1986

# Group technology based flow line scheduling to minimize maximum tardiness /

Richard Titus Jr.
*Lehigh University*

## Recommended Citation

Titus, Richard Jr., "Group technology based flow line scheduling to minimize maximum tardiness /" (1986). *Theses and Dissertations*. 4657.
https://preserve.lehigh.edu/etd/4657

# GROUP TECHNOLOGY BASED FLOW LINE SCHEDULING to MINIMIZE MAXIMUM TARDINESS

by

**Richard Titus, Jr.**

A Thesis
Presented to the Graduate Committee
of Lehigh University
in Candidacy for the Degree
of
**MASTER OF SCIENCE**

in
**Manufacturing Systems Engineering**

Lehigh University
Bethlehem,PA
1986

## Certificate of Approval

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

May 19, 1986
(date)

George R. Wilson
Professor in Charge

S. E. Kane
Chairman of the Industrial
Engineering Department

Director of the Manufacturing
Systems Engineering Program

# ACKNOWLEDGMENTS

I would like to thank my advisors, Dr. George Wilson and Dr. Mikell Groover, for their guidance in the development of this thesis. Dr. Groover provided a great deal of direction in the initial development of the simulation model. Without Dr. Wilson's assistance in directing my efforts in developing the scheduling procedure, this thesis would not have been possible. Their dedication to teaching and Lehigh is truly admired.

I would also like to thank my manager, Peter D'Souza of Ingersoll-Rand, for his direction, patience and encouragement throughout this study. My appreciation also goes out to Walter Schmidt, Vice-President of Operations for the Pump/Turbo Groups of Ingersoll-Rand, for his vision in understanding the benefits of continued CIM education. Ed Adamusinski, Mark DeNardo, Tim Foldes and Gerry Gormley of Ingersoll-Rand provided assistance which aided in the completion of this thesis. Their support is greatly appreciated.

Finally, I would like to thank my dear wife, Lisa, for her continual support and encouragement throughout my graduate study.

# Table of Contents

# List of Figures

# ABSTRACT

The primary objective of this thesis was to develop a scheduling procedure for a flow line to minimize maximum tardiness, with a secondary objective to utilize group technology to reduce setup time. A great deal of research has focused upon scheduling the flow line to minimize the makespan, which does not consider due date requirements. An examination of the literature on due date scheduling yielded a model based on a branch-and-bound procedure to minimize maximum tardiness. Embelishing this model to take into account group technology objectives was the focus of this thesis.

The model requires that production families be identified at the component level in the MRP process. GT families for the flow line are grouped at this level and a job sequence is developed by the branch-and-bound procedure. This production job schedule is examined to insure that the proper balance of tardiness and GT savings has been achieved. The scheduling horizon is modified to facilitate this tardiness/GT savings balance. This GT scheduling method was tested versus other scheduling techniques, by utilizing a SLAM II simulation model. Results indicated that the proposed GT scheduling method minimized maximum tardiness and achieved the highest amount of group technology savings for the test case flow line.

# Chapter 1
# INTRODUCTION

Integrating group technology (GT) with the scheduling of manufacturing requirements is a significant challenge facing manufacturing organizations. Applying group technology to the design/manufacturing functions can yield numerous benefits. [2,pgs.557-559.] These advantages include the following:

1. Standardization of design.
2. Standardization of tooling.
3. Reductions in setup time.
4. Improved shop layouts.
5. Improved material flow.
6. Improved product quality.
7. Improved worker satisfaction.
8. Consistent process plans.
9. Simplified shop scheduling.

The implementation of GT is a function of production quantity and the number of products produced. [5,pg.154.] This relationship is shown in Figure 1-1.

Group technology may be utilized to varying degrees. [6,pgs.682-685.] Informal part families and a functional departmental layout represents the minimal form of a GT application. The highest degree of GT benefits can be achieved by formalization of part families and a group layout. This group layout can take the form of a GT flow line, a GT cell or a GT center (see Ham for a detailed explaination of these GT layouts). [5,pgs.155-157.] The

