Journal of the Korean
OR/MS Society
Vol. 22, No. 2, June 1997

A Look-Ahead Routing Procedure in an FMS

Jaejin Jang * · Jeongdae Suh**

Abstract

Many dispatching rules have been developed for the on-line control of product flow in a job shop. The introduction of a flexible manufacturing system (FMS) has added a new requirement to a classical job shop control problem: the selection of machines by parts of different types. An FMS can keep a great deal of information on the status of the system, such as information on what is scheduled in the near future, with great accuracy. For example, the knowledge of the time when the next part will arrive at each machine can be beneficial for the routing. This paper tests the effect of the use of this knowledge for part routing on the parts flow time (sum of the time for waiting and service) under a simple routing procedure - a look-ahead routing procedure. A test under many operating conditions shows that the reduction of part flow time from the cases without using this information is between 1% and 11%, which justifies more study on this routing procedure at real production sites when machine capacity is a critical issue. The test results of this paper are also valid for other highly automated systems such as the semi-conductor fabrication plants for routing when the arrivals of parts in the near future are known.

1. Introduction

In the past three decades there has been a substantial growth in the field of sequencing and scheduling research. This research can be divided mainly into two categories: theoretical research dealing with optimization procedures limited to static problems in which all parts are ready for processing at the time of scheduling, and experimental research dealing with dispatching rules for the real time control of product flow in both static and dynamic cases. While the optimization techniques

* FA Research Institute, Samsung Electronics Co.
** Department of Industrial Engineering, Kyungwon University

are needed for planning and for better understanding of the product flow, factory operation also needs a real-time control scheme because of the random disturbances frequently encountered in a production shop. Some of the disturbance sources include machine breakdowns, tool non-availability, production of defective parts, shortage of raw material supply from outside vendors, urgent part orders, mistakes in inventory-level identification, order cancellations, operator mistakes, and operator absences.

The determination of a real-time shop control scheme is mainly constrained by two factors: computation power and information availability. In an ideal case, if all information about the factory state is always available and if a fast enough computation machine for the manipulation of the information is available, the optimal solution could be provided in real time whenever it is needed.

The application of traditional dispatching rules [1, 2, 13, 17] has been constrained partly by the information needed. For example, the use of the minimum-dynamic-slack- among-all-imminent-jobs dispatching rule [13] needs on-line information of the total factory system. The rule considers the dynamic slack (due date minus the remaining expected flow time minus the current date) for all parts in the queue and in process which will join the queue after their current operation is complete. Such information cannot be provided if the system is not linked by a computerized information network. This type of data acquisition problem creates a difficulty for the application of some dispatching rules. But a computerized manufacturing system such as an FMS can keep the most updated information of the shop and can largely eliminate those types of difficulties.

Another traditional constraining factor of dispatching rule selection is the computation time of the algorithm. While the problem of information availability is largely solved by the introduction of computerized systems, the computation time problem stays the same as before. Even though the number of machines to be considered in an FMS is reduced greatly from the systems with conventional machines, the size of dispatching problems of the FMS is not changed much due to the complex nature of the real time shop floor control problem. Moreover, the rapid development of computer hardware and software technology does not seem to have solved the problem yet. Instead, many dispatching rules have been proposed for the real time control of product flow which do not need much computation power.

To reduce the parts flow time (sum of the time for waiting and service) in an FMS, this paper presents a new look-ahead routing procedure (LARP) which uses the information of the information-intensive manufacturing systems such as an FMS, and tests the effect of the use of this knowledge. A simulation study shows that the reduction in flow time by the application of this simple procedure is between 1 to 11%.

2. Dispatching Rules with Alternative Routing

While the dispatching rule traditionally determines only the next part to be processed on a given machine, the dispatching rule in an FMS can have a new requirement - the selection of a machine by the parts of different types. Most approaches for part dispatching with routing flexibility can be grouped into three: (1) using dispatching rules similar to those of a classical job shop problem with slight modification of the definition of the rules, (2) using entropy-based dispatching rules, and (3) using look-ahead procedures.

Dispatching rules such as the shortest process time (SPT) dispatching rule and the minimum slack time rule (SLACK) tested by Kim [10] belong to the first case. Chandra and Talavage [3] propose an intelligent dispatching rule for an FMS. The rule dynamically sets the objective of the flow control considering the status of the system, and identifies the critical part. The most preferred machine by the critical part is assigned to the part. When there is a conflict for the determination of the machine, it considers the flexibility of the routing of the machine and checks secondary objectives. The fact that this system changes the machine selection criteria dynamically makes the system more practical.

Lin and Solberg [12] use data flow dispatching rule (DFDR) strategy to test several dispatching rules. The DFDR strategy assigns a part to the queues of the machines where the part can be processed. The part stays on the multiple virtual queues until it is actually assigned to a machine based on the priority rules. Several classical queueing rules including SPT, FIFO, and FCFS are tested.

Ishii and Talavage [8, 9] propose a real time control scheme for an FMS which selects a dispatching rule dynamically for the next short time period to respond to the change of system states. Simulation is used to evaluate the candidate dispatching rules, and the scheduling interval associated with the selected dispatching rule is defined based on the system transient state. A mixed dispatching rule which can assign different dispatching rules to each machine is proposed. A search algorithm which selects an appropriate mixed dispatching rule using predictions based on discrete event simulation is developed.

Piplani and Talavage [18] consider the problems of launching and dispatching of parts in closed manufacturing systems with flexible routing. They have investigated combinations of launching and dispatching rules, and have attempted to identify suitable combinations for the performance criteria of interest. To achieve production rates, they suggest that launching rules be utilized, and to affect flow time, that dispatching rules be manipulated.

Yao and Pei [24] propose a machine selection rule based on the entropy change of the system. An operation is assigned to the machine with the highest probability that the operation can be completed before it breaks down. This rule is effective when machine failure is an important factor for machine selection.

