Production planning and control in a JIT environment

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In addressing planning, design, and control issues of a production system, the solution of a normative model provides answers to planning issues at the aggregate level but fails to capture the time-dependent behavior of the system. This paper illustrates the usefulness of using both mathematical programming and simulation modelling to investigate the material flow characteristics of a "Just in time" system with part quality requirements.

Keywords: mathematical programming, simulation, quality, and just-in-time

Introduction

Basic approaches to modelling and analysis of production planning and control issues in a discrete parts manufacturing environment are as follows: (a) normative (optimization) models, (b) Markovian models, and (c) simulation models. All of these models have been used to address planning, design, and control issues associated with production systems. We focus on approaches (a) and (c) in this paper. Approach (a) provides fundamental resolution to decision issues. Approach (c) provides analysis based on more realistic, time-dynamic behavior. Approach (a) supports approach (c) by identifying system configuration, material flow, and production control characteristics to be simulated and evaluated from a time-dynamic perspective. This paper focuses on time-dependent behavior of a discrete parts production system operating in a "just in time" environment. A brief introduction of the JIT philosophy and a review of current research may help readers understand the motivation for this work.

"Just in time" philosophy, hereafter referred to as JIT, recommends that a manufacturer reduce inventory by making components just in time for the subassemblies and by making the subassemblies just in time for the final assembly. Reduction in inventory is not the only goal of the JIT philosophy and it affects overall productivity in more than one beneficial way.

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The role of the JIT philosophy in the success of Japanese farms has been highlighted by a number of researchers.[1] These researchers are of the opinion that certain worker- and management-related attributes are responsible for Japan's success. The loyal, flexible, and educated Japanese workers, working under a style of management that pays respect to the workers, promotes consensus decision making, and pays close attention to details, have made the industry successful. However, the recent success of Japanese companies with subsidiaries in the United States suggests that the management approach may be more important than worker-related cultural issues in making the JIT philosophy a success.

The success of the JIT philosophy depends on implementation of the following four basic principles[2]: (1) elimination of waste, (2) employee involvement in decision making, (3) supplier participation, and (4) quality control. Hannah,[3] Schonberger,[4] and Warne[5] have discussed some of the basic principles and methods of the JIT philosophy. Kanban and cellular manufacturing reflect the elimination of waste principle; a large body of contemporary literature has addressed these aspects of the JIT philosophy and its implementation in the manufacturing environment. In the manufacturing environment, researchers have addressed the issue of allocation of the optimal number of Kanbans at different workstations in both deterministic and stochastic environments.[6–9] Simulation studies have addressed the effects of different dispatching rules on the optimal number of Kanban cards.[10,11] Wemmerlov and Hyer[12] and Zelenovic and Tesic[13] have addressed the role of cellular manufacturing in the JIT environment.

It is interesting to note that despite recognition of the importance of part quality, limited research has been carried out to investigate quality-related issues in a JIT environment. Krupp,[14,15] Baker,[16] and Chung[17] have addressed the impact of the JIT philosophy on part quality. These researchers have focused on the design of appropriate sampling plans for a JIT system. This paper focuses on integration of part quality requirements into a production planning model of a discrete parts production system operating in a JIT environment.

The first purpose of this paper is to illustrate through one or more mathematical models the fundamental attributes of a production system and the issues involved in operating a discrete parts production system in a JIT environment. The second purpose is to validate expectations about system behavior and study the time-dependent behavior of the system in a simulation environment. The authors wish to investigate whether the behavior conforms to material flow characteristics of a JIT system and, if not, what can be done to achieve such conformance.

Production system characteristics

There are M part types that go into an assembly. The jth part type requires N_j different operations before it is ready to go into the final assembly. Each part type is processed in a separate subsystem set up as a serial flow line consisting of N_j work stations. A stage is defined as a workstation where an operation is performed on a part type. At each stage of manufacturing, a good part is sent to the next stage, whereas a part requiring rework is sent to an alternate work area. The alternate work area is set up as a job shop. The reworked parts are assembled together and sold as second-grade final products. At each stage of manufacturing the probability of creating a good part is known. At each stage a known number of control strategies are available to control the part quality. In addition, multiple operating rates are available at each stage. The manufacturing facility has to deliver a known number of final products within a specified period.

One purpose of this investigation is to develop suitable mathematical models for different decision issues relevant to this problem context. These issues, as enumerated later, are to be resolved based on a cost model. The system is expected to operate in a JIT mode. The time-dependent behavior of the system is studied to verify this expectation. *Figure 1* shows a schematic diagram of the configuration of the production system. Each serial line must complete a batch of component parts just in time for the final assembly.

