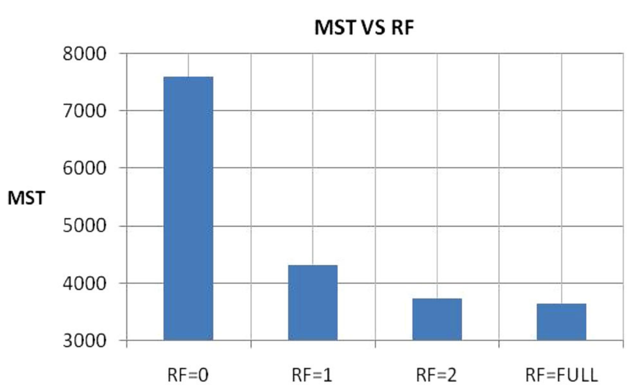

Fig. 17 Impact of RF on MST for L1UL5

Table 6 Percentage reduction in MST with increase in RF for L1UL5

RF	MST	% Reduction from RF = 0 level
RF = 0	7596	–
RF = 1	4320	43.12
RF = 2	3728	50.90
RF = FULL	3647	51.90

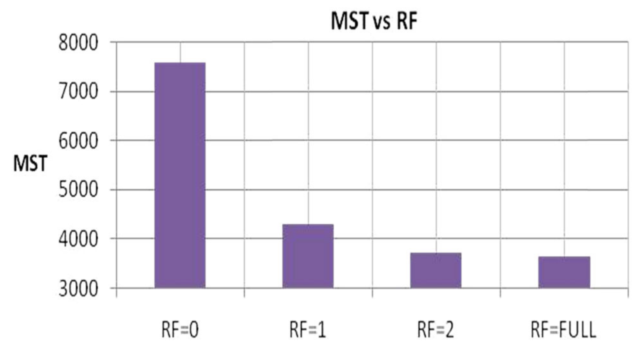

Fig. 18 Impact of RF on MST for L5UL5

Table 7 Percentage reduction in MST with increase in RF for L5UL5

RF		% Reduction from RF = 0 level
RF = 0	7599	–
RF = 1	4306	43.30
RF = 2	3707	51.20
RF = FULL	3647	51.96

level of routing flexibility for a system having single loading and single unloading station (L1UL1). The MST is obtained for 500 parts. The combination of dispatching and sequencing rule is MINQ/SPT. Total number of parts in the system at any time is 20 and buffer size at individual machine is 20. It is seen from the graph that MST decreases with the increase in the level of routing flexibility. This is due to the fact that with increase in the level of routing flexibility the number of machines also increases for the same operation. It is observed from Table 5 that the maximum reduction in MST occurs when RF increases from 0 to 1 (42.50 %). Thereafter increase in the level of routing flexibility has minimum impact on the MST performance.

Figure 17 also shows the relationship between make-span time and level of routing flexibility for system having single loading station and five unloading stations (L1UL5). The makespan time is obtained for 500 parts. The combination of dispatching and sequencing rule is MINQ/SPT. Total number of parts in the system at any time is 20 and buffer size at individual machine is 20. It is seen from the graph that MST decreases with the increase in the level of routing flexibility. This is due to the fact that with increase in the level of routing flexibility the number of machines also increases for the same operation. It is observed from Table 6 that the maximum reduction in MST occurs when

RF increases from 0 to 1 (43.12 %). Thereafter increase in the level of routing flexibility has minimum impact on the makespan performance.

Figure 18 shows the relationship between makespan time and level of routing flexibility for system having five loading and five unloading stations (L5UL5). The makespan time is obtained for 500 parts. The combination of dispatching and sequencing rule is MINQ/SPT. Total number of parts in the system at any time is 20 and buffer size at individual machine is 20. It is seen from the graph that MST decreases with the increase in the level of routing flexibility. This is due to the fact that with increase in the level of routing flexibility the number of machines also increases for the same operation. It is observed from Table 7 that the maximum reduction in MST occurs when RF increases from 0 to 1 (43.30 %). Thereafter increase in the level of routing flexibility has minimum impact on the makespan performance.