3. Existing Look-Ahead Procedures

However, the above approaches are limited in that most of them use the information of the average behavior of the system for the dispatching determination at a specific point in time. A modern computerized system such as an FMS provides much on-line information and makes it possible for the control system to 'look-ahead' to what is happening in the future for the schedule generation. Traditionally, a look-ahead algorithm looks ahead to the places for the parts to go. For example, it can consider the queue lengths of the next machines. In this case, the procedure selects a part from those waiting for the machine service. Recently, another type of look-ahead control scheme has been proposed. It looks ahead to the future states of a production shop, and uses the information of the shop obtained by looking a few steps ahead to see the effect of the current decision on the flow time of the few parts arriving next.

Koulamas and Smith [11] develop a look-ahead procedure to prevent machine interference when a smaller number of operators are attending to a larger number of machines. Zeestraten [25] proposes another look-ahead procedure for solving the minimum makespan problem for job shops with routing flexibility. Each run of the procedure results in an assignment of one operation to a machine. The procedure searches the future state space of the system within approximately twice the average cycle time. He reports the result is consistently better than that obtained with ordinary priority dispatching rules. Glassey and Wang [7] consider a batch production system, where a machine waits for the arrivals of parts so that the parts can be processed by batch. They compare the minimum batch size policy where the machine waits until the number of parts exceeds a fixed minimum batch size and a look-ahead procedure where the future part arrivals are considered for the determination of the batch size. Engell, Kuhn, and Moser [6] use a one-step look-ahead procedure to select a part from a waiting queue, where the current workload of the next machines of the waiting part to go is considered. Doulgeri, Hibberd, and Husband [5] generate non-delay schedules and simulate the future conflict of tools and other resources based on look-ahead. They use a full enumeration method for the non-delay schedules. Vepsalainen and Morton [22] develop a dispatching rule named apparent tardiness cost rule for the tardiness minimization problem using a look-ahead factor to reflect the degree of congestion in the shop. Smith and Stecke [21] modeled the look-ahead capability by delaying the decision of which input buffer for the part to enter until a machine actually becomes available.

4. Look-Ahead Routing Procedure

All of the above procedures used the information obtained by looking-ahead. However, none report the effect of routing procedures based on looking-ahead to the future on the reduction of part flow time, which is discussed in this paper. This paper analyses the effect of using this information and develops a procedure to estimate the reduction in flow time under various input and service conditions. The same procedure also can be used for other types of manufacturing and service systems such as semi-conductor production plants where there are alternative routings and the information for looking-ahead is available.

Let us consider an FMS which has alternative routings. Parts of different types can be processed by several machines possibly with different processing times. Upon the introduction to the FMS or after finishing an operation, parts select machines for next operations. The routing rule determines the machines on which the parts will be processed next. The objective of the choice is to reduce the flow time of the parts. The reduction in flow time reduces the average work-in-process (WIP) level and/or increases the production rate. In this paper, a first-come-first-assigned policy is used for machine selection by parts arriving for machine service, and a first-come-first-served policy is used for part selection by machines from queues waiting for machine service. (First-come-first-assigned policy is needed if the parts need to be shipped out from the out-buffer area to prevent blocking, and if the parts need to be shipped directly to the next machines to reduce the number of transportation by automated material handling system such as AGVs.) The reduction in flow time has been the objective of many scheduling studies and real production applications. No capacity limit is assumed for the queues in the FMS.

Traditionally, the routing decision for an arriving part is made without considering other parts arriving at the same machine later than the current part. So the current part is sent to the machine which is most favorable to it. However, this procedure does not necessarily give the minimum flow time when the total parts processed by the machine are considered. As a result of such traditional dispatching rules, for example, if a machine which can process the part is idle, the part is assigned to the machine, resulting in a non-delay schedule. But classical scheduling theory says that sometimes a delay schedule performs better than non-delay schedules, implying the intuitively obvious fact that the incoming part can yield the most preferred machine to other parts coming later.

The routing procedure used in this paper considers parts arriving in the near future in a very natural way which can be used in a real production shop very easily. An N-step look ahead routing procedure (LARP) for the reduction of flow time in an FMS is as follows:

The new part is assigned to the machine which minimizes
the sum of the flow time of the current and the next N parts.

Disney and Kiessler [4, Section 3.4] consider a similar problem, an M/M/1 overflow queue with L=0, where the arrivals are lost if the server is busy. Nawijn [14] also considers a service system with a single server, finite waiting room, and a renewal arrival process. Customers who arrive while the server is busy are lost. Upon completing service, the server either starts new service or waits for the next customer. At the time of decision making, the next part arrival time is known, but its service time is unknown. Nawijn [15] considers a similar case, where the server does not have any buffer, and the arrivals during the server's busy period are lost. With the assumption that the server knows the inter-arrival time and service time of next arrivals, the server decides whether or not to accept a customer in order to maximize the reward of all customers considering the next arrivals. Both of the above works derive analytical formulae to estimate the reward increase. Analytical work is extremely complicated for the positive buffer size cases [15].

One-step LARP

One-step LARP considers the part which just arrived (part 1) and one more part arriving next (part 2). It determines the machines for the two parts to join to minimize the flow time of the two parts, and assigns part 1 to the machine determined by the procedure. The actual machine for part 2 to join will be determined by the same procedure when part 2 actually arrives.

Figure 1 explains a look-ahead-routing-procedure. In the figure, W_a, W_b, and W_c are the current amount of work on machines A, B, and C, respectively. P_{ij} is the processing time of part i on machine j (i = 1,2; j = A, B, C). For a one-step LARP, only three machines need to be considered at maximum. The part inter-arrival time between part 1 and part 2 is x. Let machine A be most preferred by part 1. So, $W_a+P_{1a} \leq W_j+P_{1j}$ for all j. Let Part 1 prefers machine B to machine A. Now we want to determine if part 1 should be processed on machine A or not considering part 2 in order to reduce the flow time of part 1 and part 2.

The calculation procedure is as follows. Here the first and second steps are to remove trivial cases from consideration.

