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Real-Time Manipulation of Alternative Routeings in Flexible Manufacturing Systems: A Simulation Study

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This paper presents the results of a simulation study of a typical flexible manufacturing system (FMS) that has routeing flexibility. The objective is this study is to test the effectiveness of the dissimilarity maximisation method (DMM) for real-time FMS scheduling. DMM is an alternative process plan selection method developed for routeing selection in off-line FMS scheduling. An integrated framework that consists of a computer simulation model, which mimics a physical system, a C++ module, and a linear program solver is used to evaluate the effects of various operational control rules on the system performance. The hypothetical FMS employed in this study consists of seven machining centres, a loading and an unloading area, and six different part types. Owing to the existence of identical machining centres in the system, the part types have alternative routeings. For selecting an incoming part and later routeing it to a machining centre for its next operation, three control rules, namely, first-in first-out/first available (FIFO/FA), equal probability loading (EPL), and dissimilarity maximisation method/first-in first-out (DMM/FIFO) are used. In this study, DMM is

1. *Used as a real-time decision-making tool to select routeings for the parts that are in the system.*
2. *Tested and benchmarked against FIFO/FA and EPL.*

The results show that DMM/FIFO outperforms FIFO/FA and EPL on system throughput. Other measures such as average waiting time, average transportation time, and percentage utilisation rates are also investigated to provide insights for the effectiveness of the DMM rule for real-time FMS control applications.

Keywords: Alternative routeing; Dispatching rules; Flexible manufacturing systems; Flexible process planning; Real-time FMS control; Simulation

1. Introduction

Flexible manufacturing systems (FMS) consist of a computer controlled and integrated configuration of numerically controlled (NC) machine tools inter-linked with automated material handling systems. Combining the merits of job shop production and flow shop production, FMS provides a promising technology for mid-volume and mid-variety production [1]. Since each machine in a FMS is quite versatile and capable of performing many different operations, the system can machine several part types simultaneously. Owing to the capability of CNC machines, each part may have alternative routeings in the system. Since the selected routeings affect the congestion in the system, selecting the most appropriate routeing for each part becomes a critical issue and has a high impact on the system performance. The complexity due to the random part arrivals makes the real-time routeing selection and control problems multidimensional in nature.

In recent years, it has become important for manufacturing systems to be able to respond to dynamic changes in demand and product mix. Thus, effective management of existing flexibility in manufacturing systems has become a critical issue for survival in the 21st century. From this stand point, flexible manufacturing technology provides various benefits such as increased machine utilisation, reduced work-in-process inventory, increased productivity, reduced number of tools, reduced lead times, less floor space, and reduced set-up costs. On the other hand, there are various difficulties encountered through the design, planning, scheduling, and control of flexible manufacturing systems, one of which is the proper use of the existing flexibility in the system in order to enhance the system performance. From the standpoint of real-time FMS scheduling and control, this study focuses on the impact of alternative routeings on system throughput. The lack of real-time FMS scheduling methods that effectively use operation and routeing flexibility is the driving force behind this paper. The objective of this study is to test the effectiveness of the dissimilarity maximisation method (DMM) for real-time FMS scheduling via simulation. DMM is an alternative process plan selection

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method developed for routeing selection in off-line scheduling [1].

This paper employs an integrated framework that consists of a simulation model, a C++ module, and a linear program solver to evaluate the effects of various operational control rules on the performance of a flexible manufacturing system that consists of seven machining centres, a loading and an unloading area, and six different part types. The simulation model mimics a real FMS. Each part type has alternative routeings owing to the alternative machining centres in the system. Three control rules, namely first-in first-out/first available (FIFO/FA), equal probability loading (EPL), and dissimilarity maximisation method/first-in first-out (DMM/FIFO) are used.

This paper is organised as follows. The related literature is given in Section 2. Section 3 describes the simulation model developed in this study. Operational control rules are explained in Section 4. The integrated framework that uses DMM as a routeing selection tool is elaborated in Section 5. Simulation results are given in Section 6. Finally, the conclusions and recommendations for future work are presented in Section 7.

2. Literature Review

Scheduling includes time allocation on manufacturing resources for the execution of operations at the machining level. Scheduling decisions include:

1. Determining job release.
2. Starting and completion times of operations.
3. Contingency plans in case of unexpected interruptions such as machine breakdowns [2].

