Simulation Study Using Taguchi Methods: An Effective Tool for Control Of Computer Integrated Manufacturing and Logistics Systems

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Abstract: Industry is generally keen to identify avenues for phased investments in Information Technology (IT) in manufacturing enterprises. IT is a key enabler of extended enterprises involving computerization of the integrated manufacturing and logistics systems. Similar to the earlier efforts in CIM, the ultimate aim is to develop a decision and information system in organizations that provides an on -line control which is real time. A good example is the control of FMS (a mini-CIM) where we ensure an on -line control that is essentially real time control. Such capabilities are very expensive and industry is more interested in the phased development of such capabilities requiring phased investment. In our view Semi-Computerized Flexible Manufacturing (SCFM) systems [Wadhwa and Bhagwat, 1998] are a useful building block for the purpose. On-line control in SCFM systems involves decision and information delays where decisions are based on information which may be older than the real time information. To effectively control SCFM systems with defined levels of flexibility, it is essential to explicitly model and analyze the effect that decision and information delays may have on the performance of a given on-line control strategy. In this respect computer simulation is an expedient approach . However this may be expensive in which concerns time, effort and costs as the number of factors in SCFM control and their possible levels may be too large. This may result in a very large number of possible combinations to simulate in order to identify optimal control directions. The controllers ideally require tools and methodologies that help them to quickly and effectively identify the priority factors and the impact of their interactions . In this paper we present one such approach to study the makespan performance of an SCFM system under a *review period monitoring policy* that entails variable information delays.

The approach uses Taguchi methods to provide an expedient experimental platform for quick insights into the behavior of system under alternative factor level combinations. It thus allows the controllers to effectively and efficiently identify key factors and interactions to be controlled as a priority based on their relative contributions to the makespan performance in a sample SCFM system. The results indicate that the relative contribution of decision delays on the makespan performance is maximum. Further the relative contribution of other factors such as routing flexibility and control strategy decreases as the review period increases. The implication for an SCFM controller is that the decision and information delays must be well contained with a greater priority on the reduction in decision delays. We also highlight how the performance of the SCFM system may differ with that of the FMS. An important implication for the controllers is that the control knowledge of managing the FMS may not be a good substitute while managing SCFM systems. The efficacy of the simulation approach based on the Taguchi method is further proved when it is successfully able to capture the interaction effects between the key control factors and routing flexibility in the SCFM studied.

Keywords : Review period, Decision delays, Routing flexibility, Control strategy, Factor Interactions, Taguchi methods, Simulation

1. Introduction

Considerable research effort has been devoted to the development of control strategies [Kim and Kim, 1994] [Goodall and Roy, 1996] for real time control. The role of on-line control that is not real time and which entails decision and information delays with respect to the combined sequencing and dispatching control decisions has only recently been addressed [Wadhwa and Bhagwat, 1998]. There is a need to develop effective approaches based on simulation to study the performance of on-line control strategies in discrete event flexible systems operating under significant decision and information delays. We stress the importance of modeling decision and information delays to the manufacturing system controllers who seek to develop suitable control strategies to exploit available flexibility for performance improvement purposes. In the evolving manufacturing environment with a continuing emphasis on flexibility (which is costly), 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 systems. These are essentially the semi-computerized flexible manufacturing systems (SCFM) [Wadhwa and Bhagwat, 1998] that need to be effectively designed and controlled.

One of the problems faced by designers of SCFM systems is related with the modeling of SCFM systems. It is much more complex compared to the simulation models of shop floor control systems where one typically focuses on only two types of entity flows, i.e. the material and resource flows. In SCFM systems one needs to model two more flows, i.e. the information flow and the decision flow. Like all other flows, these flows require finite times (or delays) depending on the level of semi-computerization. It is both the level of these delays as well as their logical implications on the entity flows that need to be explicitly modeled. While dealing with the industrial and research problems of SCFM systems, one of the key difficulties we faced was related to describing the need and motivation for modeling these delays. In this endeavor we found the GRAI macro reference model [Doumeingts et al, 1995] and ideas on the CIM modeling very useful. While modeling an SCFM system we need to focus on four basic entity flows, i.e. decision, information, resources and material. It is interesting to note that the GRAI macro reference model also presents these subsystems as physical, operational, informational and decisional. In our opinion, it is the interaction of these four with a pivot on the decisional system that ultimately impacts on the performance of an SCFM system. We see the material flow in SCFM under the physical system, the resource flow is indirectly managed by the operational system that sets the procedures on how the material and resources should logically interact. The decision system in SCFM involves the use of a control strategy that benefits the information available through the information system. The flow of the four entities is logically interconnected to form processes at the shop floor control levels in an SCFM system.