(1) If part 2 arrives after part 1 finishes the service on machine A (i.e., $x \geq W_a+P_{1a}$), then part 1 does not have to worry about part 2, and part 1 goes to machine A.

(2) If part 2 does not prefer machine A even if the existence of part 1 is ignored (i.e., $(W_a - x)^+$

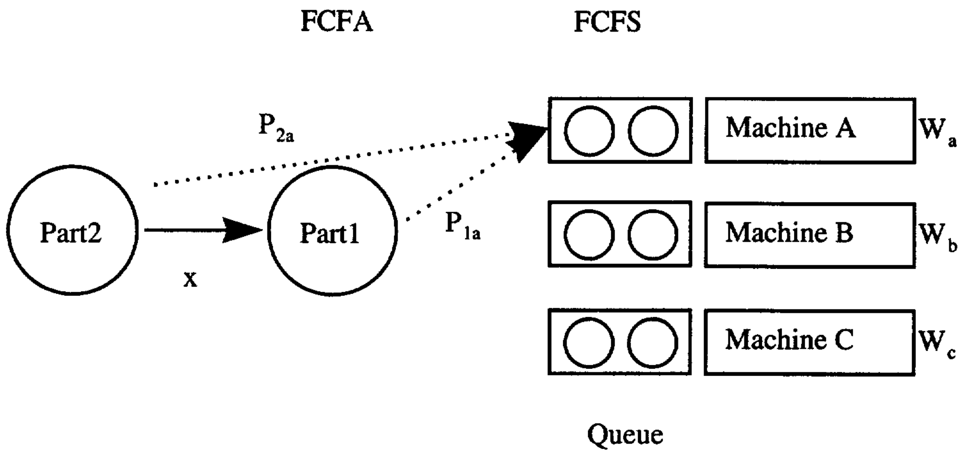

Figure 1. One-step look-ahead procedure.

$+ P_{2a} (W_j - x)^+ + P_{2j}$ for some $j \neq a$), then part 1 and part 2 prefer different machines, and part 1 goes to machine A. Here $(y)^+$ is the maximum value of y and zero; it is used to prevent a negative value of waiting time.

(3) In other cases, we need more calculation. Now part 2 also prefers machine A most. Let machine C be the machine which part 2 prefers next to machine A when it ignores the existence of part 1. Machine B and machine C can be the same machine.

Now we need to compare the following three cases.

Case 1: Both of part 1 and part 2 are processed on machine A.
Case 2: Part 1 is processed on machine A, and part 2 is processed on machine C.
Case 3: Part 1 is processed on machine B, and part 2 is processed on machine A.

The flow time of the two parts for the above three cases is given in Table 1. The assignment of part 1 is based on the sum of the flow times of the two parts. If the sum of the third row is smaller than the sum of the first row and also smaller than the sum of the second row, part 1 is sent to machine B; otherwise, part 1 is sent to machine A.

N-Step LARP

For the N-step LARP when N is larger than one, no simple result for the comparison like Table 1 is obtained, and this paper uses an enumeration method for the comparison. A total of $\sum_{i=0}^{N} {}_{N+1}C_i$

Table 1. Flow time of part 1 and part 2 for the three assignments cases.

	part 1	part 2	machine preferred by part 1
Case 1	W_a+P_{1a}	$(W_a + P_{1a} - x)+ + P_{2a}$	machine A
Case 2	W_a+P_{1a}	$(W_c - x)+ + P_{2c}$	machine A
Case 3	W_b+P_{1b}	$(W_a - x) + + P_{2a}$	machine B

cases need to be considered. The development of a computationally faster procedure for the N-step look-ahead procedure is a separate big problem from this routing problem and is not investigated further in this research. In most real application cases, the time needed for the calculation by the enumeration method would not be a big burden for the controller if N is not very large.

5. Estimation of the Flow Time Reduction

It is fairly obvious for LARP to reduce the flow time of the parts. This section tests the range of the reduction in some selected cases and develops a formula to estimate this reduction by using simulation and regression.

5.1 Simulation

To test the effect of LARP on the reduction of flow time, the simulation considers a system consisting of four machines, which is a good size for FMSs. The processing time of the parts in the system is fixed and different depending on the machine which processes the part. The parts need just one machine to finish all necessary operations. (See Section 5.5 for other cases.) The parts arrive following an inter-arrival time distribution and are served following a service time distribution.

The simulation considers the following five factors:

Factor 1: Number of Look Ahead Steps (N). This is the number of parts arriving next to the current part which LARP considers. It is anticipated that when the number increased, there would be more reduction in the flow time. The levels are as follows:
Flag 1 = 1 when N = 1, Flag 1 = 2 when N = 2, and Flag 1 = 3 when N = 3.

Factor 2: Machine Utilization (U). Because the machining time is different for different machines, the exact machine utilization is not determined before the simulation (or actual production) is complete. The levels are determined based on the average processing time of the four machines. (See the explanation of Factor 3.)

Flag 2 = 1 when U= 50%, Flag 2 = 2 when U = 70%, and Flag 2 = 3 when U = 90%.

Factor 3: The Efficiency Difference (ED). This factor is the processing time difference between the four machines.

Flag 3 = 1, when ED = 10% (Average processing time: 0.85, 0.95, 1.05, 1.15),

Flag 3 = 2, when ED = 20% (Average processing time: 0.70, 0.90, 1.10, 1.30), and

Flag 3 = 3, when ED = 30% (Average processing time: 0.55, 0.85, 1.15, 1.45).

Here, the average processing time for the four machines are set to one and the speed of each machine is determined by the percentage change from the average value.

Factor 4: Squared coefficient of variation of parts inter-arrival time (CV_a^2). (Coefficient of variation is the ratio of the standard deviation and the mean.) For Poisson arrivals, the coefficient of variation is one.

Flag 4 = 1 when CV_a^2 = 1, Flag 4 = 2 when CV_a^2 = 1/2, and Flag 4 = 3 when CV_a^2 = 1/3.

Factor 5: Squared coefficient of variation of a parts service time (CV_s^2). For exponential services, the coefficient of variation is one.