The general scheduling problem is a NP-hard type of problem [3]. One of the earliest studies on the FMS scheduling problem is the work of Nof et al.[4] who demonstrated the importance of scheduling decisions for system performance. From a traditional viewpoint, scheduling is an off-line activity where operations that are known prior to production are scheduled before the production starts. Various approaches, ranging from operations research to artificial intelligence, exist in the area of off-line scheduling [5,6]. The potential problem with generating off-line schedules is that any off-line schedule is almost immediately subject to inevitable changes on the shop floor owing to rescheduling factors such as machine breakdowns, shortage of materials, cancellation of an order, due date changes and so on. These factors make rescheduling mandatory. From this perspective, the traditional off-line scheduling approaches cause increased waiting times, increased work-in-process, low equipment utilisation, and eventually degrade the system performance [7–10]. The assumptions made during the schedule generation make off-line schedules hard to implement as generated. These idealised conditions are [5,11] as follows:

1. Only "part scheduling" (such as *n* jobs, *m* machines) is considered.
2. Set-up times are neglected.
3. Buffer capacities are assumed to be infinite.
4. Material handling devices are considered to be always available and have an infinite capacity.
5. Part and tool transportation times are neglected.
6. Machine breakdowns are not considered.
7. Cutting tool allocation related to the capacity of the tool magazines is neglected, and cutting tools are assumed to have infinite lives.
8. Alternative routeing is rarely considered.

Comprehensive surveys of research in off-line scheduling of FMS can be found in [5,6,12–14]. Toncich [15] presents a methodology, called CHESS, for resolving scheduling and dispatch problems in FMSs. The CHESS philosophy allows parts of different types to enter the system at the fastest rate allowable by the loading station, but sequences the input in such a way that when the parts pass through the system they will never have to contend for the same resources at the same time. Sabuncuoglu and Karabuk [2] present a heuristic based on filtered beam search for off-line scheduling. Beam search is a fast and approximate branch- and-bound method, which operates on a search tree. This partial enumeration technique uses a heuristic to estimate a certain number of best paths, permanently pruning the rest. This algorithm has a deadlock-resolution mechanism embedded as an integral part of the proposed algorithm. Reveliotis [16] addresses the problem of "optimal" job rerouteing in case of operational contingencies such as machine breakdowns and the arrival of expedient jobs. He tries to solve the problem using algorithms, which use one-step look-ahead deadlock-avoidance policies. Saygin and Kilic [1] present a framework to integrate flexible process plans with off-line scheduling in FMS. They propose a concept, namely the dissimilarity maximisation method (DMM), for process plan selection in order to minimise the congestion in the system and, hence, improve the system throughput.

This method is used in this study as one of the operational control rules implemented in the simulation model for real-time control purposes. Ishii and Talavage [8] present a transient based real-time scheduling algorithm in FMS that selects a dispatching rule dynamically for a next short time period in order to respond to changes of system state. Chiu and Yih [9] develop a framework of dynamic scheduling that explores routeing flexibility and handles uncertainties in a distributed manufacturing environment under heterarchical control. Mamalis et al. [17] develop a control algorithm, which considers the real-time use of alternative machine tools and/or alternative control strategies in order to optimise a given criterion. Byrne and Chutima [18] consider the real-time control of an FMS with full routeing flexibility. Ishii and Muraki [10] propose a generic on-line scheduling algorithm to handle a wide variety of uncertainties by using external scheduling algorithms. Their framework provides fundamental mechanisms to define schedule modification timing and a modification space according to changes of scheduling conditions, and dynamically modifies a schedule to minimise the effect of the changes by using adequate algorithms for each situation. Kuo and Hwang [19] develop a prototype of a real-time scheduling support system based on a model of human behaviour in scheduling tasks.

Several researchers propose various methods to accommodate flexibility into off-line scheduling in order to increase the system performance [1–3,20]. However, real-time scheduling has always remained a desirable but elusive goal [5,13]. Therefore, establishing an integrated real-time scheduling and control system, which would be responsive to the changes in the system status, is essential to improve the manufacturing system performance. Real-time scheduling and control of FMS have been popular research areas since the beginning of the 1980s when flexible manufacturing systems started gaining acceptance by the industrialised countries [6,21,22]. Although several analytical approaches, such as queuing network and mathematical programming, have been employed to solve FMS control problems, their inability to handle many realistic and dynamic features of FMS has always been an obstacle for eventual industrial applications. In addition, these models require a certain computing time to derive a solution, making them unsuitable for real-time control applications.