Many possible scenarios can exist (or be planned) for a discrete parts manufacturing facility as we describe it. Given the basic production system context defined above, there are four characteristic production (material flow) scenarios that typically occur. They are:

1. The production subsystem for each component is set up as a serial line. At each stage of processing, one of two possibilities occurs. Either a good part is produced or, if the part turns out to be defective, it can be reworked in an alternate manufacturing area. A reworked component is assembled into the final product and sold as second-grade product or is rejected following rework. Probabilities of creating good parts at the main production system as well as in the alternate area are known.

2. The production subsystems are set up as in scenario 1 but a good reworked component is fed back to the main production system at the appropriate stage to join the parent batch. The probability of conversion of a reworked part into a good part is known. The unacceptable parts following rework are rejected as scrap.

3. The production subsystems are set up as in scenario 1 but at each stage of processing defective parts are generated along with good and reworkable parts in the main production area. Reworkable parts flow through the alternate system as described in scenario 2.

4. The material flow path is identical to the flow path described in scenario 3 with the exception that reworked parts are not routed back to the main production

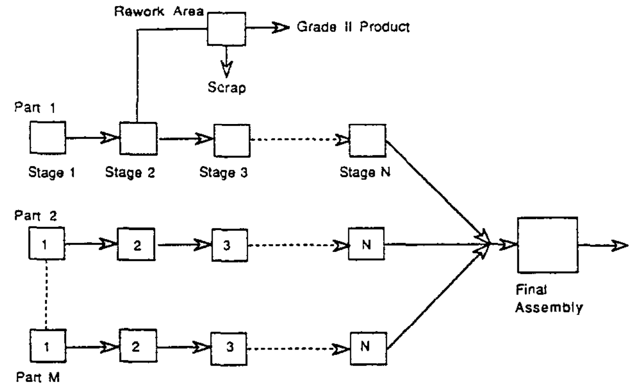

Figure 1. Part flow diagram.

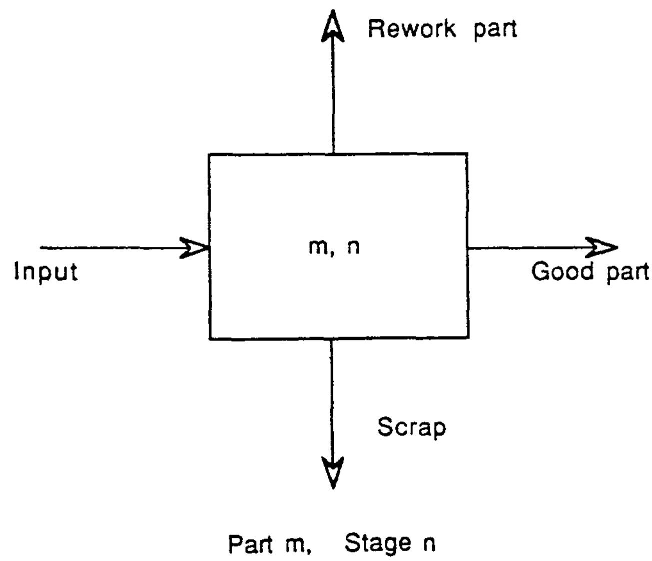

Figure 2. Flow balance at a stage (m,n).

system. The finished products from the alternate area are sold as second-grade products.

The four scenarios outlined can be viewed as basic material flow patterns. A number of variations of the basic scenarios are feasible. For example, in describing the problem context, we have considered a production facility consisting of subsystems organized as a main work area and subsystems organized as an alternate work area (*Figure 1*). In this paper, we have first modelled and analyzed a production facility without a rework area; at each stage of processing, either a good or a defective part is created. We have then modelled and analyzed scenario 1, which considers a rework area. A separate mathematical model for the basic scenario without a rework facility is not shown because it can be generated directly from the model for scenario 1.

Scenario 1 Model Development:

- Assembled parts from the main production system are considered to be good parts only. The completed parts from the alternate system are considered to be second-grade quality. Revenue generated from the second-grade parts can be accounted for in a profit-based model.
- At each stage a number of process control plans are available and the specific plan selected determines the operating rate.