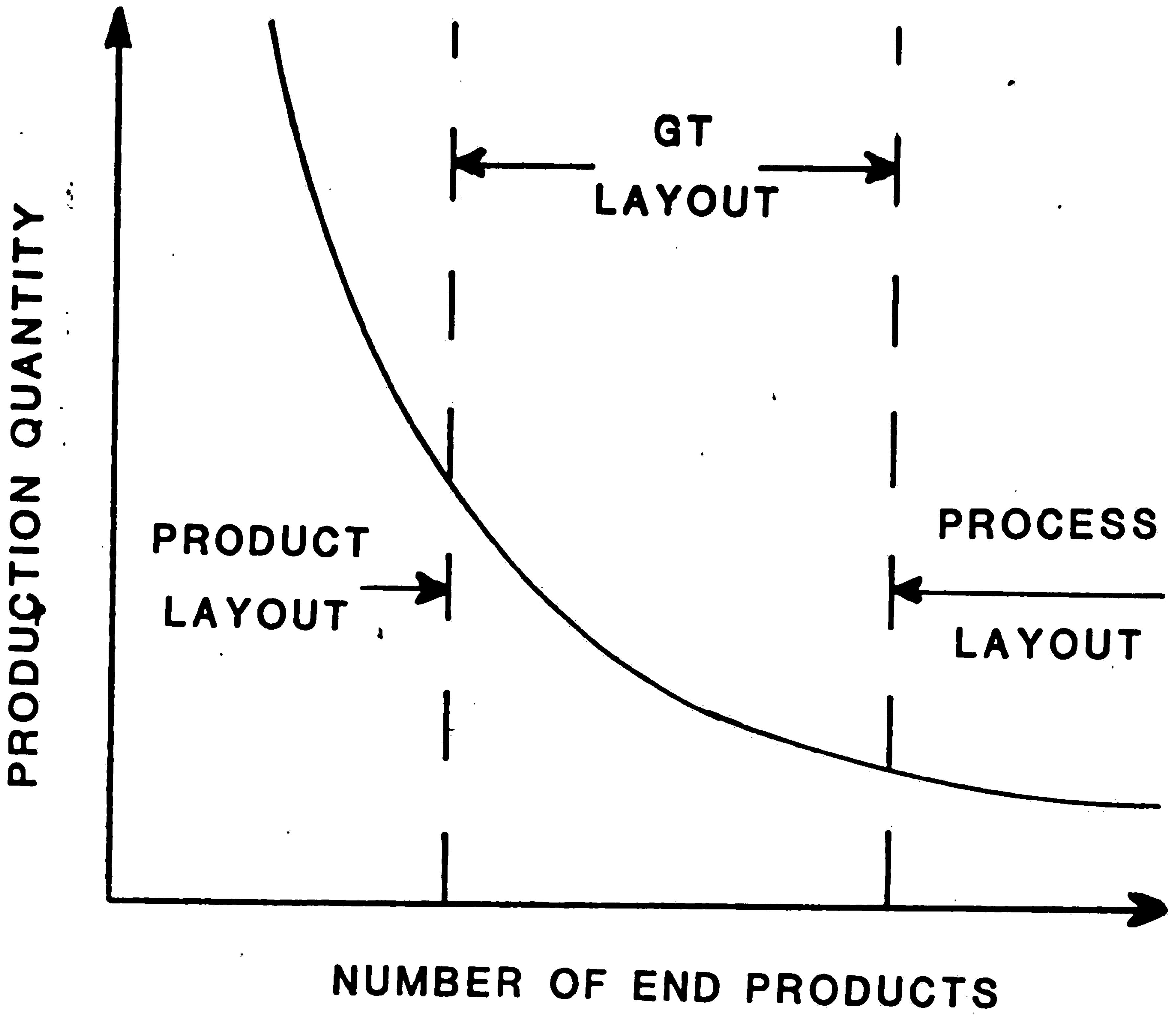


**Figure 1-1:** GT versus Production Quantity and Number of Products

group technology flow line represents the highest degree of process specialization. Part families are channeled through the group technology flow line (as shown in Figure 1-2) in the same process sequence.

Scheduling of group technology flow lines is a critical activity required to fully realize the benefits of GT. Ingersoll-Rand's Phillipsburg, New Jersey facility will be utilized as the test case for a GT scheduling methodology. A group technology flow line to manufacture pump impellers in five operations will be analyzed. The end product manufactured at Phillipsburg is an engineer-to-order product, which requires a significant amount of detailed engineering of each customer order. The production systems currently utilized are due date driven and based upon the master schedule. This thesis will propose a method