Flag 5 = 1 when CV_s^2 = 1, Flag 5 = 2 when CV_s^2 = 1/2, and Flag 5 = 3 when CV_s^2 = 1/3.

Simulation is performed for the above 3^5 = 243 cases. (See Table 2.) Each case has three simulation runs which use different random number sequences, and the average of the three runs is used for the following analysis. Each of the three runs has one million transactions (part arrivals).

Table 2. Factors and levels of the simulation.

Flag	Factor	Level
1	Look-Ahead Steps	1, 2, 3
2	Machine Utilization	50%, 70%, 90%
3	Efficiency Difference	(See the text)
4	CV_a^2	1, 1/2, 1/3
5	CV_s^2	1, 1/2, 1/3

5.2 Simulation Results

The simulation results are given in the appendix, and the relative reduction in flow time is shown graphically in Figure 2. Figure 2 shows that the reduction in flow time by LARP under the FMS configuration used in the simulation is up to 5% for one step look-ahead, 8% for two step look-ahead, and 10% for three step look-ahead procedures. Figure 3 shows the result graphically for selected cases. In the figure, the horizontal axis is the number of look-ahead steps. The vertical axis is the flow time reduction ratio (%) from the cases without look-ahead. The simulation result shows the following:

(1) As the number of look-ahead steps increases, the flow time reduction by LARP increases also. Although the curve was expected to have a convex form because the reduction in flow time due to the look-ahead should be bounded as N increases, the simulation result shows this tendency weakly within three steps of look-ahead.

(2) As the average utilization of the machines increases, the flow time reduction increases also.

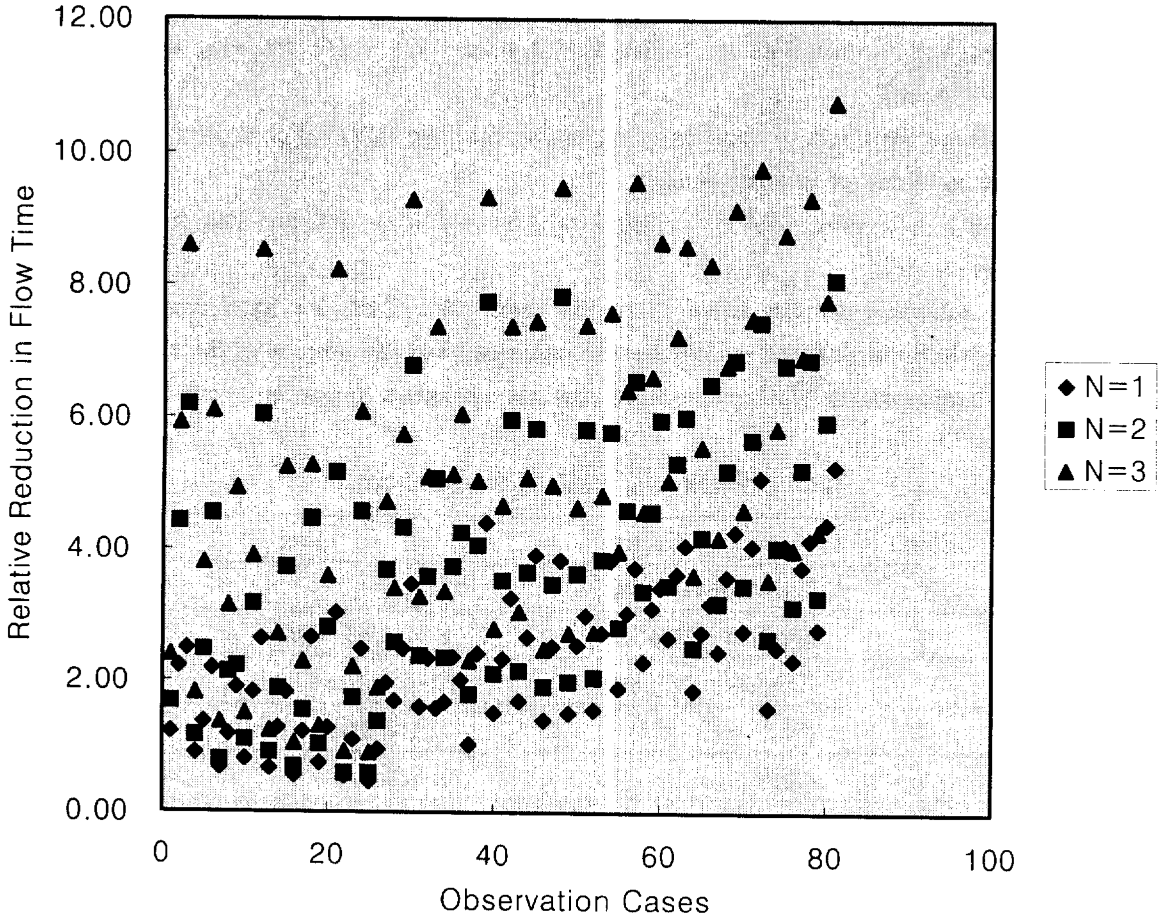

Figure 2. Relative reduction in flow time (%). N is number of look-ahead steps. Observation case number is explained in Appendix.

