Judicious Increase in Flexibility and Decision Automation in Semi-Computerized Flexible Manufacturing (SCFM) Systems

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Abstract: Flexible Manufacturing Systems (FMS) typically possess real time control capabilities by which the routing flexibility can be utilized towards performance improvements. Real time control requires a high level of computer based status monitoring and decision automation and hence high IT investments. Not all manufacturing companies can afford the real time control capabilities. However they may possess a partial level of computer based decision automation resulting in *decision delays* in decision processing and implementation. It is interesting to study how the lack of real time control in such *semi-computerized flexible manufacturing* (SCFM) systems affects their performance. In this paper we study a typical SCFM at different levels of decision delays and observe that the role of on-line control strategies is crucial for effectively exploiting the flexibility. Our efforts differ from the other researchers' who have mostly assumed real time decision making based on real time status of the manufacturing systems. Such assumptions are justified to some extent for the FMS, but are not valid in the SCFM situation. Our research indicates that it is essential to explicitly model and analyze the effect that decision delays have on the flexible system performance. Our motivation in studying this domain has stemmed from our experience in the Indian manufacturing environment where a phased development of information based automation and integration in manufacturing systems is preferred.

In this paper we first describe the motivation to study decision delays in typical SCFM operating environments. Then a simulation model is developed for studying a defined SCFM system. The makespan performance of alternative sequencing and dispatching control strategies with different levels of routing flexibility are studied under both the decision delay and real time decision conditions. The decision delays are considered for both the sequencing and dispatching decisions. The results indicate that when there is no decision delay, the increase in routing flexibility is mostly beneficial. The benefits of flexibility start reduce when the decision delays increase. At higher levels of delays, an increase in flexibility may even become counter-productive. For the system studied, it was also observed that the sequencing decision delays played a more significant role than the dispatching delays. Further the makespan performance remains sensitive to the control strategy employed despite the existence of decision delays. However the benefit of using superior priority rules to exploit the routing flexibility is justified only if the decision delays are relatively low. This implies that the SCFM systems with increasing levels of flexibility must also provide increasing levels of decision automation, if the seemingly superior control strategies are expected to yield improved performance benefits.

Keywords: Decision Delay, Sequencing Decision, Dispatching Decision, Routing Flexibility, Semi-Computerized Flexible Manufacturing (SCFM) System, On-line Control Strategy

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1. Introduction

The evolving manufacturing environment requires a judicious combination of flexibility and information based integration and automation. Flexibility, automation and integration cost money, as a result of which system designers aim to provide only the required levels. Thus, most real world manufacturing systems have varying levels and types of flexibility and employ some form of control strategy to harness this flexibility when required. All control strategies implicitly involve the following activities related to decision initiation, processing and implementation: (i) monitoring of shop/machine status; (ii) recognition of changes in the state of the system and determination of their impact; (iii) evaluation of available opportunities; (iv) selection of the most suitable control decision ; and (v) implementation of the selected control decision by providing the necessary information support. These activities are information intensive and depending on the level of automation and integration into a given flexible system, they may entail significant decision and information related delays. In our experience in Indian Industry, most manufacturing systems inherently exhibit some level of decision and information delays in the application of any control strategy. The extent of these delays and their impact depend on the decision system (and the related status monitoring system) employed.

Discrete part manufacturing systems can be modeled as discrete event dynamic systems. The role of flexibility within such systems can be viewed as one that provides alternative decision solutions at certain discrete events which the system evolves with. Wadhwa and Browne [1] refer to these events as *decision points*. Depending on the type of flexibility [2] present in a manufacturing system, decision points provide an opportunity for controlling the direction in which the system should evolve. Decision choices are typically exercised using control strategies which manifest themselves as sequencing, dispatching and/or queue selection rules. Control strategies are expected to effect decisions on the basis of prevailing system status information. The decision delays and the associated information delays may manifest themselves as delayed usage of resources with often a poor choice on priorities, at each decision point. They may result in the control strategy effecting a delayed control decision which may be based on the past status information. The greater the decision delays and older the status information, the greater the likelihood of an erroneous decision being made by the control strategy. It is important that we appreciate how the performance of alternate control strategies is influenced by decision and information delays and select a control strategy that is more tolerant.

Considerable research effort has been devoted to the development of control strategies [3,4 & 5] wherein decision and information delays have implicitly been assumed to be insignificant, i.e. for *real-time* control[6]. We propose therefore two more dimensions to Parunak's [5] five fundamental demands on scheduling[§]: decision delay dependability and information-delay-dependability (the latter was earlier proposed by Wadhwa et al [7]). As such, the idea of *delay models* is not new as it has been used in many alternate domains such as control theory and system dynamics for modeling *continuous* systems, and qualitatively mentioned by researchers [8 & 9] . In the light of the above, there is a need to study the performance of on-line control strategies in discrete event flexible systems operating under decision delays. We stress the importance of modeling decision and information delays [7] to manufacturing system designers who seek to develop suitable control strategies to exploit flexibility for performance improvement purposes[11]. In the evolving manufacturing environment with a continuing emphasis on increasing flexibility (which costs money), it may become crucial to have a matching investment in computer based decision automation and status monitoring capabilities to be able to effectively exploit the available flexibility in the manufacturing system[10]. We refer to any flexible system that does not have real time control (i.e. it has decision and information delays) as a Semi-Computerized Flexible Manufacturing (SCFM) system. An SCFM has a partial level of decision automation as compared to an FMS which possesses full automation.

2. Background and Motivation

Our primary motivation in this paper is to emphasize the importance of explicitly modeling decision and information delays in flexible systems when selecting suitable on-line control strategies. Decision delays can manifest themselves in different modes and in each mode their scheduling implications are different.

The work reported in this paper is a part of our ongoing research effort wherein we have focused on two specific flexibility types, viz. *machine flexibility* and *routing flexibility*. Browne et al [12] have suggested eight basic flexibility types in the context of FMSs, of which *machine flexibility* and *routing flexibility* are considered to be important since they lay the foundation for the other flexibility types. This paper focuses on a simplistic view of routing flexibility, one which endows the machine with the capability of

[§] (i) *desirability* to find a schedule that minimizes the score of a particular evaluation function; (ii) *stochasticity*, wherein differences between the real world and mathematical abstractions arise; (iii) *intractability*, which precludes the possibility of simulation of real world scheduling problems in realistic time frames; (iv) potential for *chaotic behavior* in FMSs which imposes an additional restriction that the planned schedule should attempt to avoid all such combinations of variables that might eventually lead to chaos on the shop floor; and (v) *decidability*, which opens the door to the possibility of non-computability of solutions to scheduling problems.

sequencing and dispatching choices in a typical SCFM system. Earlier Wadhwa et al [7] have shown motivation to study the impact of information delays where a sequencing decision to exploit machine flexibility may be employed. In this paper we describe a more realistic six -machine, flexible system with various levels of routing flexibility and focus on the decision delays related to both the sequencing and dispatching decisions at each machine in the SCFM system.