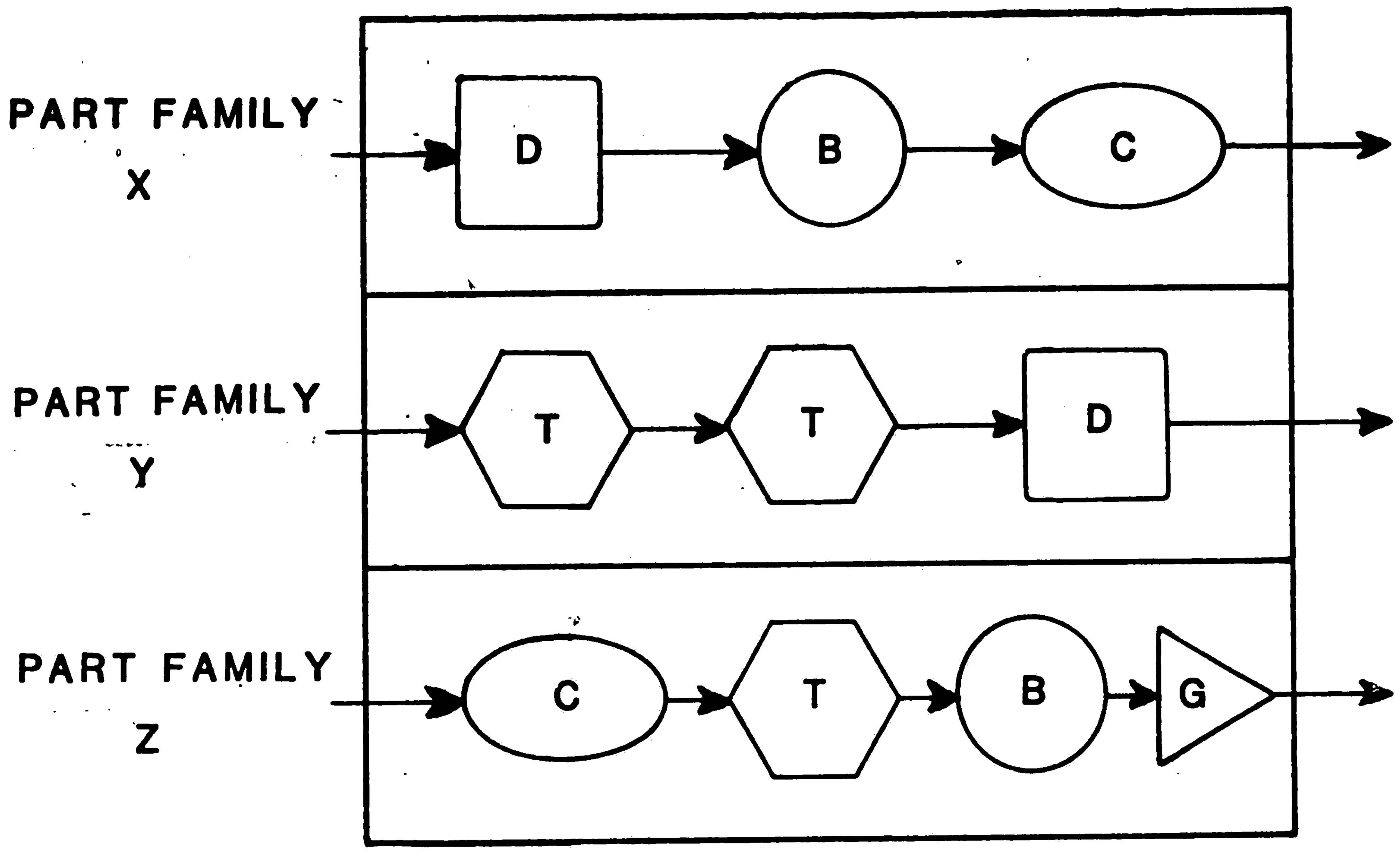


Figure 1-2: GT Flow Line

for GT flow line scheduling to yield group technology savings but still achieve the requirements of a customer due date system.

# Chapter 2

# GT Flow Line Performance Measures

Several methodologies currently exist for scheduling a GT flow line. The performance benchmark for application to GT flow line scheduling will be Ingersoll-Rand's engineer-to-order requirements which include:

1. The primary objective of the flow line is to maintain job tardiness at a minimum, facilitating improved on-time shipment of end product.
2. GT savings from the grouping of similiar production jobs is a secondary benefit, to be achieved when possible while still maintaining the due date requirements of customer shipments.

In addition to achieving the Ingersoll-Rand objectives the following scheduling conditions apply: [5,pgs.94-95., 1,pgs.136-137.]

1. All jobs scheduled for the GT flow line are available at time zero.
2. All production times are deterministic and known in advance.
3. Each machine performs only one operation.
4. Only one machine exists for each operation.
5. Machines are constantly available for processing jobs.
6. Machines can perform only one operation at a time.
7. Operations cannot overlap.
8. Transportation times are ignored.
9. Preemption of jobs is not allowed.

Consideration was given to a variety of scheduling performance measures including:

1. Minimizing Makespan
2. Minimizing Average Tardiness

3. Minimizing Maximum Tardiness

Each of these proposed performance measures will be examined as they relate to Ingersoll-Rand's engineer-to-order requirements.

## 2.1 Minimization of Makespan

Makespan is defined as the total elapsed time for a group of jobs to be completed in a flow line. [5,pg.95.] Minimizing makespan is the objective of Johnson's problem for a two machine flow line. This problem has been generalized for the 3 machine case when the second machine is not a bottleneck operation. [1,pgs.142-148.] A branch-and-bound method incorporating group technology has also been developed to minimize makespan. [5,pgs.141-148.]

Unfortunately, when compared to the benchmark of a due date based system, makespan is inappropriate. Total elapsed processing time for a group of jobs is not an adequate performance measure for a system which is driven by customer due dates.

## 2.2 Minimizing Average Tardiness

Lateness is defined as the due date ($D_i$) of a job subtracted from the completion date of that job ($C_i$). A positive result of this operation defines a job as being tardy. To compute average tardiness the sum of total tardiness for all jobs (**1,2,...,n**) would be determined. This total would be computed as shown below.

$$AVERAGE\ TARDINESS\ (\overline{\mathrm{T}}) = \frac{\sum_{i=1}^{n} \max(0, C_i - D_i)}{n}$$

Average tardiness can be utilized for due date based systems. But it must be noted that average tardiness does not identify the extremes of system performance. While the average tardiness may be within the acceptable threshold of performance, several jobs may exceed that limit on an individual basis. Therefore, average tardiness would not be an acceptable performance measure for Ingersoll-Rand's engineer-to-order products.

## 2.3 Minimizing Maximum Tardiness

Minimizing maximum tardiness is a performance measure which would allow "worst case" assessments of proposed schedules. The maximum tardiness would identify the latest job and its completion date. This information would allow production scheduling personnel to determine if this maximum tardiness will affect the end product shipment date. All other jobs would be less than or equal to the maximum tardiness.

Considering the benchmark of Ingersoll-Rand's engineer-to-order products, the maximum tardiness case would provide the most appropriate performance measure for a GT flow line. The utilization of a maximum tardiness measure will allow production scheduling personnel a "damage control" measurement. This damage control approach will identify the latest job, unlike average tardiness which could dilute the impact of the latest job through a large sample size.

# Chapter 3

# Integrating Group Technology with Customer Order Requirements

## 3.1 MRP for Production Planning

The integration of group technology with customer order requirements is a problem confronted by many GT users. Today many firms have implemented some form of Manufacturing Resource Planning (MRP) system to aid in the planning of the manufacturing process. MRP systems attempt to solve the following problems: [3,pgs.327-329.]