Notations used in the model

A stage (m, n) indicates the workstation where nth operation of mth part type is to be performed (*Figure 2*).

p_{1mnk} = probability of producing a good part in stage (m, n) using process control plan k
p_{2mnk} = probability of producing a rework part in stage (m, n) using process control plan k
p_{3mnk} = probability of producing a scrap part in stage (m, n) using process control plan k
K_{mn} = number of process control alternatives available for implementation in stage (m, n)
pA_{mn} = probability that rework produces a good part of type m sent from stage n in the main production system (to be used in a profit-based model only)
E_{mnk} = number of machines in stage n of part type m in the main production area given that process control plan k is implemented
r_{mnk} = processing rate of machine employing process control alternative k in stage n of part type m
C_{mnk} = cost of producing part type m in stage n using the process control plan k in the main production system
CA_{mn} = cost of reworking a part of type m sent to the alternate production subsystem
X = the number of each component that should reach the main assembly stage in a synchronous manner
X_{mnk} = the number of parts of type m that are to be processed in stage n, when process control alternative k is used
NP_{mnk} = the number of parts of type m sent for rework from stage n; process control alternative k is employed in stage n (needed in a profit-based model)
f_{mnk} = fixed cost of equipment per machine in stage n of part type m production line if process control alternative k is implemented
y_{mnk} = indicator variable = 1, if process control alternative k is selected at stage n of part type m; otherwise indicator variable = 0
T = production period (in appropriate time unit)
$N_j = N, \forall j$.

Model

A stage (m, n) refers to the workstation where nth operation of part type m is carried out. Consider a stage (m, n) only.

Set of constraints

1. Output from a stage is dependent on the control plan selected at that stage.

$$X_{m(n+1)k} = \sum_{k \in K_{mn}} y_{mnk} p_{1mnk} X_{mnk}$$

2. Only one control plan is to be selected at each stage.

$$\sum_{k \in K_{mn}} y_{mnk} = 1, \forall m, n$$

3. Quantity required must be met.

$$X_{m(n+1)k} \geq X, \forall m, n, k.$$

4. Each decision variable (X_{mnk}) is an integer variable.

$$X_{mnk} \geq 0.,$$

$$y_{mnk} \{0, 1\}$$

E_{mnk} integer values only

5. The production facility must possess the required number of machines at each stage.

$$TE_{mnk} = X_{mnk}/(\Sigma y_{mnk}\, r_{mnk}) \text{ for each stage } (m, n)$$

This equation balances the machine time required to produce the required quantity at each stage.

Criterion function

The criterion function has three cost elements. These elements are as follows:

(a) Deferred cost for machines = $(\Sigma_m \Sigma_n \Sigma_k f_{mnk} E_{mnk})$
(b) Machining cost for different parts = $(\Sigma_m \Sigma_n \Sigma_k C_{mnk} X_{mnk})$
Let $NP_{mnk} = \sum_{k \in K_{mn}} p_{2mnk} X_{mnk} y_{mnk}$, then
(c) Rework cost = $\Sigma_m \Sigma_n CA_{mn} NP_{mnk}$
Criterion function = minimize: (A + B + C)

Model structure

The model structure conforms to a nonlinear integer program. A subset of the decision variables are Boolean variable and the rest are integer variable.

Results of model analysis

Solution of the model provides the following information:

- control plan at each stage of manufacturing,
- number of parts to be processed at each stage,
- number of completed assemblies from the main production system,
- number of finished assemblies from the alternate production system, and
- number of machines to be used at each stage.

Scenario 3 may be modelled by modifying the constraint on scenario 1 to include the reworked parts fed back to the main production area from the rework area. A known percentage of reworked parts are routed back to the main area to join the parent batch. No other changes are required. Similar modifications are made to meet the requirements of scenario 4.

The model presented here possesses the basic flow characteristics of a JIT environment in the sense that all components needed to meet the demand for assembly are manufactured during the planning horizon. However, these models do not possess time-dependent dynamics of the production system.

Recommended procedure

A two-phase approach is presented here to address the problem outlined earlier in the paper. In phase I, a mathematical model is developed to incorporate the relevant decision issues. The optimal solution of the mathematical model provides useful information regarding batch size and control plan to be used at each stage of manufacturing for each part type. Because we are interested in investigating the system's behavior in relation to material flow characteristics of a JIT system, phase II studies the system behavior in a simulation environment. The optimal solution from phase I is used to configure the simulation model of the production system. The required number of replications are used to estimate the measure of performance within a specified precision. In the illustrative example described later in the paper, time to complete a batch of 50 parts for each part type is considered as the measure of performance. Each serial line is simulated separately to collect data. The problem presented here as an illustration considers two component parts with each part requiring two processing stages. In reality one often deals with a product with a larger number of component parts as well as a larger number of processing stages within each serial line. A relatively small problem is presented here to illustrate the nature and scope of the approach suggested. A larger problem would require a relatively longer computing time to solve the phase I problem, more simulation time since a larger number of serial lines are simulated, and might require a different statistical analysis of the simulation results.