The shop floor control or the production activity control (PAC) in manufacturing systems is well described by [Browne, 1988] [Higgins et al, 1990]. A simulation model of such a system within the context of an SCFM system is essentially a dynamic model representing the control on flow of decision, information, material and resources in the system. If the system domain through which these entities flow is enlarged to include suppliers and customers then also an SCFM model may represent an integrated manufacturing and logistics system which is partially computerized. An approach based on simulation may therefore help in more effective control in computer integrated manufacturing and logistics systems. One focal module which the concepts of effective control of SCFM may be compared with and discussed, is the PAC module.

2. Production Activity Control (PAC)

The role of Production Activity Control (PAC) is to provide the facility of real time control in manufacturing [Higgins et al, 1990]. In PAC all the control decisions are based on the available status information. Thus the decisions are contingent upon the availability of information. In fact, there exists a symbiotic and intimate relationship between the control decision and information availability [Veeramani, 1993]. To achieve real time control of shopfloor, there must be an accurate and timely data capture and analysis system within a PAC environment. This real time capability requires high level of computer based integration and decision automation, which is highly cost intensive. Some companies cannot afford such high investments and prefer to work at low level of computerization and decision automation in their PAC systems. Further the volume and product mixes that need to be controlled are changing so often that such system must incorporate flexibility at desired levels. Increased flexibility in the system increases the pressures on the control system as the complexity of the system increases and so does the challenge to effectively exploit flexibility through frequent control decisions. Thus a flexible system with a partial level of computerization represented by Semi-Computerized Flexible Manufacturing (SCFM) system may be considered as the core of a modern PAC system. The SCFM system may not have real time capability and there may be significant delays in decisions and information. The time taken by the decision process from the time of invoking the decision to its implementation is referred as decision delays. Similarly the time taken for information collection, processing and presentation for decision making is referred as information delays. In our opinion most of the real world manufacturing systems inherently exhibit some level of decision and information delays in the application of any control strategy.

In this paper we present one common status information monitoring policy based on review period. In review period status monitoring policy the status information is updated after a pre-defined time interval. This means that status information is updated on starting each review period. This information will be used for all decision making process throughout the review period. The status information will once again be updated on starting the next review period. This situation of review period monitoring leads to variable information delays in control decision at different points of time in review period. It is important that designer/controller shall decide the time interval of review period with a view at exploiting the flexibility present and the control strategy enforced. This paper presents the results of simulation experiments conducted and analyzed under the Taguchi method, to study the contribution of some design and control factors on SCFM performance. This study helps the designer/controller to quickly identify the key parameters to focus on. The factors being studied are review period time interval, decision delays, routing flexibility, sequencing rules and dispatching rules.

The evolving manufacturing environment requires a judicious combination of flexibility and information based integration and automation

[Wadhwa et al, 1997] [Wadhwa and Bhagwat, 1998]. 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. Further, Wadhwa and Browne (1989) indicate that flexibility can be properly exploited through decision points where control rules must be implemented at the operational level. This means that a proper control strategy must be enacted to exploit the flexibility through effective decisions at the shop floor level. The decisions require information that needs to be collected and processed efficiently (i.e. with minimal delays). Thus it has little value to have a very flexible system that is well integrated in terms of possible availability of status information but has an inadequate level of information processing. In phased development of CIM one may not assess the information in real time. The system designers must focus on providing the appropriate levels of information systems [Montazemi and Miltenburg, 1991]. In this paper we demonstrate use of Taguchi method to study SCFM operating under review period based status information monitoring policy. We now explain the working of an SCFM system under the review period mode, which has been modeled in the simulation experiments.