1. Insufficient capacity planning resulting in production delays, unplanned overtime, etc.
2. Suboptimal production scheduling resulting in longer manufacturing lead times, rush jobs and interruption of in-process jobs.
3. Increased manufacturing lead times due to improper planning and scheduling.
4. Inefficient inventory control increasing inventory costs.
5. Reduced work center utilization due to improper planning and scheduling.
6. Errors in engineering design or manufacturing planning.
7. Product quality reductions resulting in increased rework and scrap.

MRP is the process of "exploding" the end product into the required components and subassemblies required to manufacture the end product. The first step in the MRP process is to determine the end requirements. These requirements are managed via a master schedule. A bill of material is constructed for each of the end products. The MRP system couples the bill of material and master schedule to determine the component/subassembly procurement and production schedules. Scheduling is accomplished utilizing known purchasing and manufacturing lead times. Manufactured parts are assigned a start date and due date based on the MRP "explosion". An example MRP explosion of an end product is shown in the Figure 3-1.

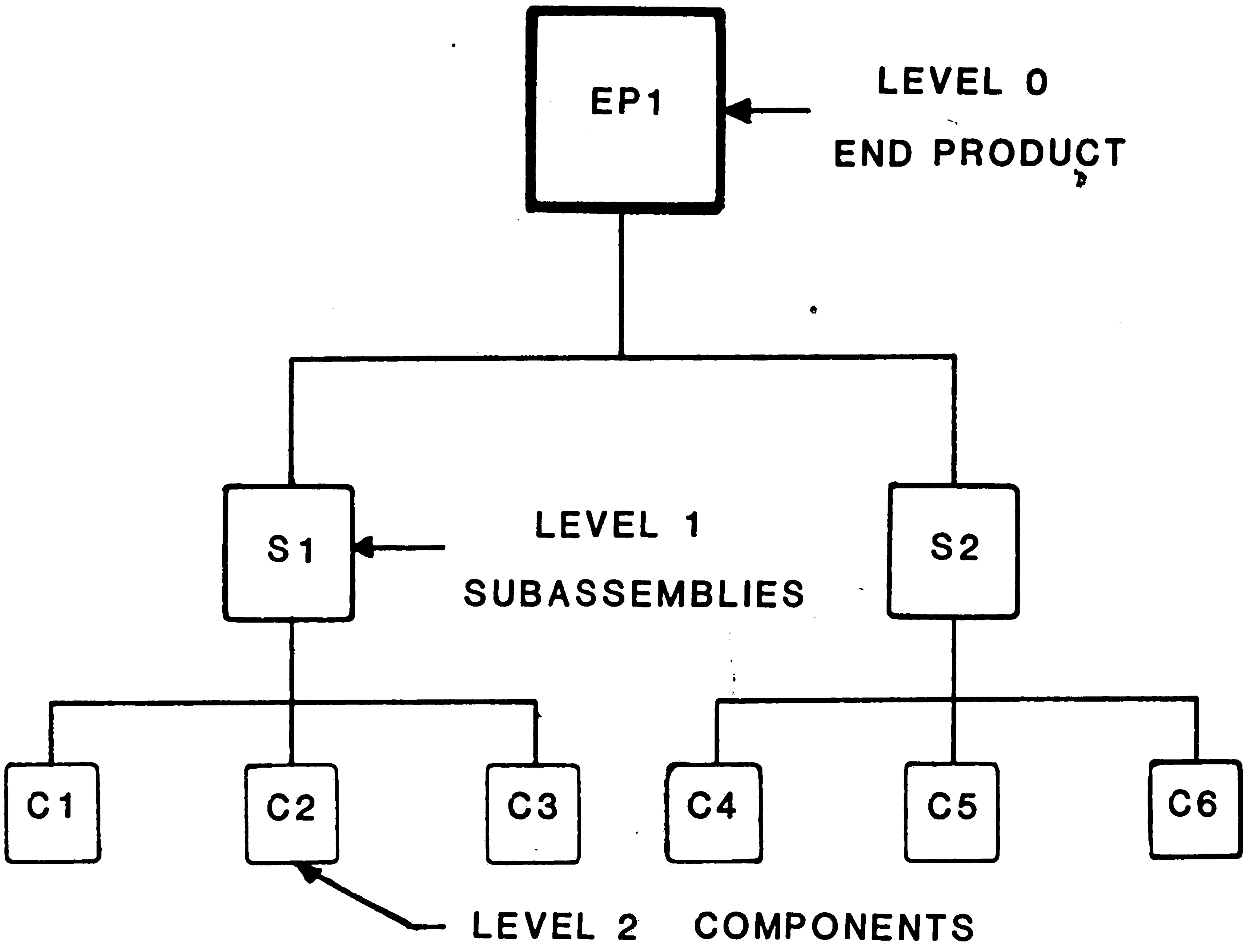


**Figure 3-1:** Typical MRP "Explosion" of Components and Subassemblies

This MRP process requires extensive computer resources to generate the massive scheduling breakdown. [3,pgs.325-348.] Manufacturing lead time is a critical component in this MRP process. Manufacturing lead time determines the start date for all manufacturing requirements.

GT flow lines can be MRP scheduled utilizing this approach. It should be noted that order point systems are often applied with MRP systems to manage stock replenishment on stock items (i.e. nuts, bolts, tools, maintenance items, etc). [3,pgs.338-340.]