Owing to the lack of successful analytical methods, simulation has been used for real-time scheduling of FMS by several researchers. The framework of simulation based real-time FMS scheduling includes a simulation model linked to a physical system [5,13,22–24]. The simulation model works as a monitor, continuously refreshing the system states based on the progressing events in the real system. The system simulation model is activated when rescheduling of the FMS is needed, usually at the beginning of each planning horizon or when monitoring finds that the system is not performing as expected owing to system disturbance. When the simulation model is activated, deterministic discrete-event simulation may be conducted to evaluate a set of sound scheduling policies (usually dispatching rule combinations) for a short planning horizon. The scheduling policy with the best simulated performance in the time period is then applied to the physical system. The literature to date indicates that various efforts, such as the effect of the levels of detail in simulation models, differences in monitoring periods, and the self-reconfiguration capability of simulation models, have been made to develop a simulation-based FMS scheduler [7,23,25–27]. Knowledge-based on-line simulation systems [28–30] are considered to be effective approaches to the decision-making problem in an FMS environment. The integration of the expert system with an appropriate simulator has been the challenge for obtaining satisfactory results. Combination of genetic algorithms and simulation approaches seeking to obtain an appropriate production schedule efficiently under specific performance measures has also been studied [31]. Nevertheless, all of the aforementioned simulation-based frameworks are far from practical for use in real-time FMS scheduling. First, a typical FMS simulation effort requires the simultaneous evaluation of multiple scheduling policies. The complex structure of an FMS, along with the inherent large number of control policies, requires an excessive computational burden. As the scale of FMS increases, it is often found that simulation is extremely time consuming. This directly affects the degree to which a true "real-time" capability can be proclaimed. Secondly, research work to date indicates that discrete event simulation software is always used to develop the simulation model for the FMS, which obviously cannot provide a concurrent control capability. These shortfalls make the pure simulation-based scheduling framework infeasible for use in real FMS settings.

One of the major research fields related to FMS control is the use of various dispatching rules in simulation models. A dispatching rule (also referred to as scheduling, sequencing, or operational control rule) is used to select the next job to be processed from a set of jobs awaiting service, or to resolve a conflict in the case of an unexpected event in a manufacturing system. Exhaustive surveys on dispatching rules are provided in published literature [32,33]. A review of past literature [34–42] reveals very few general results. No dispatching rule has shown to have consistently outperformed all other rules under a variety of FMS configurations and operating conditions. The use of a "fixed" dispatching rule leads to a failure to address a dynamically changing manufacturing environment as in the case of FMS. Results of each study in the literature seem to be very much system dependent and should not be generalised carelessly for other systems. The importance of adopting different dispatching rules for dynamic system states becomes even more evident in FMSs because of the alternative routeing possibilities, and the need for increased coordination among the machines. It is believed that the manufacturing system performance can be further improved if dispatching rules can be dynamically selected and switched, based on real-time system status and information obtained continuously at a global level. A consensus among researchers is that a combination of simple dispatching rules or a combination of heuristics with simple dispatching rules works better than using individual static dispatching rules.

Many studies in real-time FMS scheduling and control area do not consider the influence of routeing flexibility [18,43]. Most of the studies that consider routeing flexibility in FMS focus on the problem of routeing selection prior to production [44–46]. This approach is not applicable to random-type FMS (also known as non-dedicated FMS [47]) in which no knowledge about incoming part types is available prior to production. Here, part routeings can be different, even for parts of the same type [47]. Thus, the control system of a random-type FMS is required to have the capability to adapt to the randomness in arrivals and other unexpected events in the system by effectively using operation and routeing flexibility in real-time [17,47,48]. There are many studies that have adopted this objective in the literature that employ dispatching rules as real-time decision-making tools for real-time FMS scheduling and control. On the other hand, most reported studies agree that the myopic nature of dispatching rules leads to poor schedules since the dispatching rules do not capture the global view of some system-level information [47,49,50]. In addition, the efficiency of dispatching rules depends on the system characteristics, operating conditions, and performance measures [51]. For an extensive review and classification of FMS scheduling procedures refer to Rachamadugu and Stecke [47] and Gargeya and Deane [52].