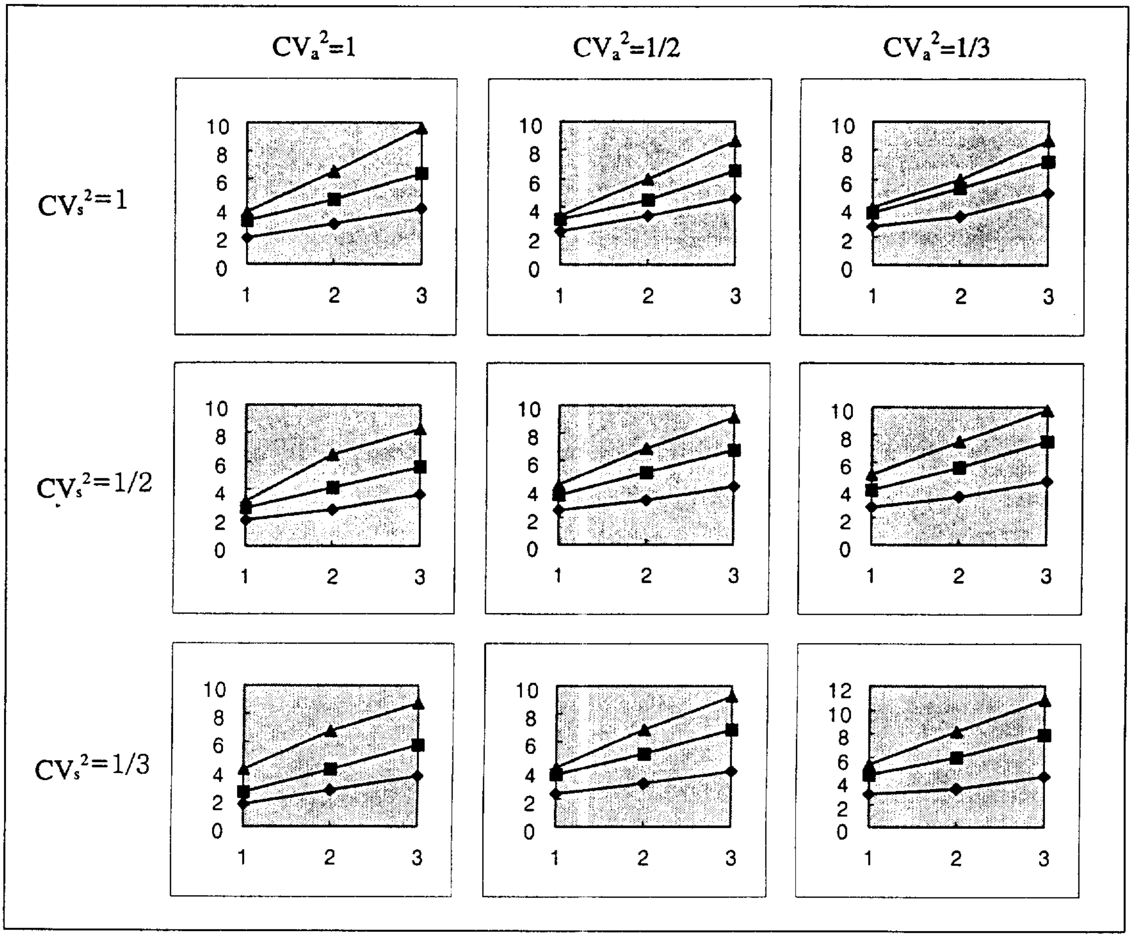

Figure 3. Relative reduction in flow time obtained by simulation for selected cases of ED=30%.

(◆ U=50%; ■ U=70%; ▲ U=90%)

Utilization affects the degree of reduction most significantly among the five factors except for the number of look-ahead steps.

(3) As the processing time difference among the machines increases, the flow time reduction increases also. This tendency is larger for larger value of CV_s^2.

(4) CV_a^2 does not affect the degree of reduction much. This result is important for the application of LARP to the system in a similar configuration to what is used in the simulation. The calculation of CV_a^2 needs the variance of the parts inter-arrival time. However, among the means and variances of inter-arrival time and service time, the observation (or estimation) of this value is most difficult. To get the information for the mean inter-arrival time, we only have to count the parts processed by the system during a fixed time period, and this value

can usually be obtained from the production plan. The mean and the variance of the service time can be obtained from the machines operation records or from the NC codes. On the other hand, the acquisition of the variance of parts inter-arrival time needs the observation of the queue (or buffer area) of the machines, and typically this value is monitored far less frequently than the other values. The fact that CVa2 does not affect the reduction of the flow time much by LARP makes the application of the routing rule easier and more practical. Quantitative analysis is given in the next section on the basis of regression.

5.3 Estimation of the Reduction in Part Flow Time

Based on the shape of the curves shown in Figure 3, a regression model is designed as a second order curve of the number of look-ahead steps (N) as follows:

$$FTR = A_o + A_1*N + A_2*N^2 + (\text{Error Term}),$$

where FTR is Flow Time Reduction by LARP.

Although when N=0 FTR should be zero also, the shape of the curves in Figure 3 requires the Ao term in the regression model. The coefficients of this second order curve are modeled as the sum of zero, first, and second order terms of the other factors (U, ED, CV_a^2, CV_s^2) such as U, ED,

Table 3. Regression result when CVa2 is used. EFTR = $\sum_{j=0}^{N}(C_j * V_j)$.

No j	Variable V_j	Coefficient C_j	Sig T
1	(Constant)	-0.625451	.0601
2	N	-1.956038	.0000
3	ED	12.668008	.0000
4	ED^2	-11.212593	.0449
5	$U*CV_s^2$	-1.643531	.0011
6	$ED*N$	8.821247	.0000
7	CV_a^2*N	1.353141	.0000
8	U^2*N	2.866305	.0000
9	$U*CV_a^2*N$	-1.692998	.0000
10	$U*CV_s^2*N$	4.964798	.0000
11	$ED*CV_a^2*N$	-2.588305	.0000
12	$ED*CV_s^2*N$	-11.483934	.0000
13	$U*CV_s^2*N^2$	-.792766	.0000
14	$ED*CV_s^2*N^2$	1.160013	.0186
15	$CV_a^2*CV_s^2*N^2$	.278830	.0000