## 3.2 MRP versus Group Technology

MRP is a method through which extensive manufacturing planning is accomplished. This scheduling of requirements in "time buckets", predefined periods of time, is primarily concerned with production of the end product within master schedule requirements. Timing is the critical element of the MRP process. The grouping of components or subassemblies for procurement or manufacture efficiency is occasionally accomplished via MRP. Since MRP is primarily an ordering system, these efficiencies are unplanned and are an unexpected result.

Group technology is primarily concerned with improving the efficiencies of the manufacturing process. These efficiencies are often optomized without regard to MRP requirements. This demonstrates the diametrically opposed objectives of MRP and GT.

## 3.3 Period Batch Control for Integrating GT and MRP

Period batch control, introduced in Great Britain, is a method by which the goals of GT and production requirements are accomplished simultaneously. [6,pg.686.] Researchers have correlated the relative low level of computer application in manufacturing to period batch control. [6,pg.687.] Period batch control (PBC) does not require the computer resources associated with MRP. PBC is based on a single cycle ordering philosophy. The length of this cycle is equal to or slightly greater than the manufacturing lead time for the end product. All manufacturing planning for end product requirements is completed for a given cycle. The end products component's manufacturing and procurement requirements are determined by a "list order form". Next the component parts required for a given part are grouped according to GT families to increase manufacturing efficiencies.

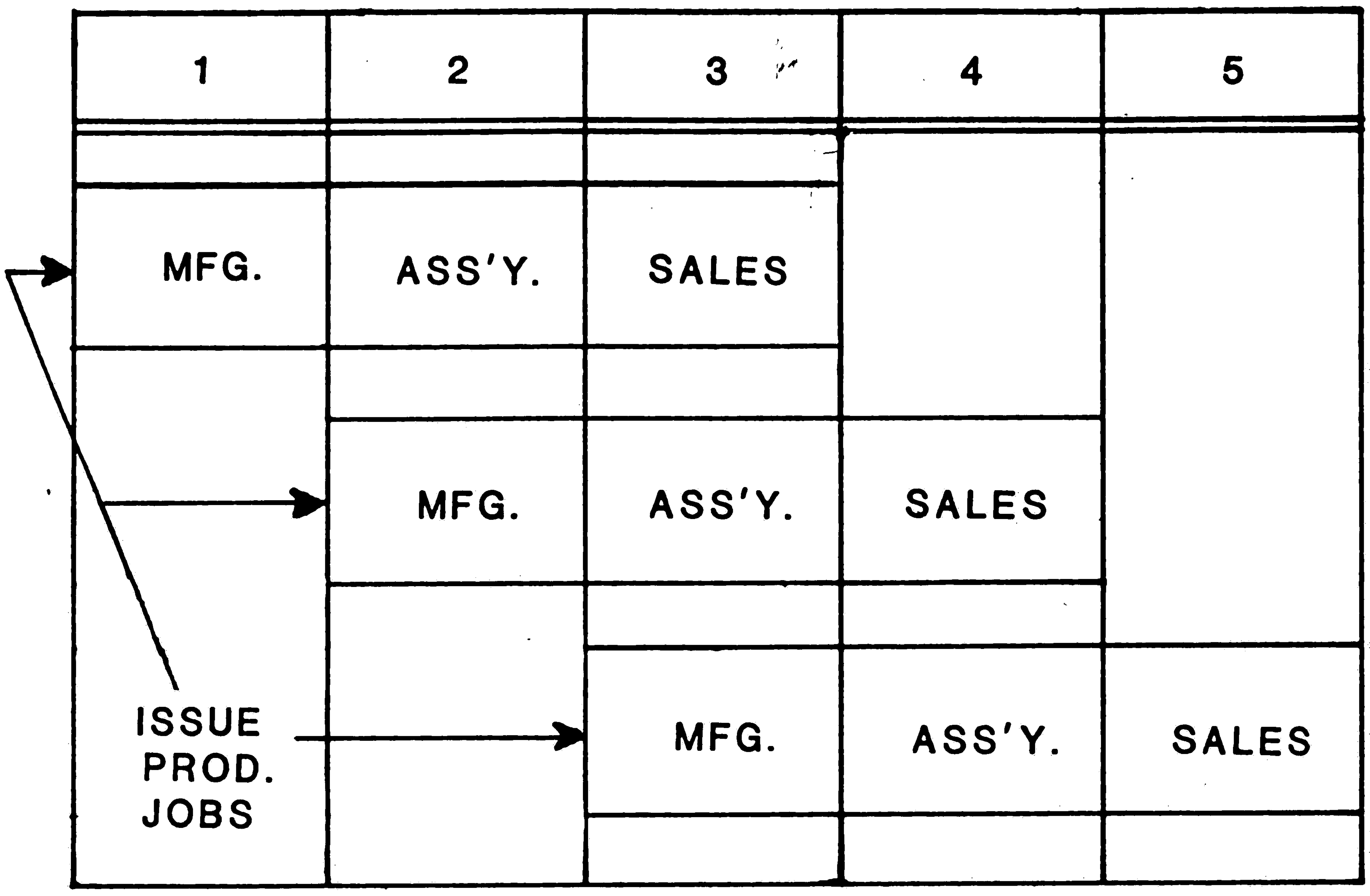


Figure 3-2: Production Cycles for Period Batch Control

Finally, parts are manufactured for a given period and assembly of the end product occurs in the next cycle. The single cycle approach to PBC is shown in Figure 3-2. [6,pg.687.]