The lack of real-time FMS scheduling methods that effectively use operation and routeing flexibility is the driving force behind this paper. Operation flexibility of a part refers to its ability to be produced in a different way (i.e. different operations and/or different sequences of operations). Routeing flexibility of FMS is its ability to produce a part by alternative routes through the system. These definitions are adopted from Sethi and Sethi [53]. The objective of this study is to test the effectiveness of the dissimilarity maximisation method (DMM) for real-time FMS scheduling. DMM is selected for two reasons:

1. It captures the system-level information, thus it is not myopic in nature.
2. It makes use of operation and routeing flexibility.

3. FMS Model

The hypothetical FMS is assumed to be composed of:

1. Two vertical milling machines (VMC).
2. Two horizontal milling machines (HMC).
3. Two vertical turning centres (VTC).
4. One shaper (SHP).
5. One loading station (L).
6. One unloading station (UL).

The configuration of the FMS is shown in Fig. 1.

Each machine in the system has an input and output buffer with a capacity of two parts. The loading and unloading stations have capacities of two parts and one part, respectively. There are six part types. The alternative routes and processing times of each part type are shown in Table 1. The production ratio of the part types that are randomly arriving at the loading station is shown in Table 2.

The operation of the FMS model used in this study is based on the following assumptions:

1. The flexible process plan (i.e. alternative routeings) of each part type is known prior to production.
2. Processing times are known deterministically and they include tool change, set-up, and machining times.
3. The processing time of an operation is the same on the alternative machines identified for that operation.
4. Each machine can process only one part at a time.
5. A materials handling system is available at all times with infinite capacity (i.e. parts do not wait for the materials handling system).
6. Transportation time between machines is calculated based on the distance between machines.
7. Raw materials, tools, jigs, fixtures, etc. are present and released immediately when required.
8. No cancellation of orders.
9. Machines do not break down.

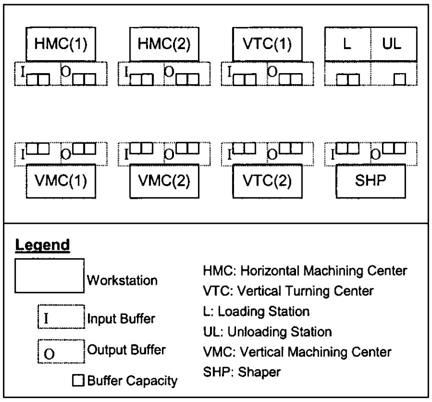


Fig. 1. Configuration of the FMS model.

4. Operational Control Rules

As shown in Fig. 1, the FMS considered for this study includes seven machining centres, a loading and an unloading station, and six different part types. Owing to the existence of alternative machining centres in the system, the part types have alternative routeings (see Table 1). Three simulation models with different operational control rules, namely first-in first-out/first available (FIFO/FA), equal probability loading (EPL), and dissimilarity maximisation method/first-in first-out (DMM/FIFO) are used for selecting an incoming part and later routeing it to a machining centre for its next operation.

First in First Out/First Available (FIFO/FA). This rule is used to select a part from a buffer or the loading station. The part that has arrived first is selected from among the parts awaiting service and delivered to the first available workstation among the alternative machines that are defined in its process plan.

Equal Probability Loading (EPL). This rule is used to deliver parts to workstations by maintaining a balanced loading among the alternative machines that are defined in the process plan of the part. Similar to FIFO/FA, the part that has arrived first is given a higher priority than the other parts awaiting service at the same location (i.e. input buffer, output buffer, or loading station).

Dissimilarity Maximisation Method (DMM). DMM is an alternative process plan selection method developed for routeing selection in off-line scheduling of FMS. With the goal of reducing the congestion in the system, the DMM concept is based on the objective of maximising the dissimilarities among the alternative routeings. DMM uses a dissimilarity coefficient, which is based on the types of machines in routeings, as a measure for routeing selection among alternative routeings. It selects a routeing for each part so that the cumulative dissimilarity, in terms of machine tool requirements, is maximised. In this scope, dissimilarity between routeings i and j is defined as follows:

$$D_{ij} = \frac{\text{Number of machine types that are not common in both routeings } i \text{ and } j}{\text{Total number of machine types in both routeings}}$$

An integer linear program formulation, as shown below, is developed to implement the DMM concept [1].

n = number of parts
q = number of routeings
D_{ij} = dissimilarity between routeings i and j
c_{ij} = 1 if routeing j belongs to part i. Otherwise, $c_{ij} = 0$
X_j = 1 if routeing j is selected. Otherwise, $X_j = 0$

Table 1. Alternative routeings of part types*.