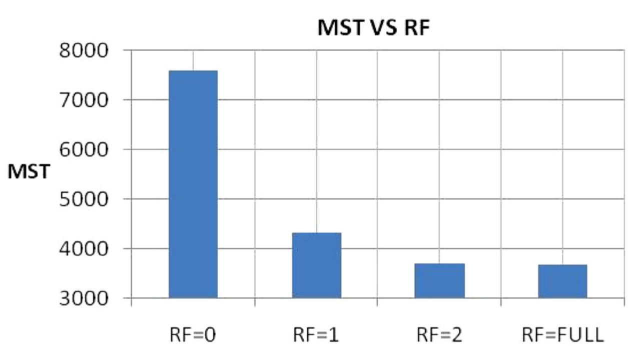

Fig. 19 Impact of RF on MST for L5UL1

Table 8 Percentage reduction in MST with increase in RF for L5UL1

RF	MST	% Reduction from RF = 0 level
RF = 0	7599	–
RF = 1	4321	43.10
RF = 2	3707	51.22
RF = FULL	3689	51.45

Figure 19 shows the relationship between makespan time and level of routing flexibility for system having five loading stations and one loading stations (L5UL1). The makespan time is obtained for 500 parts. The combination of dispatching and sequencing rule is MINQ/SPT. Total number of parts in the system at any time is 20 and buffer size at individual machine is 20. It is seen from the graph that MST decreases with the increase in the level of routing flexibility. This is due to the fact that with increase in the level of routing flexibility the number of machines also increases for the same operation. It is observed from Table 8 that the maximum reduction in MST occurs when RF increases from 0 to 1 (43.10 %). Thereafter increase in the level of routing flexibility has minimum impact on the makespan performance.

Table 9 shows the comparative studies of all the four different types of system models. We make the following observations from Table 9.

At RF = 0, the makespan performance is L5UL5 = L5UL1 > L1UL1 = L1UL5
At RF = 1, the makespan performance is L5UL5 > L1UL5 > L5UL1 > L1UL1
At RF = 2, the makespan performance is L5UL5 > L5UL5 = L1UL5 = L1UL1
At RF = FULL, the makespan performance is L1UL1 > L5UL5 > L1UL5 > L5UL5

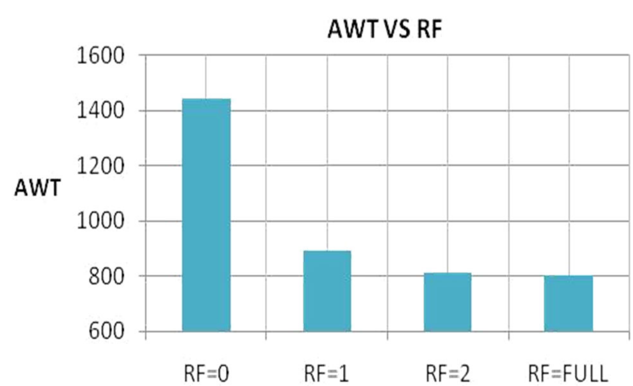

Fig. 20 Impact of RF on AWT for L1UL1

Table 9 Comparison among different system models fro MST

Level of routing flexibility	Model = L1UL1		Model = L1UL5		Model = L5UL5		Model = L5UL1	
	MST	% Reduction from RF = 0	MST	% Reduction from RF = 0	MST	% Reduction from RF = 0	MST	% Reduction from RF = 0
RF = 0	7596	–	7596	–	7599	–	7599	–
RF = 1	4367	42.50	4320	43.12	4306	43.30	4321	43.10
RF = 2	3728	50.90	3728	50.90	3707	51.20	3707	51.22
RF = FULL	3647	51.98	3647	51.90	3647	51.96	3689	51.45

Table 10 Percentage reduction in AWT with increase in RF for L1UL1

RF	AWT	% Reduction from each level
RF = 0	1443	–
RF = 1	892	38.18
RF = 2	811	9.19
RF = FULL	806	0.74