3. Review Period Based Status Monitoring Mode

Now we explain how these decision and information delays manifest themselves in review period based status monitoring policy. Figure 1 shows the review period (RP) starting at time $t_{rp(n)}$ and ending at time $t_{rp(n+1)}$. The information is updated at the starting of review period at time $t_{rp(n)}$. This information will be used for all the decision events during the review period, i.e. up to the time $t_{rp(n+1)}$. Consider any event at time t_c requires the decision. For this decision event the old information of time $t_{rp(n)}$ will be used, i.e. there will be an information delay in decision process. The decision event can occur at any time between the review periods. The information used for decision process will be of time $t_{rp(n)}$, which leads to variable information delay. The decision for event at time t_c is invoked at time t_c without any delay. But the decision process takes some time and the decision gets implemented at time t_{imp} after delay of time Δt as shown in the Figure. Figure 1(i) shows one of the possibilities that the decision is implemented by the end of review period. Figure 1(ii) shows another possibility, that of decision process taking time so that the decision should be implemented after starting the next review period. Under these circumstances although the new information will be available at time $t_{rp(n+1)}$ the decision will be based on the old information of time $t_{rp(n)}$ because the decision process has started before the time $t_{rp(n+1)}$. The review period mode used in the simulation model is similar to that described in [Wadhwa and Bhagwat , 1998] but this paper focuses on its use in a simulation based approach using the Taguchi methods.

4. Motivation for Taguchi Methods

Taguchi's experimental design procedure may be

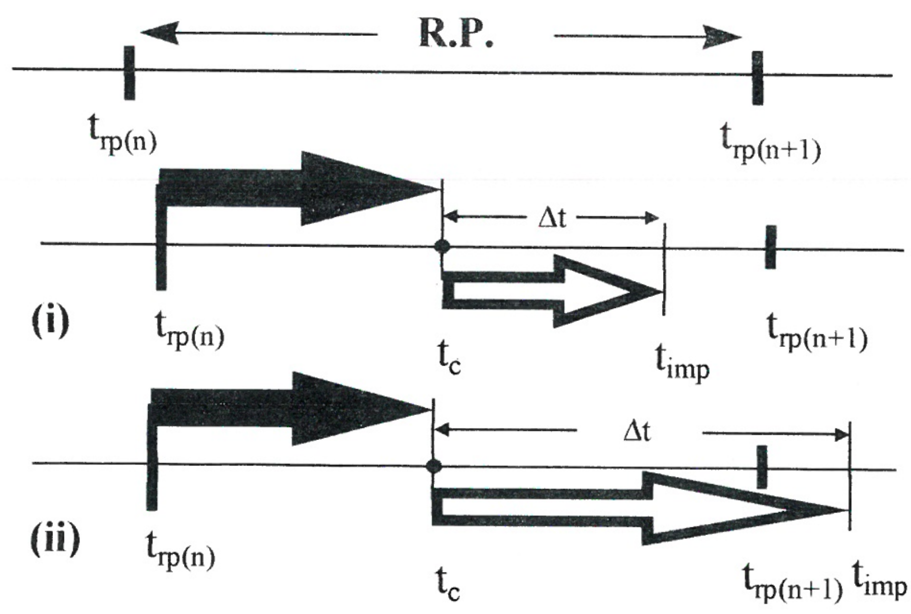

Figure 1. Decision and Information Delays in Review Period Based Information Monitoring Policy

adopted as a vehicle for conducting the simulation experiments more efficiently and effectively. Our intention in this paper is to study the effect of some key design and control parameters on the performance of SCFM, within which, information delay in the form of review period and decision delays are present. Our motivation here is in outlining a methodology which would help system designers/controllers get a quick insight into the relative importance of various design and control factors with respect to a defined measure of performance.