Conventional scheduling rules employed for the dynamic sequencing of machines in job shop have almost always implicitly assumed that sequencing decision is made without any loss of time, based on the availability of real-time status information. For instance, when applying the *Shortest Processing Time* (SPT) rule : (i) it is implicitly assumed that the expected operation times of all waiting parts in the queue are instantaneously available; and (ii) no time elapses in processing the operation time data when choosing the part with the shortest processing time. Although in some manufacturing systems employing fully automated data collection and computer based information processing methods (e.g. FMSs) this assumption may be valid, most other manufacturing systems are devoid of this level of information automation and integration. Our experience in the Indian Industry indicates that nearly all manufacturing systems may be viewed as at most partially automated and integrated. In these systems it is important to appreciate the impact of decision and information delays on the performance of manufacturing systems.

Any flexible, semi-computerized manufacturing system(SCFM) can be viewed as comprising three main subsystems : (i) a set of flexible machines, each with a defined level of machine and routing flexibility; (ii) a status monitoring system reflecting a defined level of information integration into the manufacturing systems; and (iii) an on-line control system reflecting a defined level of decision automation in identifying and implementing a suitable control decision. An SCFM system thus renders itself as a suitable experimental platform for getting insights into the issues related to flexibility, automation and integration. Since all of these are expensive, the system designers must focus on providing the appropriate levels. Our view is similar to that of Montazemi et al [13] where a modeling tool for analyzing the information requirement of CIM is suggested. In this paper we demonstrate the use of simulation models in analyzing the decision automation and integration requirements to help benefit from flexibility. In our opinion the issue of balanced use of flexibility, automation and integration is critical for the effective design of SCFM systems. It may be viewed as a paradigm similar to that discussed by Buzacott [14].

Keeping in mind the research motivation our basic objectives can be summarized as :

(a) To study whether routing flexibility can be exploited to improve the SCFM performance (as is the case with FMS).

(b) To study the role of increased decision automation (i.e. reduced decision delays) in utilizing the flexibility more effectively.

(c) To study the relative impact of sequencing and dispatching decision delays in a defined SCFM system.

(d) To justify the need for a judicious increase of flexibility and decision automation.

3. A Representation for Decision Delays

Figures 1a) to 1d) illustrate how a decision and the associated information delays may be individually represented. We coin the term of *Decision-Information Synchronization* (DIS) delay to signify the presence and *relative timing* of the decision and the associated information delays. The DIS delays are then represented in Figures 1e) and 1f).

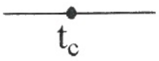
4. Manifestation of DIS Delays in SCFM Systems

Some ways of how DIS delays may manifest in the case of manual, semi-automated and automated machines in typical SCFM systems are illustrated in Figure 2.

Symbols Used

REPRESENTATION FOR TIME AT WHICH INFORMATION IS COLLECTED (TAIL) AND USED FOR AN EVENT (HEAD).

REPRESENTATION FOR TIME AT WHICH DECISION IS INVOKED FOR AN EVENT (HEAD) AND IMPLEMENTED (HEAD).



AN EVENT AT TIME t_c REQUIRES DECISION

Representations

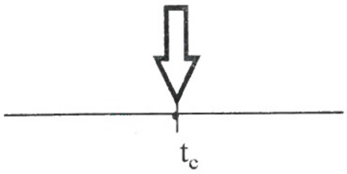


Figure 1(a) : A decision invoked at time t_c is implemented at time t_c without any delay for an event requiring a decision (i.e. a real time decision).

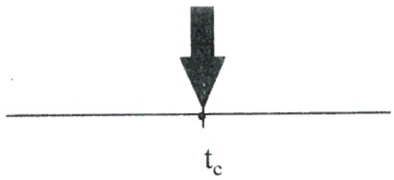


Figure 1(b) : Information of time t_c available for use in any decision event at time t_c without any delay (Real Time).

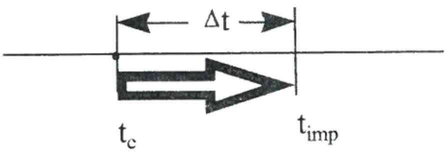


Figure 1(c) : Decision invoked at time t_c for an event and gets and implemented at t_{imp} after delay of time period Δt (decision delay).

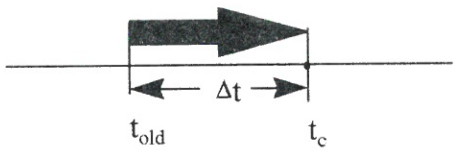


Figure 1(d) : Information of time t_{old} available for use in any decision event at time t_c after a delay of time period Δt (information delay).

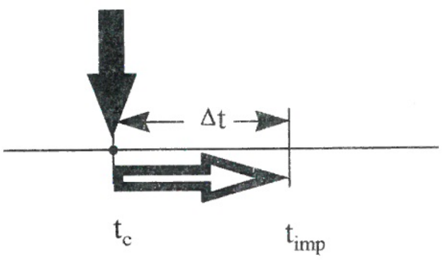


Figure 1(e) : Information at time t_c available for use in any decision event at time t_c without any delay (real time information). But the decision is invoked at time t_c and it gets implemented at time t_{imp} after a delay of Δt (decision delay).

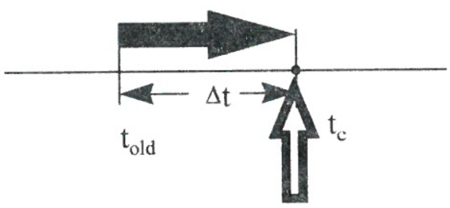


Figure 1(f) : Information at time t_{old} is available for use in any decision event at time t_c after a delay of time period Δt (information delay). The decision is invoked at t_c and it gets implemented at time t_c without any delay (real time decision).