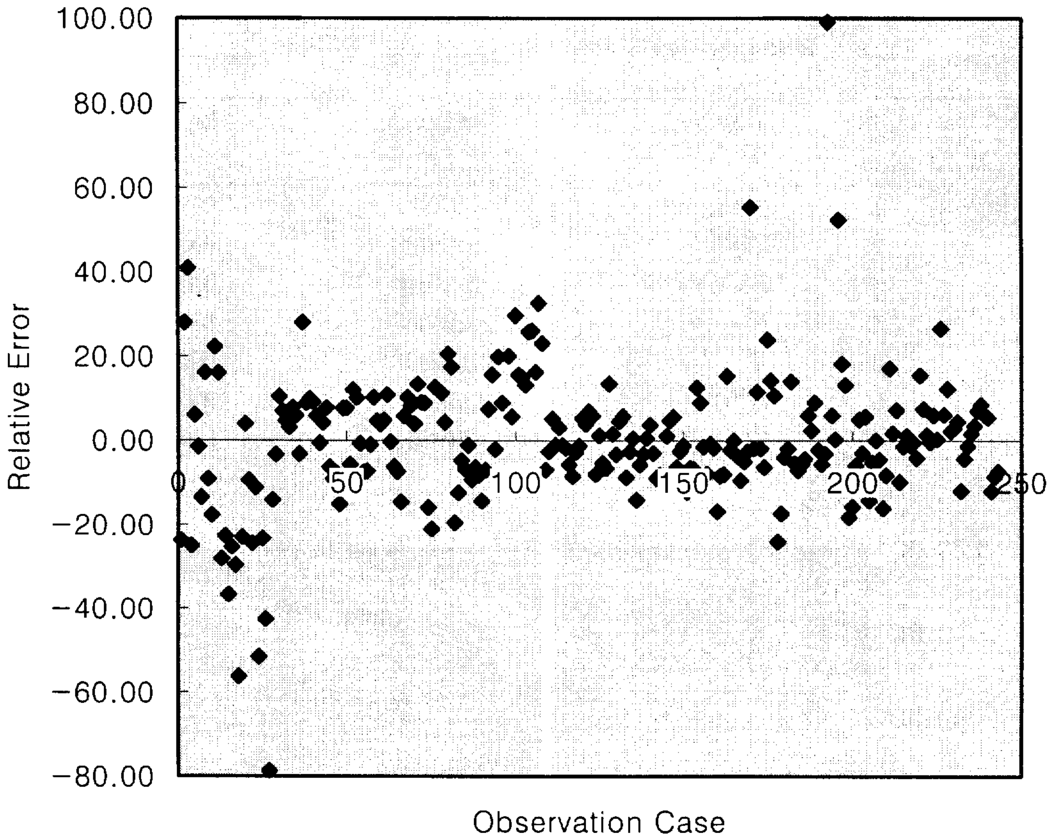

Figure 4. Relative error of flow time reduction by regression (%).

U*ED, and $CV_a^2 * CV_s^2$. A total of 44 independent values are used for the regression. The regression used a stepwise scheme for variable selection. An independent variable enters the regression when the F-value is smaller than 0.05 and leaves the regression when the value is larger than 0.1. The regression result is summarized in Table 3. In the table, EFTR is the estimated value of FTR. Figure 4 shows the relative error of the regression. In the figure, y-axis (relative error) is (EFTR-FTR)/FTR. According to Figure 4, about 87% of the estimation error is between -20% and 20% which seems to be good enough for real applications.

Because the variance of the parts inter-arrival time is difficult to observe or to estimate and the effect of this value is small, another regression is performed by using the independent variables which do not need CV_a^2. A stepwise regression is performed under the same conditions as those for Table 3. The regression result is given in Table 4 and Figure 5. About 79% of the total observation cases have relative error between -20% and 20%. Although this fitting is worse than the previous case, this also seems to be useful for an actual application when there is no information on CV_a^2.

Table 4. Regression result when CV_a^2 is not used. EFTR = $\sum_{j=0}^{N}(C_j * V_j)$.

No j	Variable V_j	Coefficient C_j	Sig T
1	(Constant)	-0.976494	.0000
2	ED*N	9.775702	.0000
3	$ED*CV_s^2*N^2$	-2.710518	.0000
4	N^2	-0.357967	.0000
5	U^2	2.9322431	.0000
6	U^2*N^2	0.303427	.0000
7	$U*CV_s^2*N^2$	0.934926	.0000

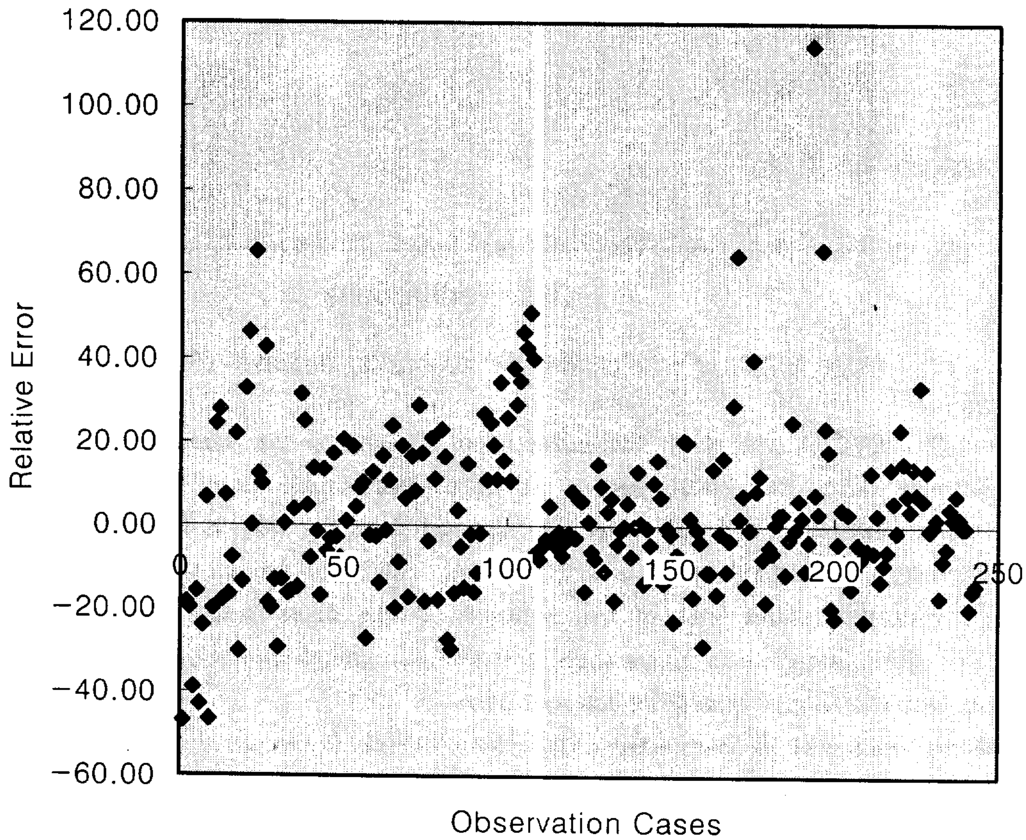

Figure 5. Relative error of flow time reduction by regression (%) when no information of CV_a^2 is used.