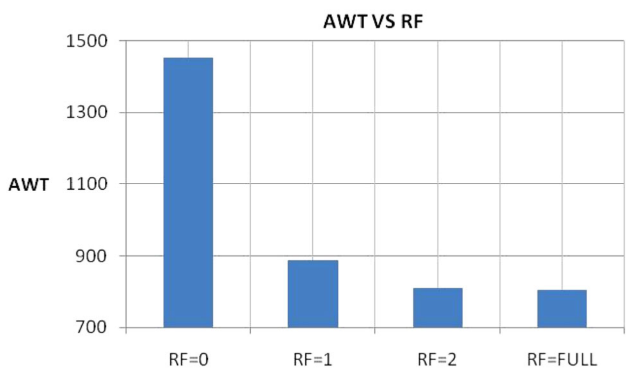

Fig. 21 Impact of RF on AWT for L1UL5

Hence we conclude that maximum reduction in MST occurs when routing flexibility level increases from 0 to 1 for all the system models. However, each of the models gives different MST performance at different levels of routing flexibility. In the next section, we discuss the average waiting time of the parts in the queue at different levels of routing flexibility for all the system models.

Impact of Routing Flexibility on AWT for Different System Configuration

Figure 20 shows the relationship between waiting time and level of routing flexibility. The AWT is obtained for 500 parts. The combination of dispatching and sequencing rule is MINQ/SPT. Total number of parts in the system at any time is 20 and buffer size at individual machine is 20.

It is seen from the graph that AWT decreases with the increase in the level of routing flexibility. This is due to the fact that with increase in the level of routing flexibility the number of machines also increases for the same operation. This helps in reducing the average waiting time of all the parts in the system. It is also observed from Table 10 that the maximum reduction in AWT occurs when RF increases from 0 to 1 is 38.18 %, from RF = 1 to RF = 2 is 9.19 % and from RF = 2 to RF = Full is 0.74 %. Hence we can conclude that the maximum reduction in the AWT is obtained when routing flexibility level increases from 0 to 1. Thereafter, increase in the level of routing flexibility has minimum impact on the average waiting time performance.

Table 11 Percentage reduction in AWT with increase in RF for L1UL5

RF	AWT	% Reduction from each level
RF = 0	1454	–
RF = 1	889	38.85
RF = 2	811	08.70
RF = FULL	805	00.71

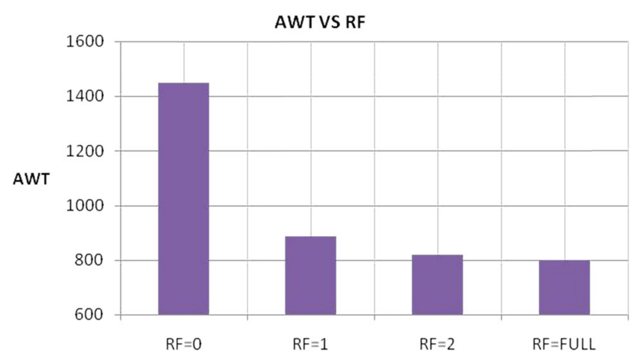

Fig. 22 Impact of RF on AWT for L5UL5

Figure 21 also shows the relationship between waiting time and level of routing flexibility. The AWT is obtained for 500 parts. The combination of dispatching and sequencing rule is MINQ/SPT. Total number of parts in the system at any time is 20 and buffer size at individual machine is 20. It is seen from the graph that AWT decreases with the increase in the level of routing flexibility. This is due to the fact that with increase in the level of routing flexibility the number of machines also increases for the same operation. This helps in reducing the average waiting time of all the parts in the system. It is also observed from Table 11 that the maximum reduction in AWT occurs when RF increases from 0 to 1 is 38.85 %, from RF = 1 to RF = 2 is 8.7 % and from RF = 2 to RF = Full is 0.71 %.

Hence we can conclude that the maximum reduction in the AWT is obtained when routing flexibility level increases from 0 to 1. Thereafter increase in the level of routing flexibility has minimum impact on the average waiting time performance.