Part type	LAPP number	Workstations								
		Loading	VTC 1	VTC 2	VMC 1	VMC 2	HMC 1	HMC 2	SHP	Unloading
A	1	1(3)	2(30)		3(20)					4(1.5)
	2	1(3)	2(30)			3(20)				4(1.5)
	3	1(3)		2(30)	3(20)					4(1.5)
	4	1(3)		2(30)		3(20)				4(1.5)
B	1	1(3)	2(20)		4(15)				3(1)	5(1.5)
	2	1(3)	2(20)			4(15)			3(1)	5(1.5)
	3	1(3)		2(20)	4(15)				3(1)	5(1.5)
	4	1(3)		2(20)		4(15)			3(1)	5(1.5)
C	1	1(3)	2(40)		3(25)					4(1.5)
	2	1(3)	2(40)			3(25)				4(1.5)
	3	1(3)		2(40)	3(25)					4(1.5)
	4	1(3)		2(40)		3(25)				4(1.5)
D	1	1(3)	2(40), 4(20)				5(35)		3(1)	6(1.5)
	2	1(3)	2(40)	4(20)				5(35)	3(1)	6(1.5)
	3	1(3)	2(40), 4(20)				5(35)		3(1)	6(1.5)
	4	1(3)	2(40)	4(20)				5(35)	3(1)	6(1.5)
	5	1(3)		2(40), 4(20)			5(35)		3(1)	6(1.5)
	6	1(3)	4(20)	2(40)				5(35)	3(1)	6(1.5)
	7	1(3)		2(40), 4(20)			5(35)		3(1)	6(1.5)
	8	1(3)	4(20)	2(40)					3(1)	6(1.5)
E	1	1(3)	2(25), 4(35)				5(50)		3(1)	6(1.5)
	2	1(3)	2(25)	4(35)				5(50)	3(1)	6(1.5)
	3	1(3)	2(25), 4(35)				5(50)		3(1)	6(1.5)
	4	1(3)	2(25)	4(35)				5(50)	3(1)	6(1.5)
	5	1(3)		2(25), 4(35)			5(50)		3(1)	6(1.5)
	6	1(3)	4(35)	2(25)				5(50)	3(1)	6(1.5)
	7	1(3)		2(25), 4(35)			5(50)		3(1)	6(1.5)
	8	1(3)	4(35)	2(25)					3(1)	6(1.5)
F	1	1(3)					2(40)			3(1.5)
	2	1(3)						2(40)		3(1.5)

*1. The cell entries under the workstations column denote the operation numbers for the specified routes.
2. The processing time (in min) of each operation is shown in parentheses next to the operation number.
3. Before machining, each part is first transferred to the input buffer of the machine. Similarly, the part is transferred to the output buffer of the machine after machining.

Table 2. Production ratio of part types.

Part type	Production ratio (arrival %)
A	17.0
B	17.0
C	17.0
D	21.0
E	20.0
F	8.0

The objective function maximises the total sum of dissimilarities between the selected routeings:

$$\text{Max} \sum_{j=1}^{q} \sum_{i=1}^{q} X_j D_{ij}$$

Subject to:

$$\sum_{j=1}^{q} C_{ij} X_j = 1 \quad \text{for all parts } i = 1, \ldots, n \tag{1}$$

Equation (1) requires that only one routeing will be selected for each part.

$$\sum_{j=1}^{q} X_j = n \quad \text{for all routeings } j = 1, \ldots, q \tag{2}$$