Figure 1. Representation of the DIS Delays

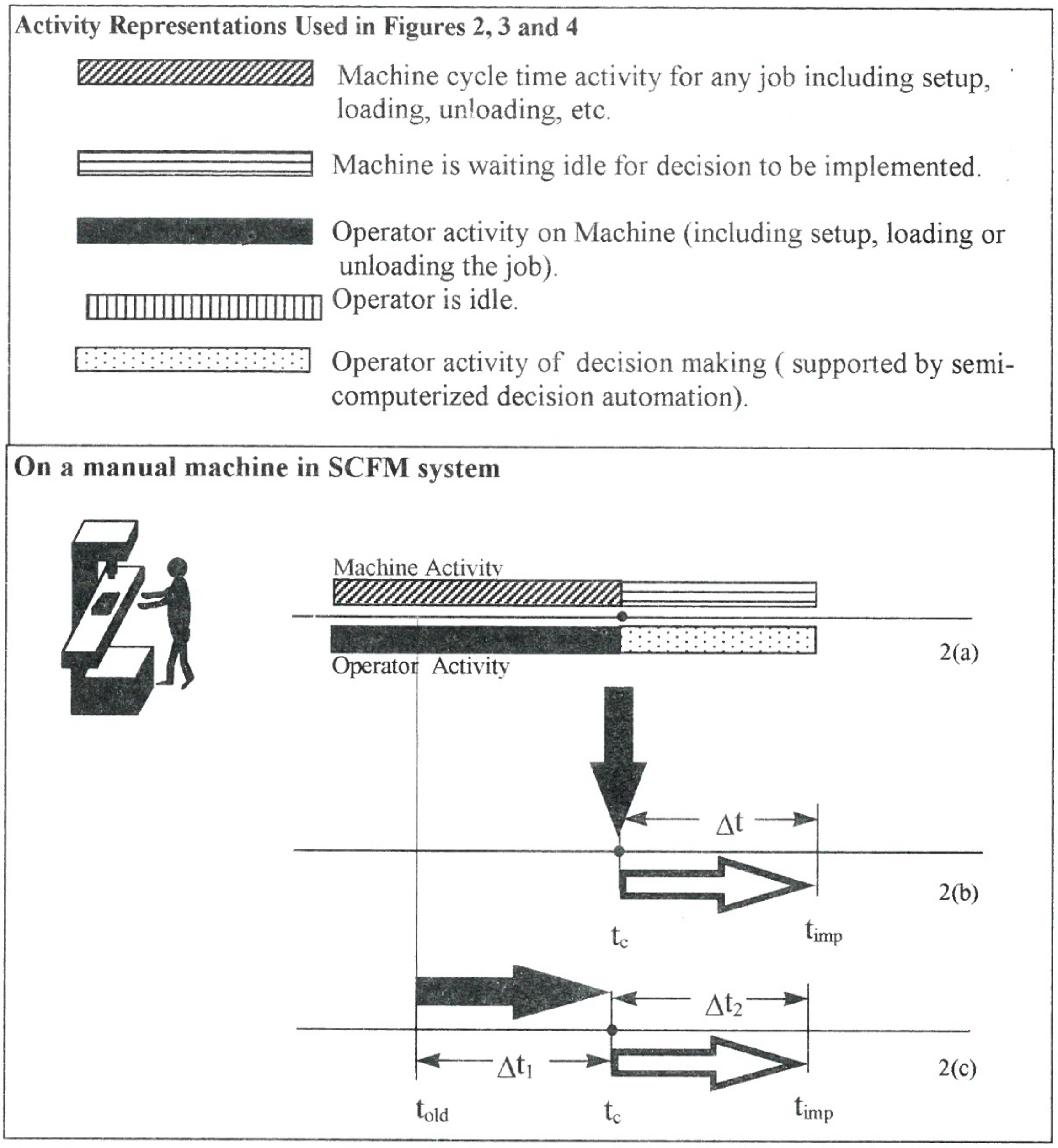


Figure 2. Illustration of Typical DIS Delays on A Manual, Flexible Machine in SCFM Systems

We assume a typical industry environment where the operators are expected to exercise decisions based on guidelines or rule provided by the supervisor. Figure 2(a) shows a conventional machine where typically the operator is busy with the machine throughout the cycle time of the machine. Decision making and its implementation can be carried out only after the completion of the machine operation. This implies that the machine may have to stay idle at the end of each part processing operation, for the decision making and its associated decision implementation time. Under such conditions, there are two possible scenarios of DIS delays, as shown in Figure 2(b) and Figure 2(c). Figure 2(b) shows the situation where the operator starts decision making at time t_c based on the real time information at that time. However the decision is implemented at time t_{imp} after a decision delay of Δt time. Figure2(c) shows another possibility where the information for decision making is not available in real time and the operator uses old information of time t_{old} (i.e. delayed by time Δt). Further the decision is implemented at time t_{imp} (i.e. after the delay of Δt_2 from time t_c at which an event requires decision). Thus there is a combined decision and information delay. In many working environments such delays are quite common and one must analyze their impact in detail before implementing any control strategy for scheduling.

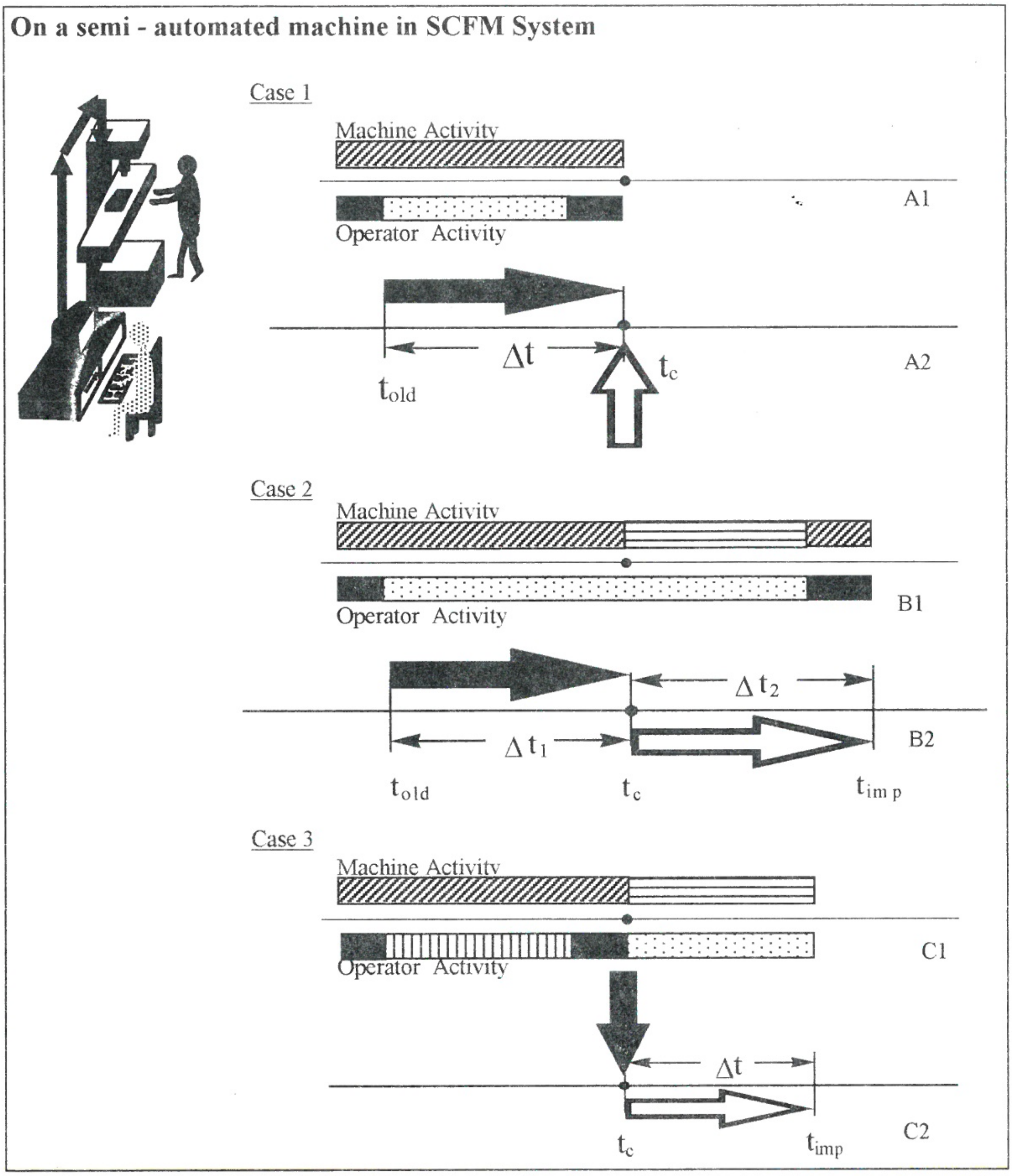


Figure 3. Illustration of How DIS Delays May Manifest on A Semi-automated, Flexible Machine in An SCFM System

In Figure 3, A1 under Case 1, shows a semi - automated machine where the operator attendance may not be continuously required. For instance he may be working on the machine in two phases, first during the start of the cycle, and second at the end of the cycle. Now we describe the manifestation of some typical DIS delay possibilities. A2 presents a DIS representation using the notations described earlier. It shows that the operator invokes decision making after completing his first phase work on the machine and he uses the real time information which is available at that point in time. He may complete the decision making before commencing the second phase work. Thus he can then implement the decision at the end of machine cycle without any delay. A2 also shows that the decision making is invoked at time t_{old} after the operator finishes the first phase of work on the machine and uses real time information of time t_{old} for the decision making. He completes decision making before the moment when the machine requires unloading (i.e. the second work phase). Thus the decision gets implemented at the end of the machine cycle time. The machine avoids being idle due to the decision related activity of the operator.