5.4 Accuracy of the Estimation

To test the accuracy of the regression curve given in Table 3, a set of relative errors between the true flow time reductions obtained from simulation and the estimated flow time reductions obtained based on the regression curves are compared. The levels of the factors used in the simulation are as follows:

Flag 1 = 1, when N = 1, Flag 1 = 2, when N = 2, and Flag 1 = 3, when N = 3.

Flag 2 = 1, when U= 60%, and Flag 2 = 2, when U = 80%.

Flag 3 = 1, when ED = 15%, and Flag 3 = 2, when ED = 25%.

Flag 4 = 1, when CV_a^2 = 1/2.5, and Flag 4 = 2, when CV_a^2 = 1/3.5.

Flag 5 = 1, when CV_s^2 = 1/2.5, and Flag 5 = 2, when CV_s^2 = 1/3.5.

While Gamma distributions are used in Section 5.1, triangular distributions are used in this section.

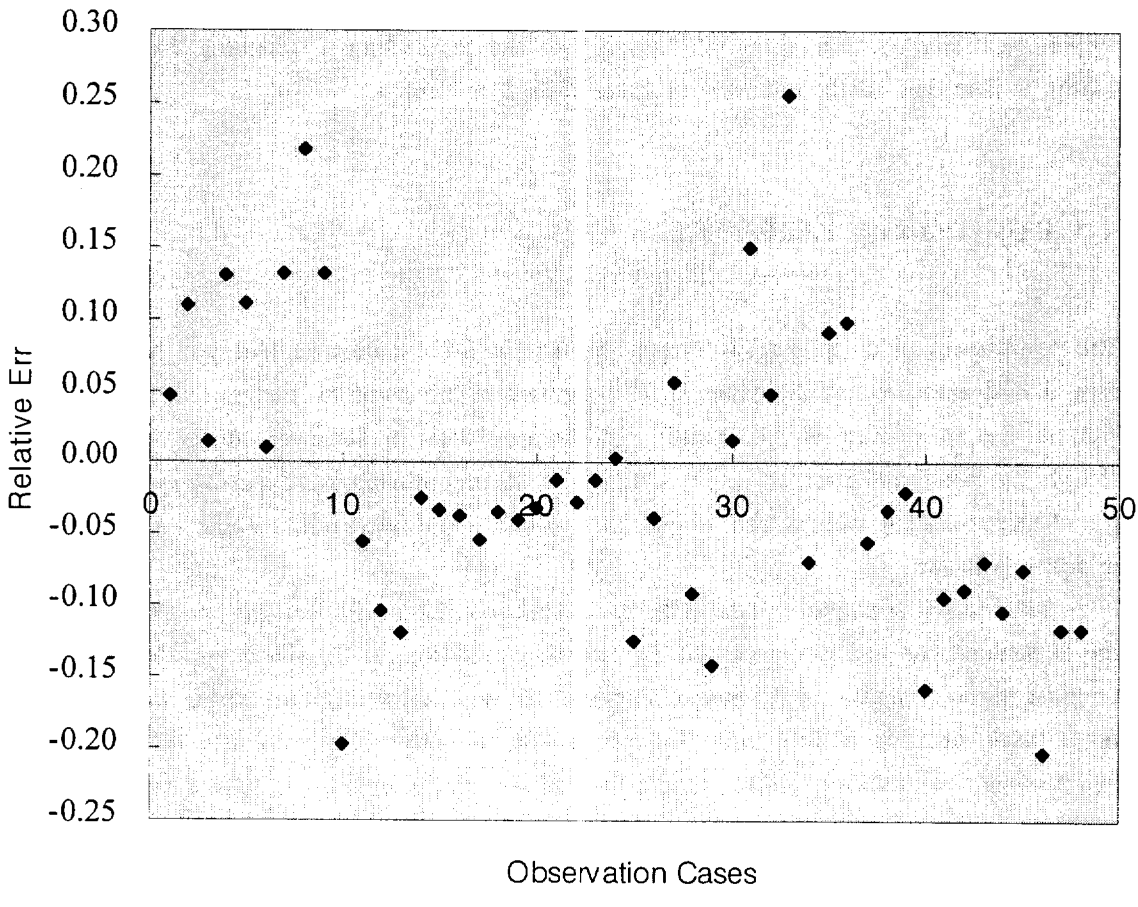

Figure 6. Relative error of the estimation of flow time reduction for the accuracy test of the regression.

The relative errors are shown in Figure 6, which shows 93.8 % of the relative estimation errors are between -20% and 20% which is better than the cases in Figure 4.

5.5 Non-Single Stage Case

Although an FMS sometimes processes each part on a single machine and a single set-up, this is not always possible. When a part visits several machines, the flow is like a queueing network. The experiment in Section 5 shows that the relative reduction in flow time can be estimated by the mean and variation of the service time and inter-arrival time.

When the arrivals of parts to a machine for various places are independent, the calculation of the mean and variance of the part inter-arrival time can be estimated by the split and merge procedures frequently used in queueing network area. Many studies have been performed to estimate the means and variances of the input and output processes of a node in a queueing network [20, 23, 16, 19]. Once the mean and variance of the inter-arrival time and service time is calculated, the percentage reduction in flow time can be estimated by using Table 3 or Table 4.