The operating conditions within the evolving manufacturing environment are often characterized by a continuous change. Within such an environment it is imperative to ensure that the system possesses appropriate levels of routing flexibility as well as an understanding of how it may be influenced by other factors such as decision and information delays. Further, we believe that system controllers are generally compelled to operate within stringent time constraints when reviewing the control decisions. As a consequence there is little justification, if any, for conducting an exhaustive simulation search while attempting to find the effect of each of the factors and its influence on the others. Not only would this be computationally prohibitive but perhaps would also be very time consuming. Even with factorial design to study the effect of 15 factors, each of two levels requires a total of 2^{15} (=32768) experiments is carried out. Hence there is a need for exploring a more effective design which, with reasonable levels of confidence could: (1) identify important factors that need be focused on; (2) prioritize amongst factors in terms of their relative effect on system performance and (3) guide us towards factor interactions that reduce the useful effects of a given control factor. Taguchi experimental design procedure provides a convenient framework for the purpose. In Taguchi method only 16 experiments are required to study the effect of 15 factors, each of two levels [Roy,1990]. In this paper we model a sample SCFM system and use simulation experiments based on the Taguchi method for estimating the contribution of individual factors and their interactions.

S.No	Factor Name (Symbol)	[Levels]
1.	Routing Flexibility(RF)	[RF=0(no routing flexibility), RF=1]
2.	Sequencing Rule(SR)	[SR = SPT (select the next job for processing which has Shortest Processing Time on machine), SR = MBPT (select the next job for processing which has Maximum Balance Processing Time)]
3.	Dispatching Rule(DR)	[DR = MINQ (send the part to the machine for next operation which has minimum queue), DR = MWT (send the part to the machine for next operation which has minimum waiting time in queue i.e minimum sum of processing times of all the parts waiting in the queue].
4.	Decision Delay	[DD = 0, DD = 8]
5.	Review Period	[RP = 0, RP = 35]

Interactions

6. Interaction between routing flexibility and sequencing rule(RF X SR)

7. Interaction between routing flexibility and dispatching rule(RF X DR)

8. Interaction between routing flexibility and decision delay (RFX DD)

9. Interaction between routing flexibility and review period (RF X RP)

10. Interaction between sequencing rule and dispatching rule (SR X DR)

11. Interaction between sequencing and decision delay (SR X DD)

12. Interaction between sequencing rule and review period (SR X RP)

13. Interaction between dispatching rule and decision delay (DR X DD)

14. Interaction between dispatching rule and review period (DR X RP)

15. Interaction between decision delay and review period (DD X RP)

Table 1. L_{16} - OA for Experimentation

COLUMN →	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Result
FACTORS → EXP. No ↓	RF	SR	RF X SR	DR	RF X DR	SR X DR	DD X RP	DR X DD	SR X RP	RF X RP	RP	DD	RF X DD	SR X DD	DR X RP	
1	RF=0	SPT	1	MINQ	1	1	1	1	1	1	RP=0	DD=0	1	1	1	16057
2	RF=0	SPT	1	MINQ	1	1	1	2	2	2	RP=35	DD=2	2	2	2	16833
3	RF=0	SPT	1	MWT	2	2	2	1	1	1	RP=0	DD=2	2	2	2	16565
4	RF=0	SPT	1	MWT	2	2	2	2	2	2	RP=35	DD=0	1	1	1	15818
5	RF=0	MBPT	2	MINQ	1	2	2	1	1	2	RP=35	DD=0	1	2	2	16200
6	RF=0	MBPT	2	MINQ	1	2	2	2	2	1	RP=0	DD=2	2	1	1	16735
7	RF=0	MBPT	2	MWT	2	1	1	1	1	2	RP=35	DD=2	2	1	1	15735
8	RF=0	MBPT	2	MWT	2	1	1	2	2	1	RP=0	DD=0	1	2	2	15698
9	RF=1	SPT	2	MINQ	2	1	2	1	2	1	RP=35	DD=0	2	1	2	15655
10	RF=1	SPT	2	MINQ	2	1	2	2	1	2	RP=0	DD=2	1	2	1	16262
11	RF=1	SPT	2	MWT	1	2	1	1	2	1	RP=35	DD=2	1	2	1	16711
12	RF=1	SPT	2	MWT	1	2	1	2	1	2	RP=0	DD=0	2	1	2	15516
13	RF=1	MBPT	1	MINQ	2	2	1	1	2	2	RP=0	DD=0	2	2	1	15542
14	RF=1	MBPT	1	MINQ	2	2	1	2	1	1	RP=35	DD=2	1	1	2	16913
15	RF=1	MBPT	1	MWT	1	1	2	1	2	2	RP=0	DD=2	1	1	2	16439
16	RF=1	MBPT	1	MWT	1	1	2	2	1	1	RP=35	DD=0	2	2	1	16090