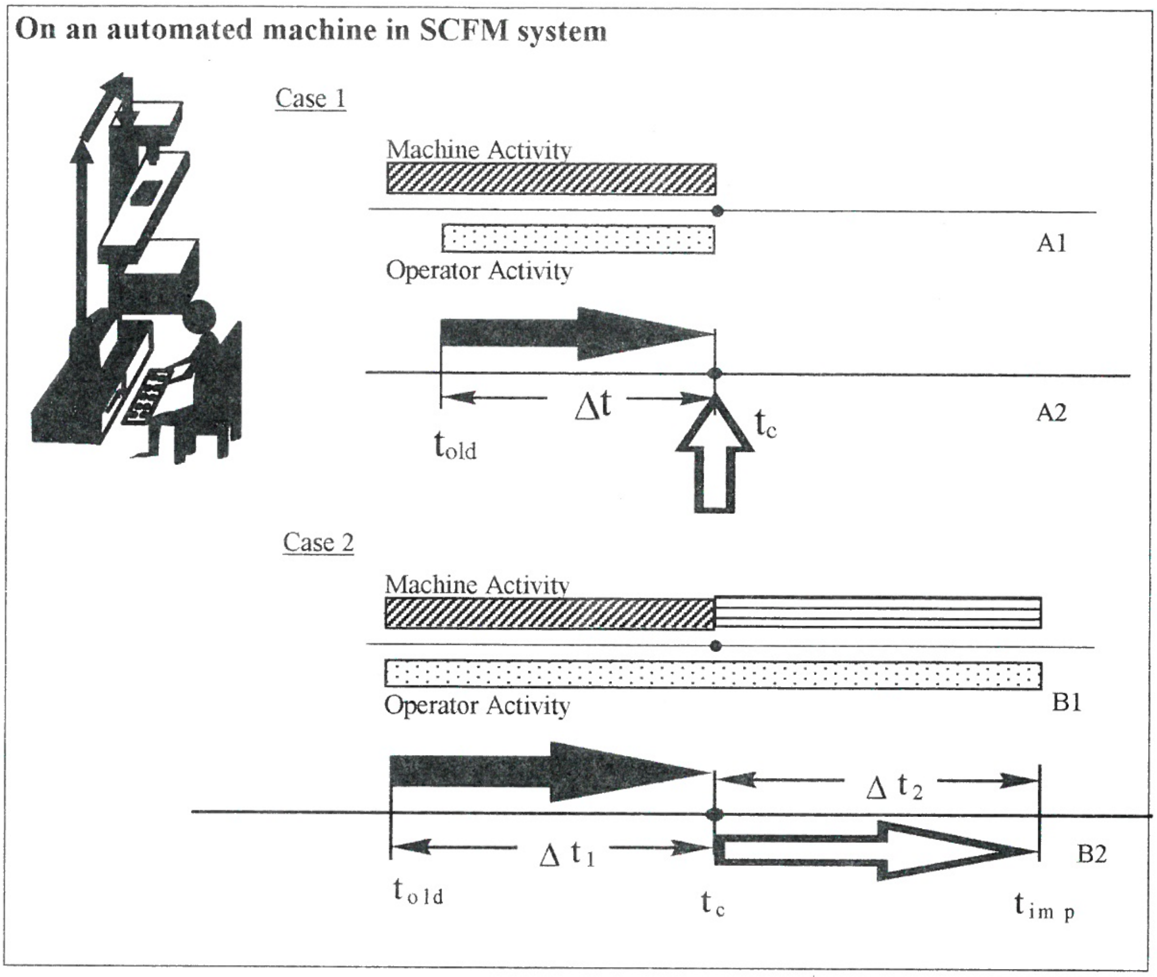


Figure 4. Illustration of How DIS Delays May Manifest on A Fully Automated, Flexible Machine in An SCFM System

However it results in a DIS delay as a consequence of using old information of time t_{old} for the decision event taking place at time t_c. This may be seen as a possibility in which the machine does not have to wait for the operator's decision making activity, but the decision quality may suffer due to the information delay of Δt. Similarly in Figure 3, Case 2 - B1 shows a condition where the operator takes more time than the cycle time of the machine in decision making and its implementation. Under this condition B2 illustrates the DIS delay manifestation. It shows that the decision making is invoked at time t_{old}, i.e. after the operator finishes his first phase of work on the machine and uses real time information of time t_{old} for the decision making. The decision gets implemented at time t_{imp} after a delay of time Δt_2 from time t_c at which the event required a decision. This shows a case of DIS delay where combined decision and information delay occur. Let us now see Case 3 - C1 and C2. They show a condition where the available time gap between the two phases (i.e. operator idle time) is inadequate for decision making. The operator remains idle between two phases of working on machine and invokes decision making only after the completion of the machine cycle time at t_c. He is then able to implement the decision at time t_{imp} after a delay of time Δt from event time t_c. This DIS delay may be viewed as a decision delay (with associated information delay).

In the case of fully automated flexible machines it is typical to have an automated loading and unloading of the machine. Here the operator can be assumed to be available for decision making at any time. Case 1 - A1 in Figure 4 shows a condition where the decision making time is less than the machine cycle time. Here the operator invokes the decision making such that the decision can be implemented just when the machine is ready to start the new part. A2 presents a possible DIS delay manifestation associated with this condition. The operator invokes decision making at time t_{old} and finishes the decision making by the end of the machine cycle time. He is able to implement the decision at time t_c itself without any machine delay. Under this condition, old information of time t_{old} has been used for decision making on an event which takes place at time t_c. This DIS delay is basically due to an information delay.

Similarly Case 2 - B1 shows a condition where the operator invokes decision making at the beginning of the machine cycle time. But it takes more time to be able to make and implement the decision than the cycle time. B2 presents the DIS representation of this case. The operator invokes decision at $t_{old,}$ uses the information of time t_{old} for decision making and is able to implement the decision at time t_{imp} after a delay of time Δt_2 from time t_c . This DIS delay refers to a combined decision and information delay, as information of time t_{old} has been used for the decision which gets implemented at time t_{imp}, thus causing the machine wait due to the decision delay.

5. A Sample SCFM System

Figure 5(a) has been drawn to incorporate the representation of both key elements of the physical system (i.e. entity flows) and the decision system (i.e. logical options on entity flows requiring decision). Figure 5(a) basically illustrates a sample SCFM system having six machines, each with an input buffer. The parts are processed according to a given processing sequence. After processing on a machine the part goes to the next machine for processing and waits in the input buffer till it gets the chance of being processed (depending on the sequencing strategy).