6. Concluding Remarks

The development of an information system provides us with information that was not available before. A look-ahead routing procedure, LARP, proposed in this paper for part routing in an FMS, utilizes on-line information of the system and considers what is scheduled in the near future. Although the initial motivation of LARP is for the FMS routing problem, it can be used for other types of manufacturing systems and service systems also if the information on the arrivals in the near future is known.

A test under a hypothetical case shows the procedure reduces part flow time consistently. The range is between one and eleven percent for the cases considered in the simulation. More steps of look-ahead, higher utilization, and larger difference of the parts processing time among the machines gives a larger reduction in flow time. The variance of the inter-arrival time does not affect the degree of flow time reduction much. Because the variance of the inter-arrival time is more difficult to estimate or observe than the mean of inter-arrival time and the mean and variance of service time in manufacturing systems, this makes the application of LARP more practical.

Although, the procedure reduces the flow time substantially even with a small number of look-ahead steps, the computation time of the procedure increases rapidly as the number of look-ahead steps increases. More work on the development of an efficient procedure for the calculation for larger value of N is left for further research.

Finally, although the simulation covered a wide range of the characteristics of the part arrivals and services in an FMSs in terms of machine utilization, coefficient of variances of service time and inter-arrival time, more testing is needed for different FMS configurations and different performance criteria.

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Appendix: Simulation Results

The values in columns 6, 7, 8 are relative reduction of the flow time from the case when LARP is not used.

Obs	Flag				Flag 1		
No	2	3	4	5	N=1	N=2	N=3
1	1	1	1	1	1.22	1.68	2.39
2	1	1	1	2	0.90	1.16	1.81
3	1	1	1	3	0.68	0.79	1.37
4	1	1	2	1	0.81	1.10	1.50
5	1	1	2	2	0.67	0.91	1.24
6	1	1	2	3	0.56	0.69	1.05
7	1	1	3	1	0.75	1.03	1.31
8	1	1	3	2	0.55	0.59	0.92
9	1	1	3	3	0.47	0.59	0.90
10	1	2	1	1	1.69	2.58	3.41
11	1	2	1	2	1.60	2.38	3.28
12	1	2	1	3	1.67	2.35	3.36
13	1	2	2	1	1.03	1.79	2.30
14	1	2	2	2	1.51	2.10	2.79
15	1	2	2	3	1.69	2.15	3.05
16	1	2	3	1	1.40	1.91	2.48
17	1	2	3	2	1.51	1.98	2.72
18	1	2	3	3	1.56	2.05	2.74
19	1	3	1	1	1.89	2.82	3.98
20	1	3	1	2	2.29	3.37	4.58
21	1	3	1	3	2.66	3.46	5.05
22	1	3	2	1	1.86	2.51	3.62
23	1	3	2	2	2.45	3.19	4.19
24	1	3	2	3	2.77	3.46	4.61
25	1	3	3	1	1.60	2.65	3.55
26	1	3	3	2	2.32	3.14	4.01
27	1	3	3	3	2.79	3.28	4.28
28	2	1	1	1	2.22	4.42	5.92
29	2	1	1	2	1.37	2.47	3.80
30	2	1	1	3	1.18	2.13	3.15
31	2	1	2	1	1.82	3.17	3.91
32	2	1	2	2	1.28	1.88	2.71
33	2	1	2	3	1.22	1.55	2.29
34	2	1	3	1	1.28	2.81	3.60
35	2	1	3	2	1.10	1.74	2.21
36	2	1	3	3	0.95	1.38	1.89
37	2	2	1	1	2.48	4.33	5.74
38	2	2	1	2	2.34	3.59	5.10
39	2	2	1	3	2.36	3.74	5.14
40	2	2	2	1	2.41	4.06	5.04
41	2	2	2	2	2.33	3.53	4.67
42	2	2	2	3	2.66	3.65	5.09
43	2	2	3	1	2.52	3.47	4.98
44	2	2	3	2	2.54	3.63	4.64
45	2	2	3	3	2.73	3.85	4.83
46	2	33	1	1	3.03	4.60	6.42
47	2	3	1	2	3.11	4.57	6.62
48	2	3	1	3	3.63	5.31	7.23
49	2	3	2	1	2.74	4.19	5.56
50	2	3	2	2	3.59	5.20	6.79
51	2	3	2	3	4.06	5.67	7.50
52	2	3	3	1	2.51	4.04	5.84
53	2	3	3	2	3.74	5.22	6.92
54	2	3	3	3	4.39	5.94	7.78
55	3	1	1	1	2.49	6.19	8.60
56	3	1	1	2	2.19	4.54	6.10
57	3	1	1	3	1.90	2.22	4.93
58	3	1	2	1	2.64	6.04	8.53
59	3	1	2	2	1.82	3.73	5.25
60	3	1	2	3	2.66	4.47	5.28
61	3	1	3	1	3.03	5.16	8.23
62	3	1	3	2	2.48	4.57	6.08
63	3	1	3	3	1.96	3.69	4.72
64	3	2	1	1	3.47	6.78	9.29
65	3	2	1	2	1.58	5.07	7.37
66	3	2	1	3	2.01	4.25	6.05
67	3	2	2	1	4.40	7.75	9.33
68	3	2	2	2	3.26	5.96	7.38
69	3	2	2	3	3.92	5.83	7.46
70	3	2	3	1	3.84	7.83	9.48
71	3	2	3	2	3.00	5.82	7.40
72	3	2	3	3	3.84	5.78	7.59
73	3	3	1	1	3.73	6.55	9.57
74	3	3	1	2	3.43	5.96	8.66
75	3	3	1	3	4.07	6.01	8.60
76	3	3	2	1	3.18	6.51	8.32
77	3	3	2	2	4.27	6.87	9.15
78	3	3	2	3	5.09	7.45	9.77
79	3	3	3	1	4.07	6.80	8.78
80	3	3	3	2	4.15	6.88	9.32
81	3	3	3	3	5.26	8.09	10.77