The Taguchi experimental design paradigm is based on the matrix experiments technique [Phadke, 1989]. Experimental matrices are essentially special orthogonal arrays (OA) which allow that simultaneous effect of several process parameters and their interaction are studied efficiently. The term interaction is used when the influence of one factor depends on the condition of the other one. Taguchi's method determines relationships for interacting columns in OA. These relationships are present in a standard table called Triangular Table of interaction and contains information about the interaction of the various columns of OA.

The process of experiment design includes selection of the suitable OA, assignment of the factors and their interactions, if present, to the appropriate columns and determination of the conditions for individual experiments. The result of the Taguchi experiments has been analyzed by using analysis of variance (ANOVA). The contribution of each factor and the interaction between various factors of an experiment can be quantitatively determined by using ANOVA [Baguchi, 1993].

5. Matrix Experiment Details

To study the impact of the assumed factors within the SCFM system with six machines and six types of parts within, standard orthogonal array based simulation experiments were performed. Processing times are assumed to be deterministic with an average of operation time of 55 units of time. Taguchi's standard L_{16} OA (with two levels) was found suitable for experimentation for 5 factors and 10 interaction. All the fifteen columns of OA have been used. The columns for interaction have been allocated by using the rules of interaction described for Taguchi's method [Logothetis and Wynn, 1989]. In order to study the impact of review period time interval in detail an experiment has been designed, keeping the review period at two levels (i.e. 0 and 35 units of time), two levels of decision delay (i.e. at 0 and 2 units of time) . This has been done to study the critical effect of decision delays, information delay and their interaction with other factors. The two levels of routing flexibility have been taken as no routing flexibility (RF=0) and routing flexibility, RF=1 (RF=1 means that there is one more alternative machine available for processing the operation). The flexibility levels have been considered as it is assumed that maximum advantage of an increase in flexibility is achieved when the flexibility increases from RF=0 to RF=1. At SCFM system's operating level, the decision points to be considered are: (1) machine loading point, where decision of which part is to be loaded next on the machine from the queue of parts waiting in input buffer, when machine becomes idle, should be made. This is generally referred to as the sequencing decision/strategy, and (2) part dispatching point on the machine, where decision to which machine the part should be dispatched for the next operation out of the available alternative machines, is to be made. This is generally referred to as the dispatching decision/strategy. The two levels of sequencing and dispatching rules used in control strategies are: Shortest Processing Time (SPT) and Maximum Balance Processing Time (MBPT) as the sequencing rules. The dispatching rules used are MINQ (select the next machine for the next operation which has a minimum queue at input buffer) and MWT (select the next machine for the next operation which has a minimum waiting time in queue, i.e. a minimum sum of processing time of all the parts waiting in the queue).

Table 1 describes the details of the column allocation to different factors and their interaction with assumed levels for experimental conditions, according to L16 orthogonal array and the last column of the Table shows the results obtained. The respective factors and their interactions considered for study under Taguchi's method together with their assumed levels are as previously shown.