When the machine becomes idle, the sequencing decision point collects the status information of parts waiting in the input buffer and makes a decision as to which part are they to be loaded next, according to the sequencing strategy. Similarly, when a machine finishes an operation the dispatching decision point requires information about alternative machines available for the next operation (according to the routing flexibility). It decides to send the part to the input buffer of the selected machine. Figure 5(b) explains the role of routing flexibility.

Figure 5(b) shows the routing flexibility concept where RF=0 means that there is exactly one machine for an operation on a given part, i.e. there are 0 alternatives. RF=1 implies that there are two possible machines, i.e. there is exactly 1 alternative machine for any operation on any part. Similarly, RF=2, RF=3 and RF=4 imply 2, 3 and 4 alternative machines respectively, for any part-operation. Figure 5(b) also illustrates that on a flexible machine, the operator will typically face both a sequencing decision and a dispatching decision. This DIS delay for both decisions may get involved.

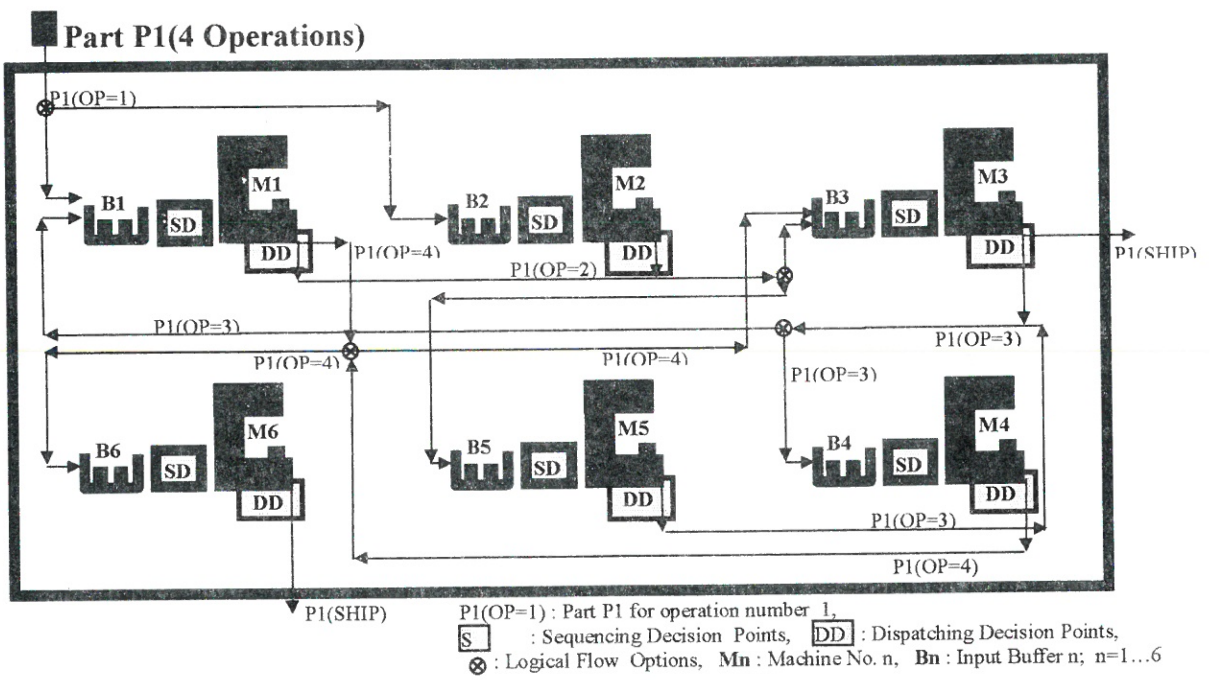


Figure 5(a). Sample Manufacturing System Showing the Routing Flexibility, Processing Sequence, Sequencing Decision Points and Dispatching Decision Points

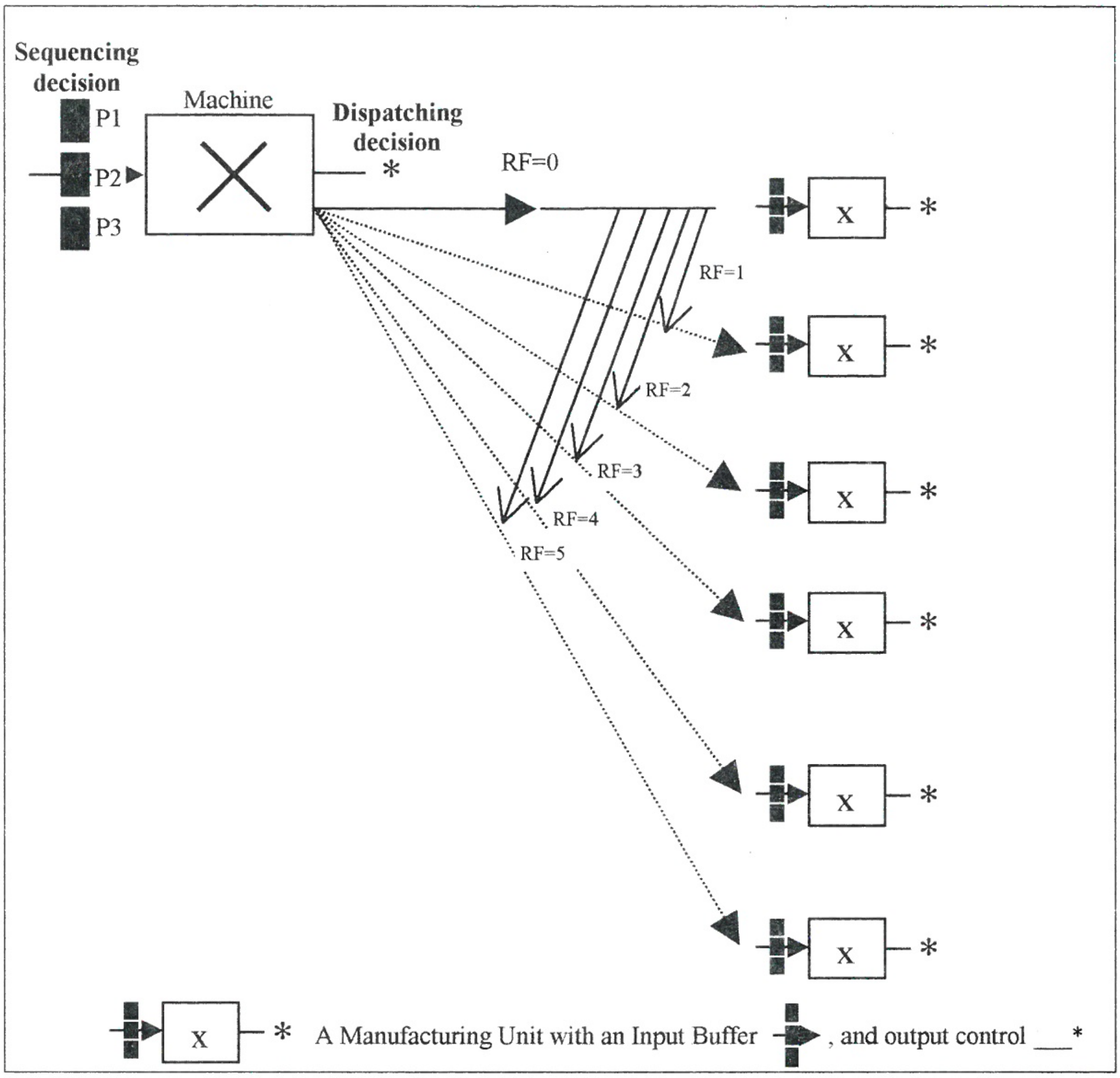


Figure 5(b). Illustrating Different Levels of Routing Flexibility (RF=0 implies no alternative machine, RF=1 implies, one alternative machine etc.)