The advantages of PBC include: [6,pgs.687-688.]

1. Single ordering cycles are planned versus random order release.
2. Production schedules are stable.
3. Planned loading sequences may be developed.
4. All orders have the same due date.

5. Work in process is maintained at a low level.
6. Shop paperwork is reduced, since scheduling is simplified.
7. GT efficiency of manufacture/procurement can be achieved.

Several disadvantages of PBC may render it ineffective for an engineer-to-order product such as Ingersoll-Rand's. It would be very difficult to define the correct cycle length due to the variety of product serviced by the GT impeller flow line. The static nature of PBC would not allow replanning, and therefore, not allow additional orders to be accepted for a given period. PBC is ideal for stable demand but does not readily adapt to changes in market conditions such as end product lead time reductions. [6,pgs.688-689.] Consequently PBC could not be readily adapted to Ingersoll-Rand's GT flow line. But the PBC concept of period, or horizon type planning, may be adapted to an integrated MRP and GT approach.

## 3.4 Integrating GT with MRP

The integration of GT and MRP may be facilitated through the adoption of several PBC techniques. Cyclical grouping of GT family manufacturing requirements utilized by PBC must be integrated into the MRP time phased planning to allow a concatenation of GT production jobs. This integration will allow the goals of GT and MRP to be achieved simultaneously. A method for such a GT and MRP integration is listed below: [5,pgs.175-177.]

1. Determine part families and identify groups.
2. Determine time phased production requirements for component parts and subassemblies.
3. Perform grouping of manufacturing requirements for time periods and GT families.

4. Utilize appropriate production group scheduling algorithm to determine optimal schedule.

Following the steps listed above for implementation of a GT-based MRP system requires the manufacturing requirements to be determined through a bill of material explosion. This formulation of requirements will determine the due dates and start dates for the manufactured jobs. At this point a grouping of families scheduled for GT flow line manufacturing can be made. This methodology for integrating GT and MRP is shown in Figure 3-3. After determining the GT job sequence, the feasibility of the schedule can be tested to ensure that the threshold tardiness values are not exceeded.

## 3.5 Scheduling a GT Flow Line

The final step in the previously detailed integration of GT and MRP requires the development of an appropriate algorithm for shop scheduling. The benchmark of Ingersoll-Rand's GT flow line necessitates that the model be developed based upon minimizing maximum tardiness. If this "worst case" tardiness is within the acceptable limits of job lateness then the schedule can be implemented. Otherwise the time horizon for grouping manufacturing requirements can be reduced and the new family groupings may be rescheduled. At this point it is possible to determine the tradeoffs between GT family setup savings and lateness for a given set of manufacturing requirements. Test results from Ingersoll-Rand's flow line indicate that while group technology savings will become asymptotic, job lateness increases dramatically as the job grouping time horizon increases.

A typical relationship between tardiness and GT savings is depicted in Figure 3-4. The center of the figure denotes an "acceptable performance"