Figure 22 also shows the relationship between waiting time and level of routing flexibility. The AWT is obtained for 500 parts. The combination of dispatching and sequencing rule is MINQ/SPT. Total number of parts in the system at any time is 20 and buffer size at individual machine is 20. It is seen from the graph that AWT decreases with the increase in the level of routing flexibility. This is due to the fact that with increase in the level of routing flexibility the number of machines also increases for the same operation. This helps in reducing the average waiting time of all the parts in the system. It is also observed from Table 12 that the maximum reduction in AWT occurs when RF increases from 0 to 1 is 38.85 %, from RF = 1 to RF = 2 is 7.7 % and from RF = 2 to RF = Full is 2.2 %. Hence we can conclude that the maximum reduction in the AWT is obtained when routing flexibility level increases from 0 to 1. Thereafter increase in the level of routing flexibility has minimum impact on the average waiting time performance.

Table 12 Percentage reduction in AWT with increase in RF for L5UL5

RF	AWT	% Reduction from each level
RF = 0	1450	–
RF = 1	887	38.8
RF = 2	818	7.70
RF = FULL	800	2.20

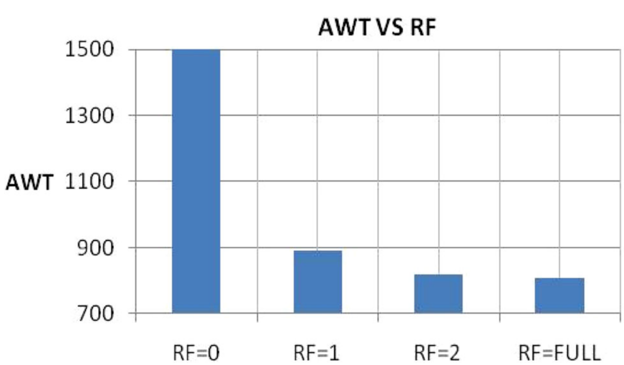

Fig. 23 Impact of RF on AWT for L5UL1

Table 13 Percentage reduction in AWT with increase in RF for L5UL5

RF	AWT	% Reduction from each level
RF = 0	1528	–
RF = 1	889	41.80
RF = 2	818	7.90
RF = FULL	806	1.40

Figure 23 also shows the relationship between waiting time and level of routing flexibility. The AWT is obtained for 500 parts. The combination of dispatching and sequencing rule is MINQ/SPT. Total number of parts in the system at any time is 20 and buffer size at individual machine is 20. It is seen from the graph that AWT decreases with the increase in the level of routing flexibility. This is due to the fact that with increase in the level of routing flexibility the number of machines also increases for the same operation. This helps in reducing the average waiting time of all the parts in the system. It is also observed from Table 13 that the maximum reduction in AWT occurs when RF increases from 0 to 1 is 41.80 %, from RF = 1 to RF = 2 is 7.90 % and from RF = 2 to RF = Full is 1.4 %. Hence we can conclude that the maximum reduction in the AWT is obtained when routing flexibility level increases from 0 to 1. Thereafter increase in the level of routing flexibility has minimum impact on the average waiting time performance.

Table 14 shows the comparative studies of all the four different types of system models. We make the following observations from Table 14. It is seen that maximum reduction in AWT occurs when routing flexibility level increases from 0 to 1 for all the system models. In addition different models give different AWT performance at different levels of routing flexibility.

At RF = 0, the AWT performance is L5UL1 > L1UL5 > L5UL5 > L1UL1
At RF = 1, the AWT performance is L1UL1 > L1UL5 = L5UL1 > L5UL5
At RF = 2, the AWT performance is L5UL5 = L5UL1 > L1UL5 = L1UL1
At RF = FULL, the AWT performance is L1UL1 = L5UL1 > L1UL5 > L5UL5

Table 14 Comparison among different system models for AWT

Routing flexibility	Model = L1UL1		Model = L1UL5		Model = L5UL5		Model = L5UL1	
	AWT	% Reduction	AWT	% Reduction	AWT	% Reduction	AWT	% Reduction
RF = 0	1443	–	1454	–	1450	–	1528	–
RF = 1	892	38.18	889	38.85	887	38.80	889	41.80
RF = 2	811	9.19	811	08.70	818	07.70	818	7.90
RF = FULL	806	0.74	805	00.71	800	02.20	806	1.40