In analyzing the simulation results a one-way ANOVA needs to be performed for a problem with more than two component parts. The requirements for ANOVA must be met.[18] These are, (a) sampling from a normal population and (b) homogeneity of variance among the batch completion times of the component parts. The central limit theorem may be used to meet the first requirement if a sufficiently large number of parts are processed in each replication to estimate the average batch completion time. Any one of the set of appropriate statistical tests such as Cocharn's C test, Barlett-box F test, or maximum/minimum variance test may be carried out to study homogeneity of variances. Failure to meet this requirement demands suitable transformation of data in a way so that transformed variables exhibit homogeneity of variance. The result of ANOVA indicates conformance to material flow characteristics of a JIT system or otherwise. An absence of a statistically significant difference among mean batch completion times is considered as conformance to the JIT requirement.

For a two-component-parts problem, the simulation results may be analyzed by a simple t-test on the difference between mean batch completion times of the component parts. Necessary corrections are to be made in computing the test statistic depending on whether a statistically significant difference exists between the variances or not. All statistical tests are performed with an α value (type I error) equal to 0.05.

Example problem

An assembly made of two components is considered. Each component requires two processing stages. Good products from the first stage of processing are sent to the second stage. Defective products are scrapped. For this illustrative problem a rework area has not been considered. Example problem data are shown in *Table 1*. Further the example problem considers variable cost per part only. Machines used in stage 1 and stage 2 have variable costs of \$25/hr and \$30/hr respectively. The model has been solved for an order quantity of 50 assemblies that are to be made in one working day.

Table 1. Example problem data.

Part no.	Stage 1						Stage 2					
	Plan 1			Plan 2			Plan 1			Plan 2		
	PT[1]	PG[2]	PR[3]	PT	PG	PR	PT	PG	PR	PT	PG	PR
1	2.5	0.8	0.2	3.0	0.9	0.1	3.5	0.8	0.2	4.0	0.95	0.05
2	3.0	0.7	0.3	3.3	0.9	0.1	3.2	0.85	0.15	3.7	0.95	0.05

[1] PT = processing time per part; [2] PG = probability of a good part (min); [3] PR = probability of making a reject.

The optimal solutions for the model is given in *Table 2*.

Analytical results provide planning decisions that will ensure a predetermined quantity of good parts at the end of the planning horizon. The JIT requirement is considered to be met if all the components required to assemble the ordered quantity are available simultaneously at the end of the planning horizon. This investigation did not look into conformance of material flow to JIT requirements for each assembly of finished product. However, the simulation model can be suitably embellished to generate this information.

The simulation model didn't consider machine breakdown, and processing times were modelled as constants. The model was run as a terminating system using the optimal decisions obtained earlier. The required number of replications were run to obtain estimates of batch completion time for each component within a predetermined level of precision, as stated earlier in the paper. The results of simulation runs are presented in *Table 3*.

An appropriate statistical test (ratio test) revealed that the variances are not equal. A statistical test (Fisher–Behrens test) on the means revealed that there is no significant difference between the completion times of batches of component 1 and component 2. Based on the results it can be concluded that the JIT requirement has been met. It is interesting to note that batch completion time for component 2 exhibits almost a four times greater variability compared with component 1.

In reality machines do break down more often than one would like. As a realistic embellishment to the previous scenario machine breakdown was included in the simulation model, and the model was run using the optimal solution obtained earlier. Machines used in stage 1 and stage 2 were assumed to have different breakdown rates, but the repair time was characterized by a single random variable for all machines. The results of the simulation runs are presented in *Table 4*.

The results appear to be consistent with the expectation that batch completion time should increase due to machine breakdown. Once again appropriate statistical tests confirmed inequality of variances (ratio test) and no significant difference between mean batch completion times (Fisher–Behrens test) of the two components. Again, it may be inferred that the JIT requirement has been met.

Table 2. Example problem results.

Part 1, Stage 1	Select control plan 1
Part 1, Stage 2	Select control plan 2
Part 2, Stage 1	Select control plan 2
Part 2, Stage 2	Select control plan 1
Objective function value = $360.94	
Quantities to be processed at different stages are as follows:	
Part 1, Stage 1	67
Part 1, Stage 2	53
Part 2, Stage 1	66
Part 2, Stage 2	59

Table 3. No machine breakdown.