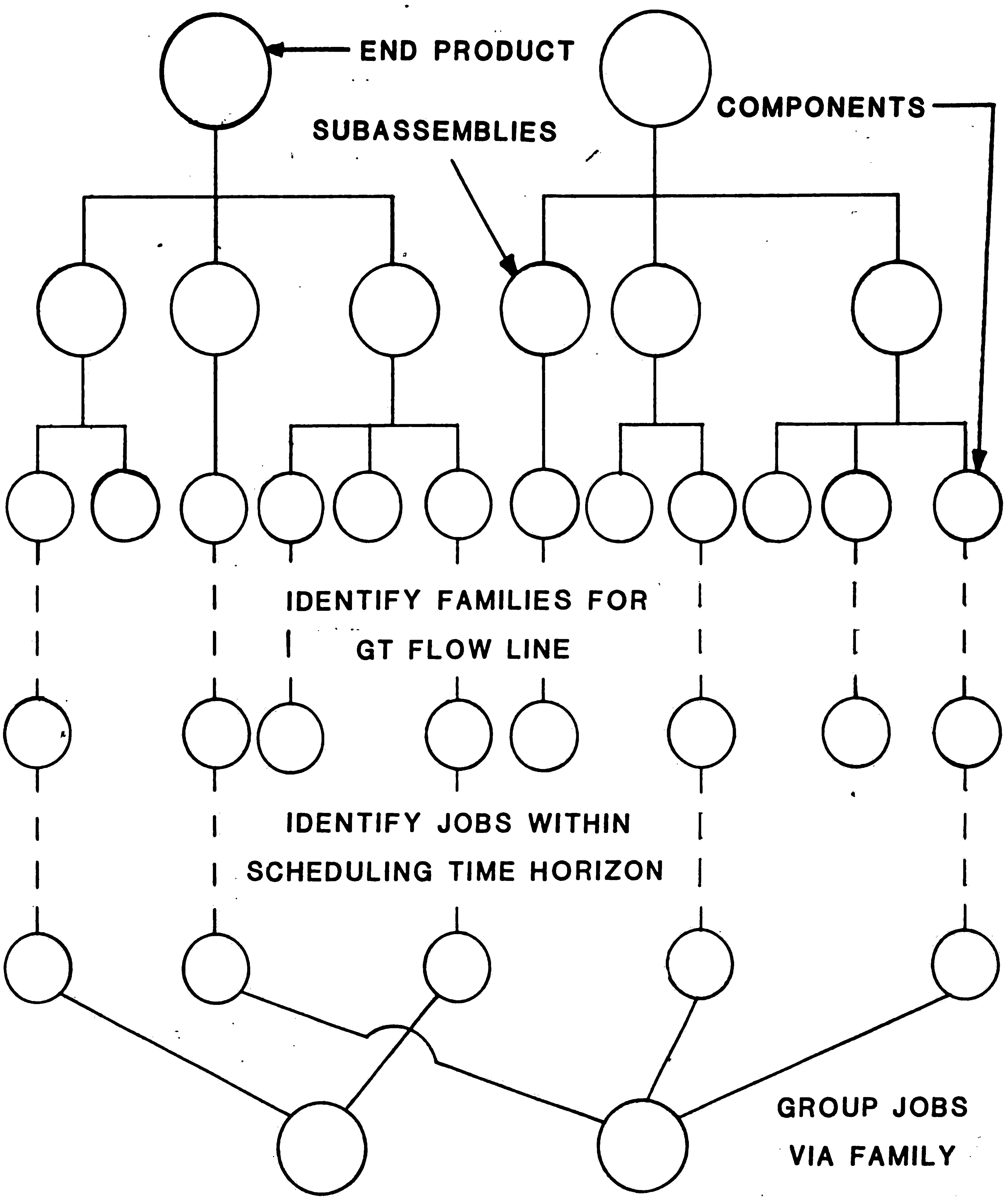


**Figure 3-3:** Integrating GT and MRP

region. Once this acceptable system performance has been defined, the time horizon for grouping jobs may be adjusted to maintain the proper balance of

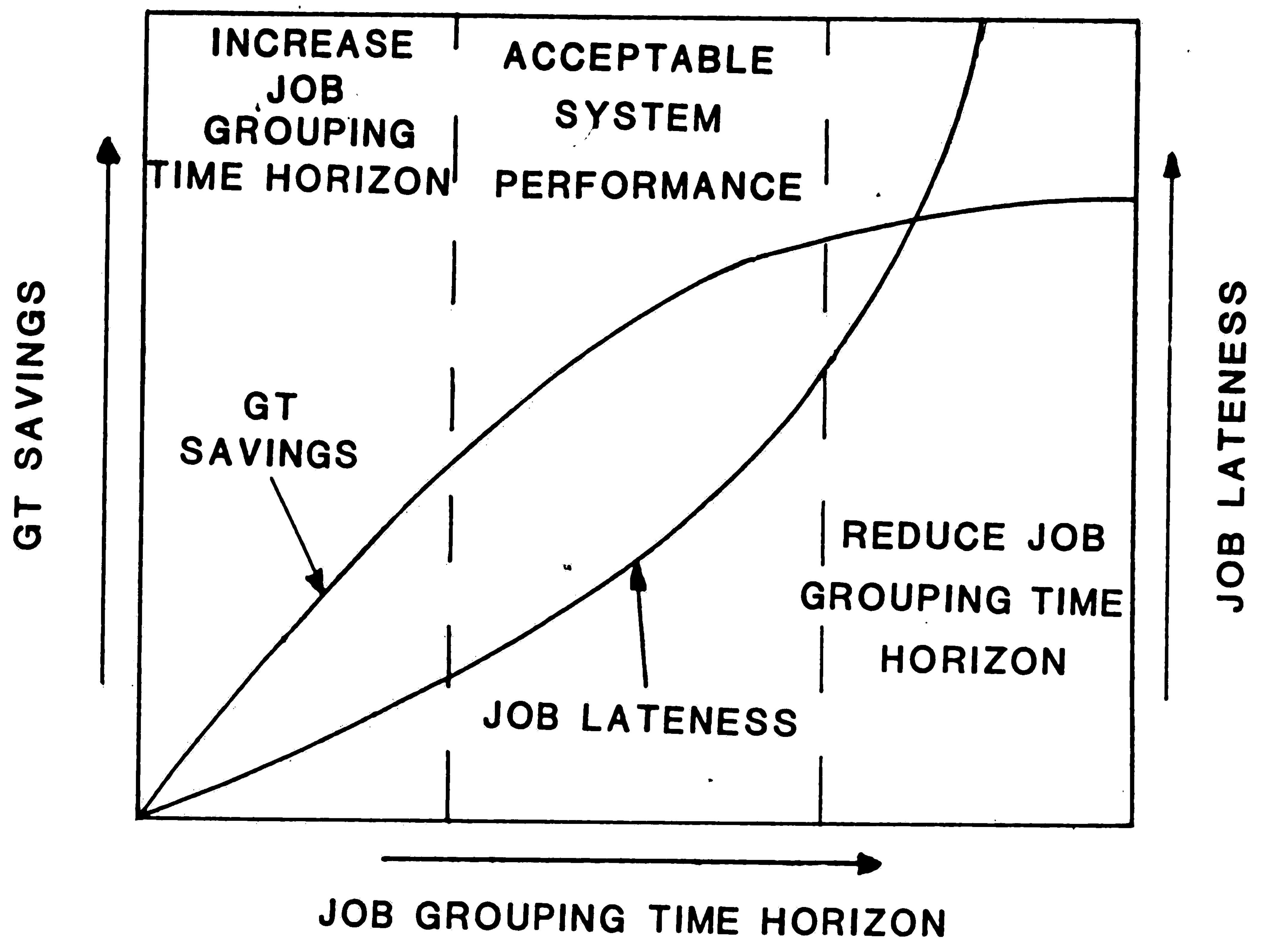


**Figure 3-4:** The GT Savings/Job Lateness Balance

tardiness and GT savings. Adjustments in the time horizon may be either positive or negative depending upon the projected lateness versus group savings. This balance is a function of many factors (i.e. product lead time, manufacturing lead time, machine utilization, etc.) relevant to a specific GT flow line. Dynamic adjustments in the job grouping time horizon is the differentiating characteristic between this proposed model for GT flow line scheduling and PBC or other single cycle scheduling methods.