Table 15 Comparison of performance of all the models at RF = 1

Models	MST	AWT
LIULI	4	1
LIUL5	2	2
L5UL5	**1**	**1**
L5ULI	3	2

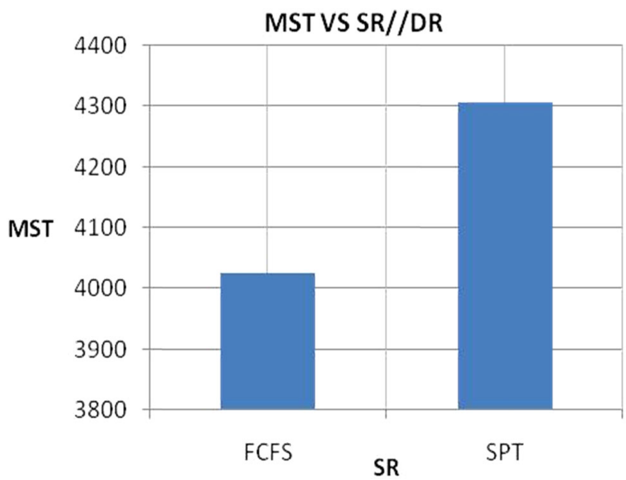

Fig. 24 Impact of SR on MST for L5UL5

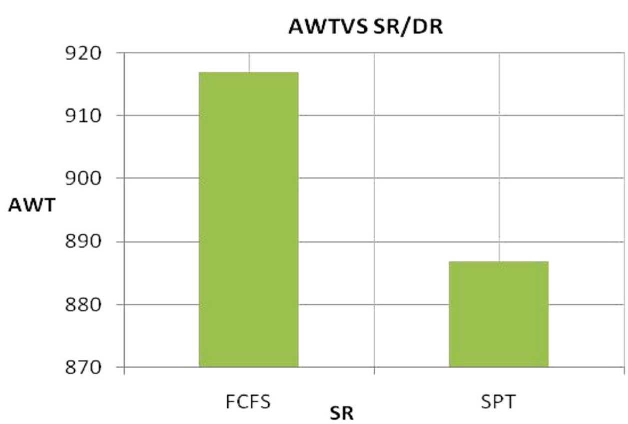

Fig. 25 Impact of SR on AWT for L5UL5

From the above studies, we observe that there is maximum percentage reduction in MST or AWT occurs when the routing flexibility level increases from 0 to 1. Therefore, comparison of the performance of different system models is made at RF = 1 (see Table 15). After comparing the performance of the system at RF = 1 for all the performance measures it is concluded that model L5UL5 is the best model i.e., system having five dedicated loading and unloading stations for the respective parts. Some more studies are conducted on model L5UL5 for further evaluation of the performance of the system. We will study the effects of sequencing rules, change in buffer size and number of parts on the system performance.

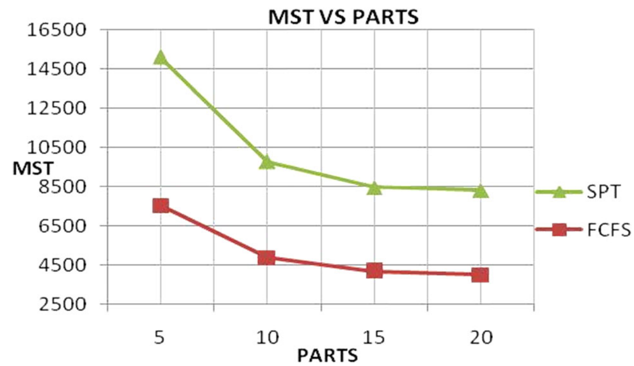

Fig. 26 Impact of number of parts on MST for L5UL5

Table 16 MST at different number of parts

No. of parts	FCFS/MINQ	SPT/MINQ
5	7562	7562
10	4883	4907
15	4206	4276
20	4027	4306

Effect of Different Manufacturing Factors on System Configuration (L5UL5)

From the above studies and Table 15 we have identified that system model L5UL5 that is system having five loading and five unloading stations perform best with respect to all the performance measures. Additional studies are performed on this system. We will discuss the results in the following sections.