6. Results and Discussion

The simulation experiments based on Taguchi methods under L_{16} orthogonal array have been conducted for the assumed design and control factors explained earlier. Figure 2 shows the average effect of the five factors studied. Figure 2 illustrates that the decision delay (DD) has maximum influence on the makespan performance and next to decision delay, the review period time interval has an impact on the

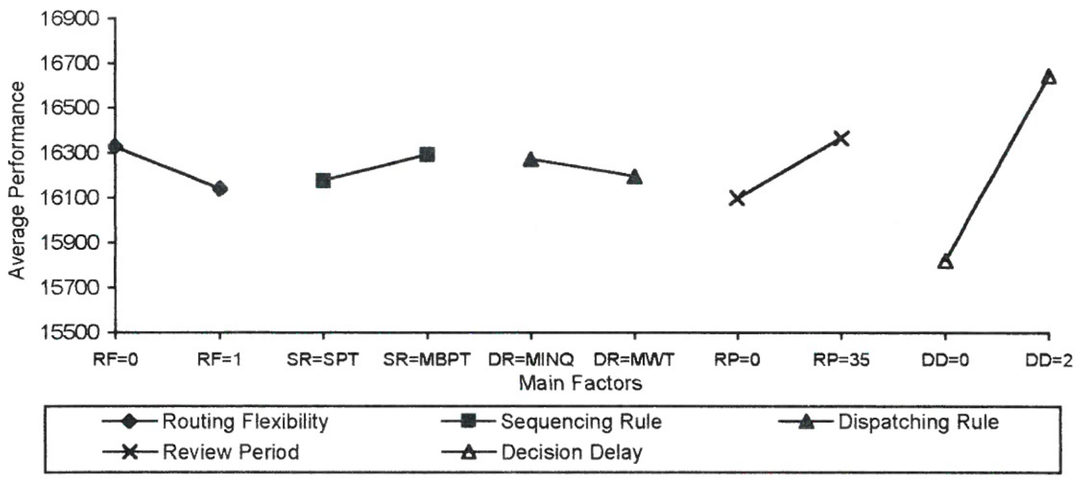

Figure 2. The Average Effects of Assumed Main Factors

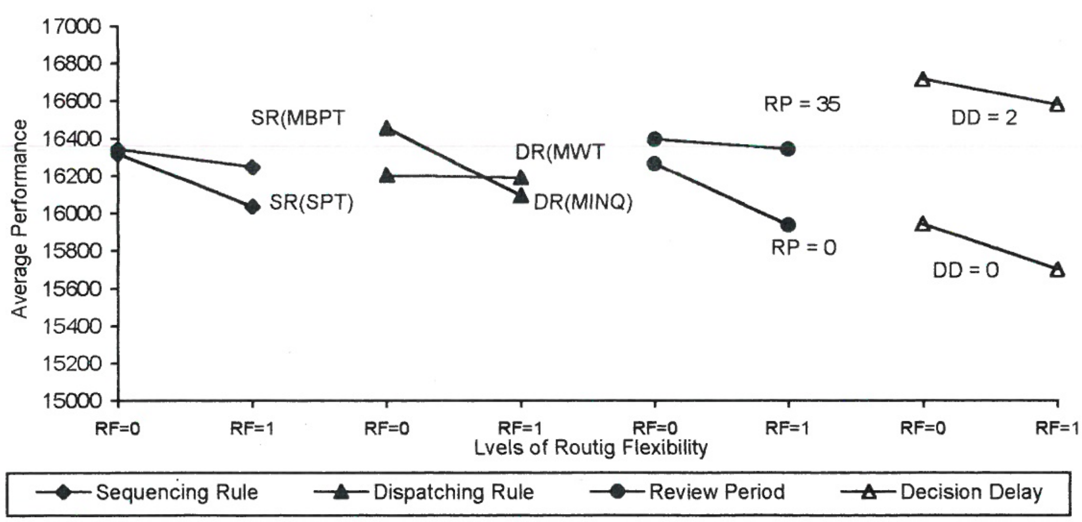

Figure 3. The Interaction of Routing Flexibility with Other Assumed Factors

makespan performance. It is to be noted here that the influence of review period time interval means more than the influence of the routing flexibility. The decision delay, which has 2 units of time variation between the two levels DD=0 and DD=2 [i.e. approximately 3.6% of the average processing time of the parts in the system], has maximum average effect on the makespan. The minimum effect is due to the dispatching rules. The Figure also illustrates that an increase in routing flexibility is quite advantageous.