6. Study of An SCFM Using Simulation Models

Simulation models have been developed in the "WITNESS" package for a typical manufacturing system with decision delay features. The "WITNESS" software has no available feature to explicitly model the DIS delays. Extensive efforts were made to achieve this. In our opinion it may be expedient for the simulator developers to include primitives to model DIS delays explicitly. It will also motivate users for developing more realistic models of the SCFM systems.

The simulation models were developed to study the performance of SCFM systems at higher levels of flexibility, and at different levels of DIS delays . Since one of the key parameters to focus on was the flexibility, it was considered as necessary also to study the impact of both the sequencing and the dispatching control strategies. Thus some of the models were designed with decision delays related to both the sequencing decisions and the dispatching decisions. The general purpose of the simulation models presented in this paper was to study:

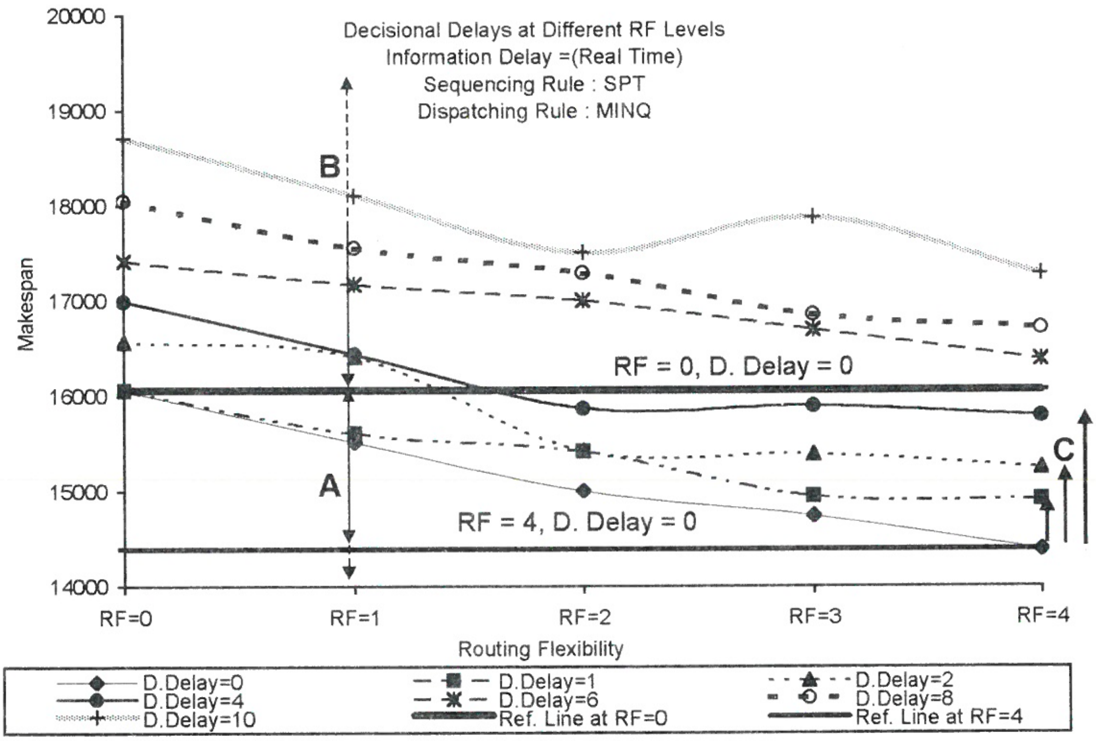
1. the impact of *sequencing decision delay* on the performance of an SCFM system at different levels of routing flexibility, under a given control strategy (i.e. sequencing/dispatching rule).

2. the impact of *combined sequencing and dispatching decision delay* on the performance of an SCFM at different levels of routing flexibility under the same conditions as above.

For all the studies, a makespan was used as a performance measure. Similar to a typical FMS, an SCFM was modeled with limited parts in the system. Similarly the machine set up time was considered to be negligible. The part entry was controlled so that the mix should also remain constant. This was done as the parameters generally had a significant impact on the makespan. This could make sure that the systems concerned were performing in a sensitive way to the changes in our key parameters of interest, i.e. decision delays, sequencing rules, dispatching rules and the routing flexibility. Before discussing the results, it is expedient to first explain how the decision delays in sequencing and dispatching typically get introduced in SCFM systems, in environments and work practices generally prevailing in the Indian industry. This will also highlight the underlying logic of the model and the associated assumptions.

In SCFM systems with relatively lower levels of information based automation and integration, the modeling of DIS delays is more important for developing realistic insights into their design and control problems. In a typical working of an SCFM system, the machine, whenever idle, is generally loaded by the operator through selecting one from the queue of parts waiting in the buffer. The operator may take some time to select the part if a priority rule needs to be applied as part of his sequencing decision task.

An SCFM system can entail various forms of decision delays. In this paper we are motivated to study a typical form where the operator takes time for selecting the part from the queue (using a sequencing strategy) and the machine has to wait idle for that period of time. To further illustrate, let us consider the application of the SPT rule compared to the FCFS rule to be employed as a sequencing decision in such systems. For a FCFS rule the operator has to simply select the first job in the queue. This is done immediately even in a fully manual system and would cause decision delay of no significance. On the



A - Increase in flexibility is beneficial in this region, for the rules studied
B - Increase in flexibility is counter-productive in this region
C - Flexibility benefit decreases as Decision Delays increases

Figure 6. Impact of Sequencing Delays on the Performance of Routing Flexibility Under A Given Operating Condition

other hand the application of the SPT rule may require the collecting of the job cards for all the jobs in the queue and the extracting of the operation time information. In a fully manual system this will require some time, which we can broadly view as a form of decision delay. We need to study the impact of this delay on the manufacturing system performance before recommending that FCFS is changed to SPT. If we plan to computerize the system for providing a semi-automated decision support , then the decision delays will reduce in magnitude. Now the important point is to ensure that the level of computerization is so established that a significant benefit from SPT, over the present FCFS sequencing decision, should result. At the same time we should not over-invest, i.e. attempt to decrease decision delays to a level where investments are high but the benefits are marginal.