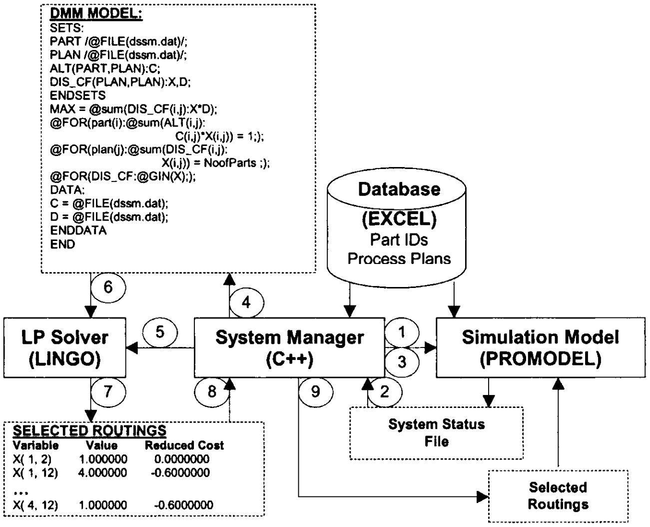
Equation (2) requires that the number of selected routeings will be equal to the number of parts.

5. DMM as a Real-Time Routeing Selection Tool

In this study, DMM is used as a real-time routeing selection tool. Similar to the other two rules, the part that has arrived first is given a higher priority than the other parts awaiting service at the same location (i.e. input buffer, output buffer, or loading station). Thus, the DMM-based compound control rule is called DMM/FIFO. The method is integrated within a software environment that acts as the FMS controller of the simulation model. The framework shown in Fig. 2 operates in the following manner: ① System manager invokes the Simulation model; ② ProModel generates the system status file during run time which is monitored by the system managers; ③ In case of a change in the system status (such as a new part entering the system), the system manager pauses the simulation and ④ generates the DMM model based on the current system status; ⑤ System manager runs Lingo; ⑥ Lingo reads the DMM model and ⑦ generates the selected process plans output file; ⑧ System manager reads the selected process plans output file, ⑨ updates the selected routeings file, and ① resumes simulation. The cycle repeats itself until the end of simulation period is reached.

As shown in Fig. 2, the DMM-based FMS controller integrates four software modules. They are as follows:

1. System manager.
2. Simulation model.
3. LP solver (DMM solver).
4. Database.



```
DMM MODEL:
SETS:
PART /@FILE(dssm.dat)/;
PLAN /@FILE(dssm.dat)/;
ALT(PART,PLAN):C;
DIS_CF(PLAN,PLAN):X,D;
ENDSETS
MAX = @sum(DIS_CF(i,j):X*D);
@FOR(part(i):@sum(ALT(i,j):
                    C(i,j)*X(i,j)) = 1;);
@FOR(plan(j):@sum(DIS_CF(i,j):
                  X(i,j)) = NoofParts ;);
@FOR(DIS_CF:@GIN(X););
DATA:
C = @FILE(dssm.dat);
D = @FILE(dssm.dat);
ENDDATA
END
```

```
SELECTED ROUTINGS
Variable     Value       Reduced Cost
X( 1, 2)     1.000000     0.0000000
X( 1, 12)    4.000000    -0.6000000
...
X( 4, 12)    1.000000     -0.6000000
```

Fig. 2. DMM-based FMS controller.

A detailed description of each module is given below.

1. System Manager. The system manager acts as a synchroniser by linking all three software modules within the developed framework. It is written in C++. It generates the DMM model based on the current system status, calculates the dissimilarity coefficients of the routeings, and then invokes the DMM solver. After the DMM solver finds the optimum solution (i.e. the best combination of routeings that has the maximum dissimilarity), the system manager reads the output file of the DMM solver and passes the new selected routeings to the simulation environment.

2. Simulation Module. Promodel is used to develop the FMS model described in Section 2. During run time, Promodel mimics the physical production environment. From its graphics, the user can see the parts moving in the system, being processed on machines, and exiting the system. The simulation module keeps track of the status of the parts that are in the system. When a part arrives at the loading station, moves from one location to another, or exits the system from the unloading station, the system status is updated and stored in the database. Promodel reads the selected routeings file to continue the simulation. Each move between machines on each routeing is assigned a variable. When a routeing is selected by the DMM solver, the system manager assigns the value "1" to each variable that corresponds to a move between any two machines on the selected routeing. The other variables of other alternative routeings are assigned the value of "0". Before a part is moved from one location to another, Promodel checks the variable that has a value of "1" and then routes the part along that selected routeing.

3. LP Solver (DMM Solver). Lingo is used to solve the DMM model that is generated by the system manager based on the current system status. The input to Lingo is the dissimilarity coefficients of the routeings of the parts that are currently in the system. The routeings that are selected by Lingo are processed by the system manager and stored in the database before Promodel is resumed.