Effect of Sequencing Rules on System Model (L5UL5) at RF = 1

In this study we evaluate the performance of system model (L5UL5) operating with buffer size of 20 and 20 parts in the system. The makespan time and average waiting time are collected for 500 parts in the system. Figure 24 shows the graph between MST and sequencing rules. The graph trend shows that with SPT as sequencing rule makespan time is 4306. This is more than that obtained with FCFS sequencing rule (4027). Figure 25 shows the graph drawn between average waiting time and sequencing rules. It is seen that with SPT as sequencing rule the average waiting time is 887. This is less than that obtained at FCFS sequencing rule (917).

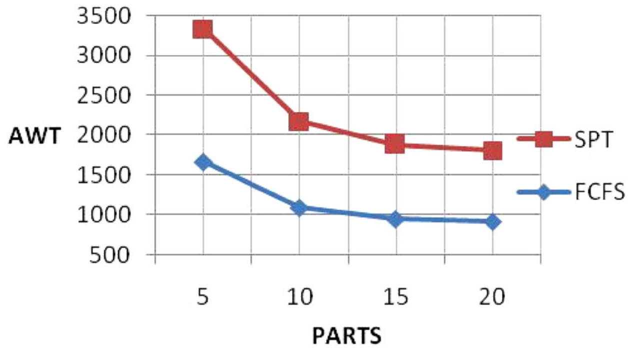

Fig. 27 Impact of number of parts on AWT for L5UL5

Table 17 AWT at different number of parts

No. of parts	FCFS	SPT
5	1666	1666
10	1092	1081
15	953	921
20	917	887

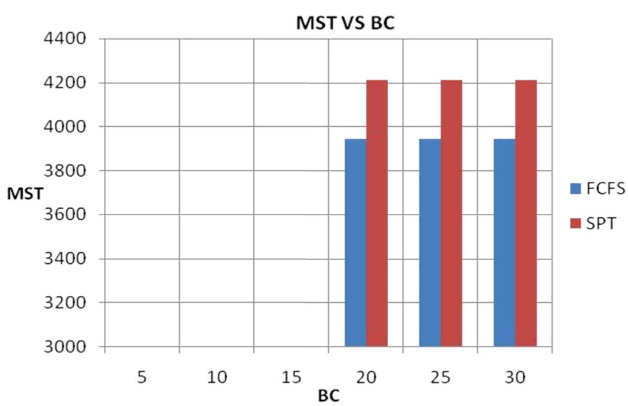

Fig. 28 Impact of buffer size on MST for model L5UL5

Table 18 MST at different BC

Buffer size	FCFS	SPT
5	Block	Block
10	Block	Block
15	Block	Block
20	3945	4212
25	3945	4212
30	3945	4212

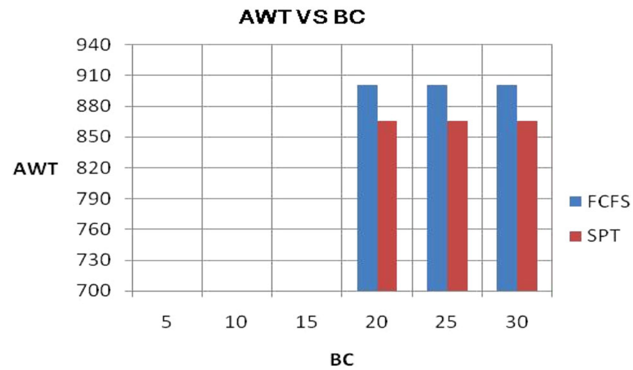

Fig. 29 Impact of buffer size on AWT for model L5UL5

Table 19 AWT at different BC

Buffer size	FCFS	SPT
5	Block	Block
10	Block	Block
15	Block	Block
20	901	866
25	901	866
30	901	866

Effect of Number of Parts in the System Model L5UL5 at RF = 1

Figure 26 shows the relationship between number of parts and makespan time for model L5UL5. The capacity of the buffer is to hold 20 parts at a time. It is observed that as parts are increased makespan time decreases. But further it is found that decrement is more in FCFS rather than in SPT sequencing rule. This is shown in Table 16. A very significant decrement is observed at part number 10 in both sequencing rules. On further increasing the number of parts, no significant decrement takes place in MST.