The same when a machine finishes the processing of a part, the operator/supervisor generally makes a decision to select the next machine for the next operation out of the available alternative machines (i.e. a dispatching decision to use routing flexibility). The decision is generally based on the information of the shopfloor status available with the operator/supervisor. This shopfloor status information will be older

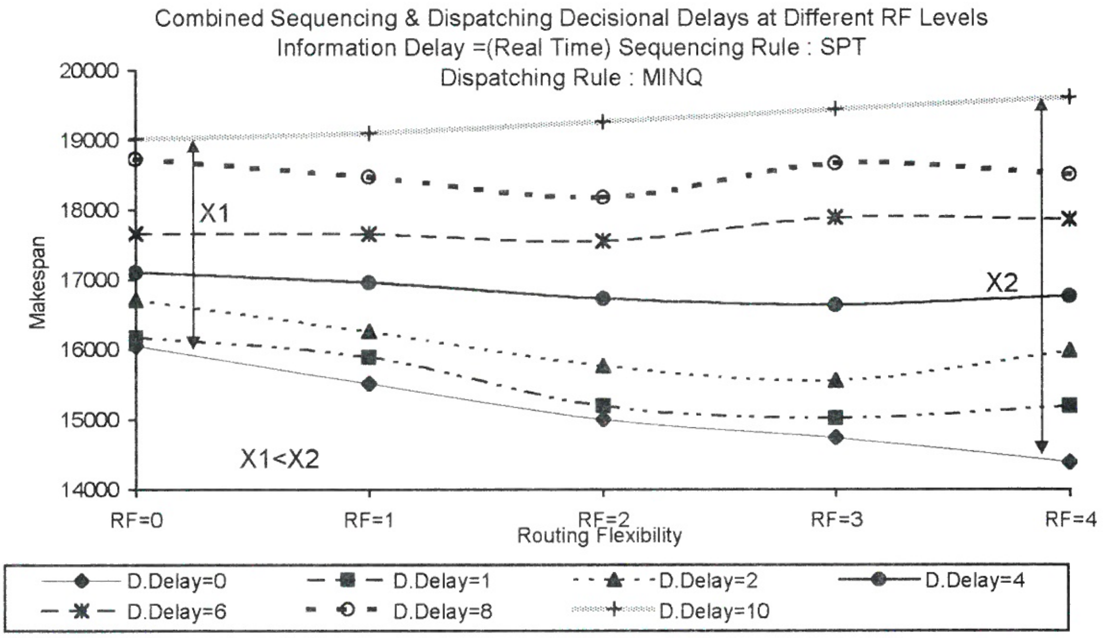


Figure 7. Showing Impact of Combined Sequencing and Dispatching Decision Delays with SPT Sequencing Rule and MINQ Dispatching Rule on Makespan At Different Levels of Routing Flexibility

than that which may be the case in real time control (partly because of decision delays in non-real time control). This may further lead to erroneous decisions in time. From our experience in India, such situations of decision delays are quite common and many times the early efforts of computerization yield no benefits over the present system. Similarly many times one invests a lot towards virtually real time control, but the benefits are not matching. This further highlights our motivation to study decision delays in the scheduling of the SCFM systems.

The control strategies incorporated in our simulation study for the sequencing and dispatching decisions are as follows:

Sequencing Decisions : The sequencing rules used are: 1. First Come First Served (**FCFS**); 2. Shortest Processing Time (**SPT**); 3. Minimum Number of Operations left **(MINOPR)**; 4. Maximum Balance Processing Time (**MBPT**).

Dispatching Decisions: For dispatching decisions two alternative dispatching rules are used: 1. Select the alternative machines with minimum number of parts waiting in the queue (**MINQ**); 2. Select the machine where the total sum of processing time of the parts waiting in the queue is minimum (**MWTQ**).

The study was conducted at various levels of decision delays, ranging from real time to about ten units of time.

7. Results and Discussion

It is generally believed in the Indian industry that an increase in the flexibility of a given SCFM system will always result in better performance. While this is mostly true for FMS, we are motivated to study if this also holds for SCFM where the DIS delays are inherently present. Further we are interested in studying the impact of the increase in flexibility at various levels of decision delays. Figure 6 shows the effect of sequencing decision delay on the makespan with an increase in flexibility when using SPT as a sequencing rule and MINQ as a dispatching rule. It shows that with the real time (i.e. delay=0) decision making there is a clear advantage, associated with an increase in flexibility. But with DIS delays the advantage of having more flexibility may decrease with an increase in delays. Figure 6 illustrates that for the SCFM studied, it may not be worth having any flexibility, when the sequencing decision delays are of the order of 6 units of time (compare the line of D. Delay=6 with reference line at RF=0). We refer this time as the tolerance limit for the SCFM studied.

We conducted a number of studies on this SCFM which indicated that the lower bound for the tolerance limit was set by the difference in two lowermost operation times (here it equals 4 units of time) in the routing data. This is an interesting observation as it may help reduce the simulation efforts for determining at least a conservative estimate of the tolerance limit for a given SCFM. The results also suggest that when the decision delays have been more than 4 units of time, the system performance decreased with an increase in flexibility (particularly when the routing flexibility is higher than RF=2). This implies that an increase in flexibility when decision delays are high, can even be counter-productive. It can also be inferred that the increase in flexibility without a proper change in the decision system may be disadvantageous.

Next we have been motivated to study the cases where the decision delay in dispatching the part to the next machine may also be compounded with the sequencing decision delay. Figure 7 shows the impact when the combined sequencing and dispatching decision delays are considered. Comparing Figure 6 and Figure 7, we can say that when both sequencing and dispatching delays turn up simultaneously, the system performance decreases more sharply. With only the sequencing delay (Figure 6), when the flexibility level increases, there is an advantage (at least up to RF = 2). But with the combined delays the

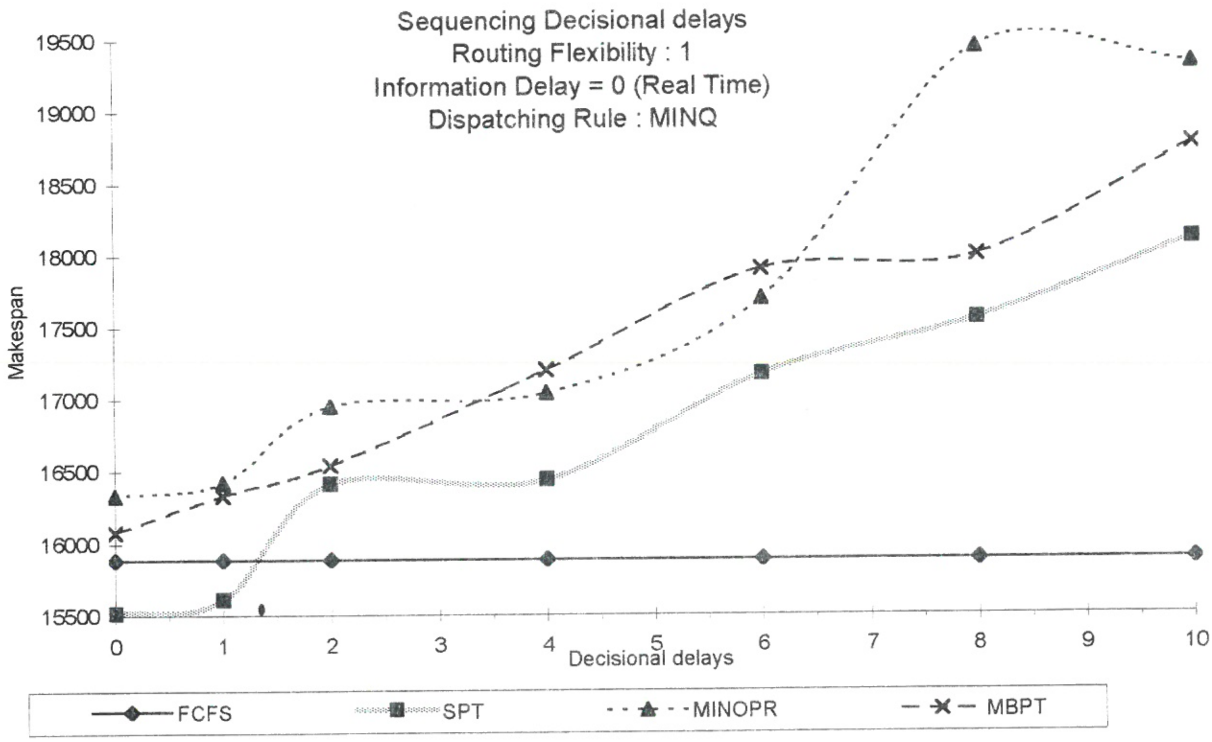


Figure 8. Showing Impact of Decision Delays with Different Sequencing Rules on Makespan When Routing Flexibility Is Present, i.e. RF=1