4. Database. The database is developed in Excel. It stores process plans, routeings, variables, dissimilarity coefficients, and system status. All other three modules share the same database during run time.

6. Simulation Results

ProModel 4.1 is used to develop the FMS simulation model described in Section 2. The simulation experiments are conducted to compare the three operational control rules, namely first-in first-out/first available (FIFO/FA), equal probability loading (EPL), and the dissimilarity maximisation method/first-in first-out (DMM/FIFO), on the basis of production rate. These three operational control rules are simulated using the same product data and layout as shown in Table 1. Random arrival of six part types according to the production ratio shown in Table 2 with the interarrival time of 7 min is used. Using the same

Table 3. Production rate data.

Replications	Production rate (parts/20 h)		
	FIFO/FA	EPL	DMM
1	53	53	55
2	56	55	59
3	59	61	61
4	50	41	54
5	55	55	56
6	56	41	58
7	52	53	53
8	56	52	58
9	54	55	56

random number set, nine replications are made for each model. The production rates that are given in Table 3 are analysed by using the paired-*t* test with a 90% confidence interval. According to the analysis as shown in Table 4, DMM/FIFO outperforms FIFO/FA and EPL on the basis of production rate. It takes about 10–20 s to generate the DMM model and optimise the routeings on a Pentium II computer, thus it is possible to use this integrated framework for real-time FMS control purposes for the FMS model described in Fig. 1.

Although DMM/FIFO performs better than the other two operational control rules, the average waiting of parts in the DMM/FIFO model are not less than the other two rules, as shown in Fig. 3(*a*). EPL has the lowest and FIFO/FA has the highest average waiting time per part whereas the values of DMM/FIFO lie in between the two. Part D having eight alternative routeings has the lowest average waiting whereas part F with two alternative routeings has the highest waiting time. The parts in the DMM/FIFO model spend more time in transportation compared to FIFO/FA and EPL, as shown in Fig. 3(*b*). Although having both the highest production rate and the longest average transportation time seems to be contradictory, a careful examination of the DMM concept clarifies this situation. DMM-based real-time routeing selection is employed every time the system status changes. This means that each part having being assigned a routeing might be assigned a different routeing for the rest of its uncompleted operations when a new part enters the system (i.e. system status changes). In this case, the DMM-based controller re-routes some of the parts along the new routes that are selected by the DMM/FIFO model. This re-routeing leads to additional transportation time.

Another analysis is done by comparing the utilisation rates of the machines in the EPL, FIFO/FA, and DMM/FIFO models. Figure 4(*a*) shows the balanced loading achieved among the alternative machines in the system by using the EPL policy.

Table 4. Paired-*t* test results.

Comparison	90% confidence interval
[FIFO/FA − EPL]	[−0.75, +6.31]
[DMM − FIFO/FA]	[+1.54, +2.70]
[DMM − EPL]	[+1.10, +8.70]

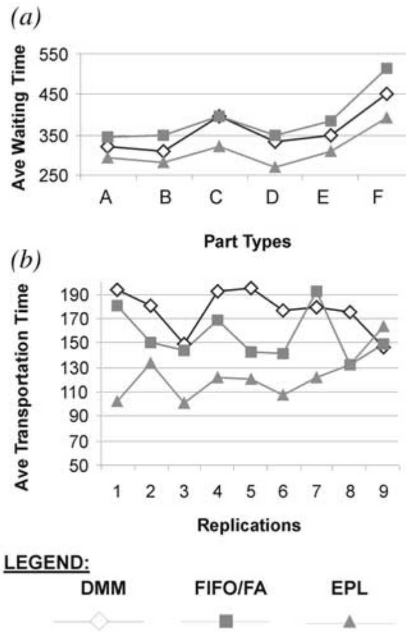


Fig. 3. Comparison of (*a*) average waiting time, and (*b*) average transportation time for DMM, FIFO/FA, and EPL.