Figure 27 is the graph between parts and average waiting time, for model L5UL5. The capacity of the buffer is to hold 20 parts at a time it is observed that as parts are increased average waiting time decreases. But it is found that decrement is more in FCFS rather can in SPT sequencing rule. This is shown in Table 17. A very significant decrement is observed when number of parts in the system is 10 in both sequencing rule. On further increasing the number of part there no significant decrement in AWT.

Table 20 ANOVA analysis with MST as performance

Source	Type III sum of squares	df	Mean square	F	Sig.
NP	406244715	3	135414905.0	87.804	.000
BC	46710125.2	3	15570041.74	10.107	.000
RF	90956414.8	3	30318804.92	19.681	.000
SC	1642924.074	3	547641.358	0.356	.785
Error	374336107	243	1540477.807		
Total	7996075201	256			

Dependent variable: MST, R Squared = .593 (Adjusted R Squared = .573)

Table 21 ANOVA analysis with AWT as performance

Source	Type III sum of squares	df	Mean square	F	Sig.
SC	171772.130	3	57257.377	.977	.404
NP	26859722.545	3	8953240.848	152.745	.000
BC	1995844.722	3	665281.574	11.350	.000
RF	1085775.690	3	361925.230	6.175	.000
Error	14243621.686	243	58615.727		
Total	370270860.5	256			

Dependent variable: AWT, R Squared = .679 (Adjusted R Squared = .663)

Effect of Buffer Size on the System Model L5UL5 at RF = 1

Figure 28 shows the graph between MST and buffer capacity for 19 each parts at different buffer size. Thegraph shows that at buffer capacity 5–15 system gets blocked due to unavailability of the space in the buffer. This is shown in Table 18. As we increase buffer size to 20, the model starts to execute and on further increasing the buffer size the MST becomes constant.

Figure 29 shows the relationship between average waiting time and buffer capacity for 19 each parts at different buffer size. The figure shows that at buffer capacity 5–15, system gets blocked due unavailability of the space in the buffer. This is shown in Table 19. As we increase buffer size 20, the model start to execute and on further increasing the buffer size the average waiting time is constant.

Analysis of Results Based on ANOVA

Analysis of variance (ANOVA) is a statistical technique that tests the significant difference of the impact of individual factors of the system. In this paper, ANOVA technique was used to find the impact of (NP, BC, RF and SC) on MST and AWT in queue. ANOVA analysis is carried out using SPSS-10 statistical package. The test is conducted at confidence level 0.05. Based on the ANOVA results given in Table 20, it is observed that number of parts, buffer capacity and routing flexibility have significant impact on MST performance of the system. System configurations based on loading and unloading strategy is found to be less significant when MST is considered to be the performance measure. It is also observed that number of parts has the maximum effect followed by routing flexibility, buffer capacity and system configurations respectively.

From Table 21 it is observed that for AWT as performance measure, number of parts, buffer capacity and routing flexibility have significant effect whereas system configuration based on loading and unloading strategies are less significant. It is also observed that number of parts have the maximum effect followed by buffer capacity, system configurations and routing flexibility respectively.

Conclusion

In this paper, a methodology based on the computer simulation procedure is proposed that can be used by system designers to gain quick insights into the behaviour of flexible manufacturing system under given manufacturing parameters such as loading and unloading strategies, routing flexibility, buffer size, number of parts in the system at a time, sequencing and dispatching rules. It is suggested that different loading and unloading strategies will have different effect on the system performance. Also the role of increasing routing flexibility should not be taken for granted as a direction for performance improvement as shown in this work. For the conditions assumed in this paper, we observe that there is an optimal flexibility level, beyond which the performance is seen to deteriorate. The proposed methodology can further help system designers and controllers not only in setting priorities to focus on the assumed manufacturing factors but also in highlighting likely factor-level combinations that would result in near-optimal shop performance. We also observe that there is some impact of sequencing and dispatching rules, buffer size and number of parts on the system configuration having five loading and five unloading stations.

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Key Questions

1. How material handling system improves routing flexibility in manufacturing systems?
2. State different manufacturing strategies that can enrich flexibility in manufacturing system.
3. What are different types of manufacturing flexibility?

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