system performance deteriorates with an increase in flexibility, particularly when delays are more than 6 units of time. In Figure 7, X1 and X2 are meant to highlight an important point (note X1<X2). This implies that the relative deterioration of the performance with increased flexibility is higher at higher delays. We can say that if the combined decision delays are of higher order, the increase in flexibility can be counter-productive. In Figure 7 there is no advantage of increasing flexibility even if the delay is of the order of 4 units of time (which is less than 10% of the average processing time) for the system studied. Thus it may be preferable to first upgrade the decision system to reduce the decision delay rather than first increase the flexibility. The discussion above reflects that a judicious increase in flexibility and automation is important in SCFM systems. For such systems in operation, considerations on the increased automation of the decision and information system should be mandatory before thinking of an increase in flexibility.

Similarly Figure 8 shows the impact of sequencing decision delays on an SCFM with a routing flexibility, RF=1 and operating under the dispatching rule as MINQ. Figure 8 clearly showed that with an increase in decision delays, the performance of the studied SCFM decreased for all the rules. However at different levels of sequencing decision delay, a different sequencing rule may perform as the best. Even at a relatively low level of delays (up to 2 units of time) associated with superior control strategies (e.g. SPT), the dumb rules such as FCFS may perform better. We can also say that if the decision system is not capable of making and implementing the decision within a certain time limit, then it is better to use simple rules likely to cause negligible delays. Further unless the IT investments in the system are able to reduce the delays below a certain level, it may not be advisable to invest in IT. Thus if our decision

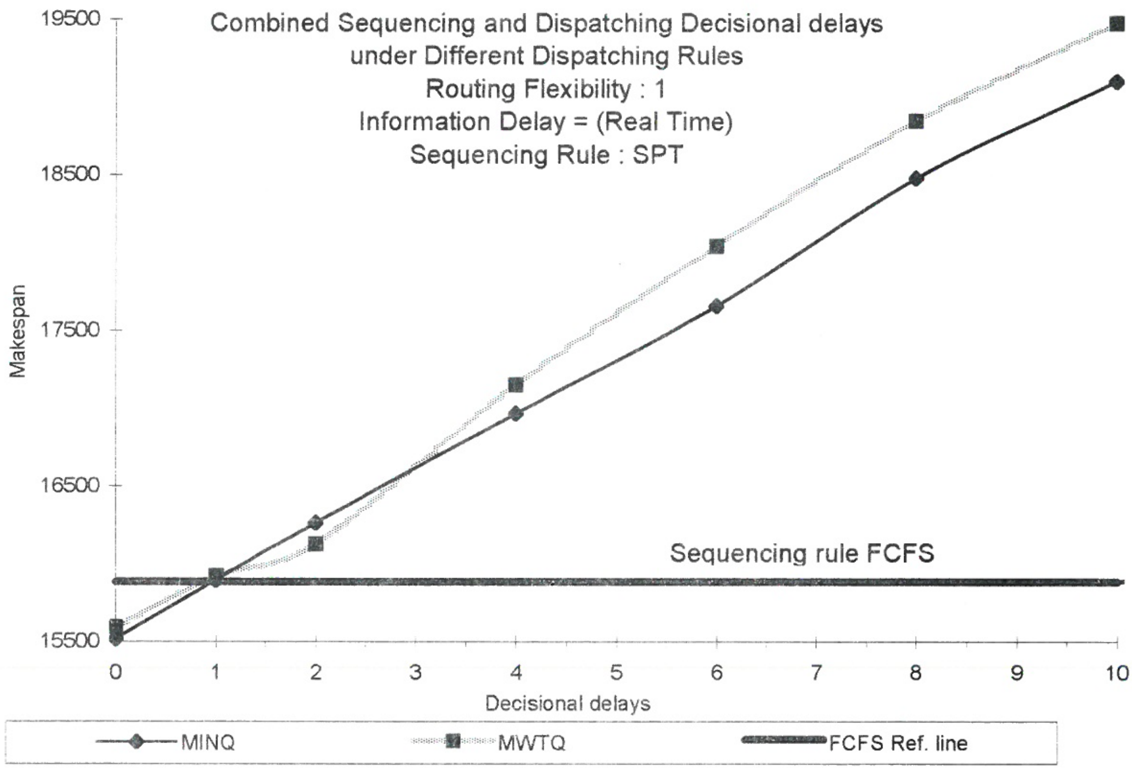


Figure 9. Showing the Impact of Combined Sequencing and Dispatching Decision Delays on Different Dispatching Rules on Makespan At RF=1

system is not capable of making and implementing the decision within the tolerance limit, it may be better to continue to simply use relatively dumb rules such as FCFS for their decision easiness.

Figure 9 illustrates the impact of two different dispatching rules on routing flexibility, RF = 1, when there are both sequencing and dispatching decision delays. It indicates that the comparative performance of alternative dispatching rules differs more significantly beyond a certain decision delay level. Figure 8 and Figure 9 also indicate the relative importance of sequencing versus dispatching decision delay for the SCFM studied. In the case of a combined delay (Figure 9) the tolerance level is only reduced marginally compared to the sequencing delay case (Figure 8). Further by comparing the SPT/MINQ line in Figures 8 and 9, one suggests that it may be useful to prioritize the phased IT implementations. For instance for the

SCFM studied, if the delays are present at a 2 - units - of - time level, then one will first invest in the increased automation of the sequencing decision system.

8. Conclusions

This paper arguments the need for explicitly modeling the impact of decision delays on the performance of various control strategies in SCFM systems, at different levels of flexibility. We have defined various forms of decision and information delays that can determine the performance of a given system. The effect of these delays on the makespan performance at different levels of flexibility in an SCFM system, has been studied using a simulation model. The study reveals that the makespan performance deteriorates with an increase in decision delays, and this deterioration is higher at higher levels of flexibility. That means, while in general it is advantageous to have more flexibility, the advantage of having more flexibility decreases with an increase in sequencing decision delays. This has serious implications on the performance of the SCFM system, as actually the increase in flexibility will increase the number of decision options and the information requirement, and thus the decision delays. Hence the flexibility and decision delays will interact in such a way that, beyond a certain level of decision delays, their cumulative effect will be to reduce the performance of the system. Thus a judicious increase in flexibility and decision automation may be highly desirable in SCFM systems. In phased computerization efforts, the study of SCFM may help suggest priorities for decision automation directions.

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