Figure 3 shows the graph of interactions of routing flexibility with sequencing rule, dispatching rule, decision delay and review period time interval of the SCFM system studied. It illustrates that there exists a strong interaction between routing flexibility and sequencing rule (as the average performance lines of two levels of the sequencing rule are intersecting each other). This indicates that change in routing flexibility may influence the performance of sequencing rule significantly and vice versa. It can also be inferred that a different sequencing rule may perform better at different levels of routing flexibility. Further the dispatching rule also has a strong interaction with routing flexibility. This indicates that the control strategy (i.e. sequencing and dispatching decisions) has a strong interaction with routing flexibility in the SCFM system studied. The industrial implication for a SCFM controller is that if the flexibility in an SCFM system changes then its control strategy should also be re-examined.

The interaction effects of decision delays and review period time interval with the routing flexibility are also presented in Figure 3. It indicates that both of them have strong interaction with the routing flexibility. The change in the level of one factor will influence the performance of another factor. When review period is equal to zero (RP=0, a real time information) there is an advantage in the increase of flexibility (see line of RP=0), but this advantage minimizes when review period RP=35. This indicates that with an increase in review period time interval the advantage of the increase in routing flexibility decreases. Similar observation can be made for decision delays. The results also indicate that the sequencing rule has a strong interaction with review period. This means that performance of sequencing rule may depend on review period time interval. If the review period time interval changes, the performance of sequencing rule may also get affected. At different levels of review period, the different sequencing rule may perform better. It also suggests that if the review period of the SCFM system changes then the control rules must also be reviewed.

Finally, Table 2 shows the ANOVA analysis of experiments based on Taguchi's method. The Table shows factor names, Degree of freedom (df), Variance (V)(mean square), Variance ratio (F), Pure sum of squares (S') and Percent contribution on the makespan (P) after pooling the result. In Table 2 the degree of freedom of the error is 8 after pooling. The value of F-test from the standard Table for 8 degrees of freedom of the

Table 2

NAME OF FACTOR	df	S	V	F	S'	Production
RF	1	143073.06	143073.06	14.54	133235.62	3.76
SR	1	54639.06	54639.06	5.55	44801.62	1.26
DR#	1	24414.06	24414.06	-	-	-
RP	1	286492.56	286492.56	29.12	276655.12	7.80
DD	1	2736543.10	2736543.10	278.16	2726705.7	76.92
RF X SR#	1	34689.06	34689.06	-	-	-
RF X DR	1	121278.06	121278.06	12.32	111440.62	3.14
RF X DD#	1	11395.56	11395.56	-	-	-
RF X RP	1	72765.06	72765.06	7.39	62927.62	1.78
SR X DR#	1	3335.06	3335.06	-	-	-
SR X DD#	1	68.06	68.06	-	-	-
SR X RP	1	72765.06	72765.06	5.22	41578.12	1.17
DR X DD#	1	51415.56	51415.56	-	-	-
DR X RP#	1	1072.56	1072.56	-	-	-
DD X RP#	1	3630.06	3630.06	-	-	-
ERROR#	8	78699.47	9837.43	-	-	4.17
TOTAL	15	3544905.9	236327.06			100.00

Pooled Factors

error is 5.5 at 95% confidence interval. The value of variance ratio (F) of almost all the factors and interactions in Table 2 are more than the standard value 5.5, which shows that the percentage contribution of all factors and interactions having value of 'F' more than 5.5 has significance. Table 1 shows that the decision delays have the maximum percent contribution on the makespan performance. The second important factor is the review period time interval and its relative contribution is greater than the routing flexibility. The presence of interaction between routing flexibility and review period shows that the benefit of routing flexibility gets affected by the review period.

The control system in SCFM is crucial to effectively exploit the flexibility. Since the entity flows are more complex in SCFM systems than even in FMS, its control is more challenging and must effectively use simulation models. An approach based on the Taguchi methods can dramatically reduce the need for simulating all possible factor level combinations in order to identify the priority factors. In the case discussed above, with only 16 simulations (for the sample SCFM modeled) we are able to identify the priority factors (i.e. those with relatively high contribution) and the key factor interactions. A controller should mainly focus on the priority factors and should make sure that factors that cause counter-productive interactions are kept under severe control. This paper demonstrates and establishes the efficacy of the use of the Taguchi methods in order to effectively and efficiently determine what the controller should focus on to ensure high performance in the SCFM systems.