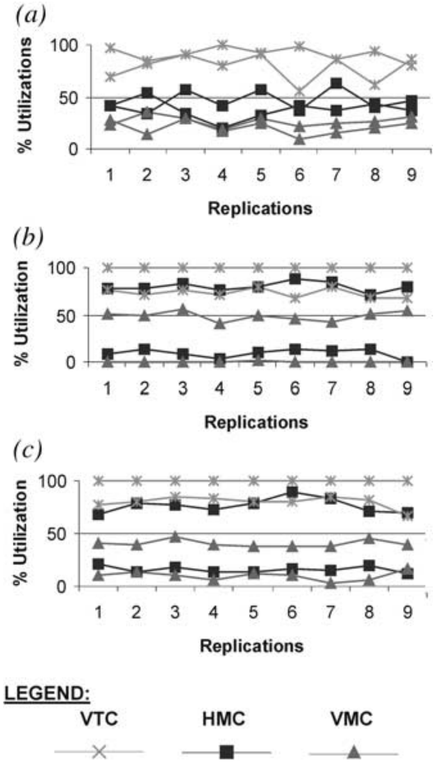


Fig. 4. Comparison of utilisation rates of alternative machines in (*a*) EPL, (*b*) FIFO/FA, and (*c*) DMM models.

In Fig. 4(*b*), it is shown that FIFO/FA leads to an unbalanced workload. The utilisation rates in DMM/FIFO, as plotted in Fig. 4(*c*), show a trend that lies between the values of FIFO/FA and EPL. This leads to the conclusion that a higher production rate does not necessarily mean a minimum waiting time for parts and a balanced loading among the alternative machines.

7. Conclusion

This paper presents an integrated framework that consists of a simulation model, a C++ module, and a linear program solver used to evaluate the effects of various operational control rules on the performance of a flexible manufacturing system that consists of seven machining centres, a loading and an unloading area, and six different part types. This study uses three operational control rules, namely first-in first-out/first available (FIFO/FA), equal probability loading (EPL), and dissimilarity maximisation method (DMM/FIFO) for selecting an incoming part and later routeing it to a machining centre for its next operation. Among these three control rules, DMM is an alternative process plan selection method proposed for the routeing selection in off-line scheduling of an FMS. In this study, DMM is:

1. Used as a real-time decision-making tool to select routeings for the parts that are in the system.
2. Tested and benchmarked against FIFO/FA and EPL.

The results show that DMM/FIFO outperforms FIFO/FA and EPL on the basis of system throughput. Compared to FIFO/FA and EPL policies, DMM/FIFO does not lead to:

1. Reduced waiting time of parts or
2. Balanced loading among the alternative machines.

In addition, it leads to higher transportation times owing to excessive re-routeing, yet it provides a higher production rate than that of the other two control policies, which shows that high production rate does not necessarily lead to reduced waiting time of parts or balanced work loads. The simulation model used in this study assumes that the materials handling system is available at all times with infinite capacity. Because of this assumption, the high transportation time in DMM/FIFO does not create a bottleneck that will, in a real production environment, cause additional waiting time and lead to a lower production rate.

The results presented in this paper are valid under the experimental conditions described earlier. Hence, there is a need for further research to develop new rules and continue testing the existing ones under different FMS configurations and experimental conditions. Such research should address the impact of varying system parameters. Some of those system parameters that affect the system performance are as follows:

1. Changes in arrival rates.
2. Variation in processing times.
3. Machine tool breakdowns.
4. Material handling system type, availability, and capacity.

The DMM concept requires further research and improvements from various perspectives for a better adaptation to real-time FMS control:

1. The dissimilarity coefficient currently used in DMM is based on the type of machines. Various coefficients that incorporate the “sequence” of operations and the “processing times” would improve the decision-making related to scheduling and system control.
2. In order to reduce the computation time, the optimisation module can be replaced by a heuristic so that DMM becomes more suitable for real-time control.
3. The relationship between the dissimilarity coefficient definition and the objective(s) in scheduling also needs further elaboration.
4. The DMM/FIFO rule uses DMM for routeing selection and FIFO for part selection (the part that has arrived first is given a higher priority than the other parts awaiting service at the same location). The study can be expanded by testing various DMM-based compound rules, such as DMM/EDD in which the part with the earliest due date will be selected from the parts awaiting service at the same location. This leads to another analysis where different performance measure can be used.

Overall, this study shows that the dissimilarity maximisation method developed as a routeing selection tool for off-line scheduling purposes can be used for real-time FMS control and outperforms the other two control rules, which are myopic in nature, on the basis of throughput rate.

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