Part no.	Batch completion time (min)	SD (min)
1	214.0	6.30
2	226.0	24.9

Table 4. Machine breakdown included.

Part no.	Batch completion time (min)	SD (min)
1	242.0	12.9
2	253.0	26.1

Table 5. Example problem results.

Part 1, Stage 1		Select control plan 2
Part 1, Stage 2		Select control plan 2
Part 2, Stage 1		Select control plan 2
Part 2, Stage 2		Select control plan 2
Objective function value = $392.33		
Quantity to be processed at different stages is as follows:		
Part 1, Stage 1	66	Parts requiring rework 7
Part 1, Stage 2	56	Parts requiring rework 3
Part 2, Stage 1	61	Parts requiring rework 3
Part 2, Stage 2	55	Parts requiring rework 3

The previous two simulation models treated the processing times as constants. Variability in processing time may be considered as a next logical extension of this investigation.

A similar analysis using normative modelling followed by simulation experiments was performed for scenario 1. The normative model considered variable cost per part and rework cost per part only. It was assumed that all parts were routed to a work area equipped with machines identical to those in stage 2 of the main production area. It was further assumed that rework on each part requires half of the original processing time. The optimal solutions for this model are presented in *Table 5*.

Simulation experiments were carried out under two different experimental conditions. The first experimental condition didn't consider machine breakdown, whereas the second experimental condition included it. The completion of 50 good parts, of each part type, in the main production area was considered to be the terminating criterion for each simulation run. The required number of replications were run under each experimental condition to ensure statistical validity of the simulation results. The results generated from the first experimental condition are summarized in *Table 6*.

The statistical tests indicated no significant difference in variability (ratio test) between batch completion times as well as no significant difference between mean (t-test) batch completion time of the parts. A similar conclusion was reached based on statistical analysis of the simulation results generated under the second experimental condition. *Table 7* summarizes the simulation results. The data related to machine breakdown rate and repair time are presented in *Table 8*.

Table 6. Machine breakdown excluded.

Part no.	Batch completion time (min)	SD (min)
1	261.0	23.2
2	253.0	26.1

Table 7. Machine breakdown included.

Part no.	Batch completion time (min)	SD (min)
1	268.0	22.6
2	264.0	29.0

Table 8. Machine failure/repair data.

Stage	Time between failure (distribution)	Time to repair (distribution)
Machines in Stage 1	Exponential (mean = 45 min)	Uniform (4 min, 6 min)
Machines in Stage 2	Exponential (mean = 60 min)	Uniform (4 min, 6 min)

Discussion

The importance of operating a manufacturing facility in a JIT mode is well understood by today's manufacturers. The investigation outlined in this paper provides a mechanism to study time-dependent behavior of a system to monitor one or more performance criteria. Use of simulation to study system behavior is a well-established practice. What this paper presents is a two-phase approach to a problem. In the first phase, a mathematical model is developed and solved to find the optimal solution. The results of the mathematical model provide answers to key planning decisions such as batch size, number of machines, and control plans at different stages. Development of an analytical model to study time-dependent behavior of a real system would yield a model that is quite complex and difficult to solve expediently. However, such behavior can be studied in a simulation environment. The optimal decisions found in phase 1 can be used to run a simulation model of the system. If the material flow characteristics of a JIT environment are not met then system parameters can be adjusted. For example, additional resources may be deployed to a workstation that operates with a longer queue. Additionally, the effect of changing one or more system parameters can also be studied in a simulation model. In the example described here the JIT requirement was met under each of the two environments considered. This may be attributable to the nature of the optimal solution, which recommended balanced product lines with equal total processing time for each product. Variability in processing times within a sequence as well as between the product lines may also have contributed to the results.

For further investigation

This investigation has assumed that the method of assembly is known and parts can be assembled without generating defective assembly. The selection of a suitable assembly process from a set of competing processes may be incorporated in the model as an additional decision.

Conclusion

This paper highlights the utility of using both normative models and simulation models in the planning, design, and control of production systems. The solution of the normative model provides answers to planning issues at the aggregate level. This solution may then be used to drive a simulation model to study in depth the dynamic responses of the system. The measures of performance that cannot be included in a normative model, because of their time-dependent nature, can be included and studied in a simulation environment. This paper provides an illustration of material flow characteristics of a JIT system.

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