We now briefly discuss the industrial implications of the SCFM model on an increased control effectiveness using the Taguchi method. In our opinion the SCFM model may be seen as a phased CIM development building block to cater for the needs of the evolving manufacturing environment. Similar to an FMS (which is a mini-CIM), an SCFM is essentially a flexible system whose flexibility is realizable through the use of on-line control strategies provided the decision delays are within given limits. In FMS we have an on -line control which is a real time control. In SCFM we have an online control which is not necessarily real time control as it is associated with decision and information delays. As the level of decision automation and/or information automation increases, an SCFM approaches the performance of a similar configuration based FMS. In many industries computerization is carried out in phases while evolving towards a CIM system. An SCFM system represents this along the decision automation dimension. Thus we consider the SCFM model as a phased CIM development model within a manufacturing system. If the domain of SCFM is enlarged to include the interacting entities on the supplier and customer sides, then the SCFM model may also represent a phased Computer Integrated Manufacturing and Logistics (CIML) system. The motivation for focussing on the decision automation dimension resides in our experience with the GRAI methodology for CIM development where decision system is considered to be an important system. We believe that the evolution towards supply chain management and extended enterprises is also going to be in phases from a decision automation viewpoint. Hence the concept of SCFM model as an underlying framework may be quite useful.

6. Conclusions

The simulation experiments based on Taguchi methods under the L_{16} orthogonal array have been conducted for a sample SCFM system. It is shown that the decision delays have a maximum influence on the makespan performance followed by the review periods. The results indicate that the influence of review periods is more than the influence of the routing flexibility. Contrary to our knowledge about the FMS, the minimum factor effect in SCFM system was that of the dispatching rules. However, similar to the FMS, an increase in routing flexibility is quite advantageous. There exists a strong interaction between routing flexibility and the sequencing control rules used. This indicates that a change in routing flexibility may influence the performance of the sequencing rule significantly and vice versa. It can also be inferred that a different sequencing rule may perform better at different levels of routing flexibility. Further the dispatching rules also have a strong interaction with the routing flexibility. This indicates that the control strategy (i.e. sequencing and dispatching decisions) has strong interactions with the routing flexibility in the SCFM system considered. An important industrial implication for an SCFM controller is that that while changing the flexibility of any SCFM system, its control strategy should also be carefully reviewed.

The decision delays and review periods have strong interaction with routing flexibility. The change in level of one factor will influence the performance of another factor. With an increase in review period, the advantage of increase in routing flexibility decreases. Similar observation can be made for decision delays. The results also indicate that the sequencing rule has strong interaction with review period. This means that the performance of sequencing rule may depend on review period. If the review period changes, the performance of the sequencing rule may also get affected. Thus if an increased computerization may result in an improved information system with reduced review period then the control rules should also be reviewed. The ANOVA analysis shows that the decision delays have the maximum percent contribution to the makespan performance. The second important factor is the review period time interval and its relative contribution is greater than the routing flexibility. The presence of interaction between routing flexibility and review period shows that the benefit of routing flexibility gets affected by the review periods.

The control system in SCFM is crucial to effectively exploit the flexibility. Since the entity flows are more complex in SCFM systems than even in FMS, its control is more challenging and must effectively use simulation models. An approach based on Taguchi methods can dramatically reduce the need for simulating all possible factor level combinations in order to identify the priority factors. In the case discussed above, with only 16 simulations (for the sample SCFM modeled) we are able to identify the priority factors (i.e. those with high relative contribution) and the key factor interactions. A controller should pay his highest attention to the priority factors and should make sure that factors that cause counter-productive interactions must be kept under severe control. This paper demonstrates and establishes the efficacy of the use of the Taguchi methods to effectively and efficiently determine what the controller should focus on to deduce high performance from the SCFM systems. We propose that the SCFM model shall be used in phased development of Computer Integrated Manufacturing and Logistics systems as well.

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