# Chapter 4

# Minimizing Maximum Tardiness for a GT Flow Line

## 4.1 Model Structure

As stated previously, the direction of this thesis is to develop a scheduling algorithm for a GT flow line based on minimizing maximum tardiness. Examining the literature revealed that a model by Townsend had been proposed to schedule **n** jobs on **m** machines to minimize maximum tardiness based on a branch-and-bound procedure. [12,pgs.1016-1019.] Townsend's model was an expansion of a single machine scheduling case proposed by Smith.

The objective of the model is to develop a sequence of jobs which minimizes tardiness such that:

$$\min_{S}\ \{\max_{i \in I}(t_i + d_i)\}\ \textit{for some job sequence } S^*,$$

where $\mathbf{t}_i$ is the completion time of i within job set I and $\mathbf{d}_i$ is the due date of job **i**. Jobs for scheduling are defined $i \in I$ and the set of jobs **I** = **(1,2,...,n)**. Machines of which jobs in **I** are to be processed are defined as

$$j \in J$$

where **J** is the set of machines **J** = **(1,2,...,m)**. Townsend states that if queueing is ignored the finishing time of job **i** on machine **m** is at least:

$$t_{i1} + \sum_{j=2}^{m} a_{ij}$$

Where $\mathbf{a}_{\mathbf{ij}}$ is the operation time of the **ith** job on the **jth** machine. If tardiness of a job **i** is defined as

$$l_i = t_i - d_i$$

then the actual completion time must be greater than or equal to the minimum completion time. This relationship is shown below:

$$l_i = t_i - d_i \geq t_{i1} + \sum_{j=2}^{m} a_{ij} - d_i$$

or restated

$$l_i \geq t_{i1} - (d_i - \sum_{j=2}^{m} a_{ij})$$

so, tardiness will be equal to or greater than this minimum condition. This condition represents a lower bound on the maximum tardiness for the job sequence S. This maximum lateness satisfies

$$\max_{i \in I}(l_i) \geq \max_{i \in I}(t_{i1} - d'_i)$$

Where

$$d'_i = d_i - \sum_{j=2}^{m} a_{ij} \quad .$$

$\mathbf{d'}_i$ is defined as the "adjusted due date" for job **i**. The adjusted due date serves as a basis for a preliminary ordering of jobs in the branch-and-bound calculations. For the case of one machine (**m=1**), $\mathbf{a_{ij} = 0}$, and $\mathbf{d'_i = d_i}$, the maximum tardiness is minimized by arranging jobs according to their adjusted due date, $\mathbf{d'_1}$.

If jobs are organized by the adjusted due date and the ordering is found to be $(\mathbf{i_1, i_2, \ldots, i_n})$ then a lower bound (**LB**) for maximum tardiness $(\mathbf{max(l_i)})$ is equal to:

$$LB(\max(l_i)) = \max_{r \in I}[\sum_{p=1}^{r} a_{i_p 1} - (d_{i_r} - \sum_{j=2}^{m} a_{i_r j})]$$

or

$$\max_{r \in I}(T_{i_r} - d_{i_r}),$$

where

$$T_{i_1} = \sum_{j=1}^{m} a_{i_1 j},$$

if **r** equals the first job in **I**, else

$$T_{i_r} = \sum_{p=1}^{r-1} a_{i_p 1} + \sum_{j=1}^{m} a_{i_r j} \quad for \quad r > 1.$$

The model is enhanced further by extending the bounding logic to multiple machines. A pre-sequence of jobs, $\overline{A}$, is formed and $t_{\overline{A}s}$ is defined as the completion time of the last job in $\overline{A}$ on machine **s**, $s \in J$.

A machine lower bound for maximum tardiness for a job sequence starting with $\overline{A}$ is determined by:

$$LB_s(\overline{A}) = \max\{\max_{j \in \overline{A}}(t_{jm} - d_j), \max_{r \in I; i_r \notin \overline{A}}(t_{\overline{A}s} + \sum_{p-1; i_p \notin \overline{A}}^{r} a_{i_p s} + \sum_{j=s+1}^{m} a_{i_r j} - d_{i_r})\}$$

such that $(i_1, i_2, \ldots, i_n)$ is the sequence of jobs on machine **s** which minimizes the the expression [12,pgs.1017-1018.]

$$\max_{r \in I; i_r \notin \overline{A}}(t_{\overline{A}s} + \sum_{p=1, i_p \notin \overline{A}}^{r} a_{i_p s} + \sum_{j=s+1}^{m} a_{i_r j} - d_{i_r}),$$

which is equivalent to minimizing

$$\max_{r \in I; i_r \notin \overline{A}} \left[ \sum_{p=1; i_p \notin \overline{A}}^{r} a_{i_p s} - (d_{i_r} - \sum_{j=s+1}^{m} a_{i_r j}) \right].$$

This minimum condition is determined by ordering jobs not contained in $\overline{A}$ according to a "S-machine adjusted" due date for any job. The S-machine adjusted due dates are calculated by:

$$d_{i_r}^{\,s} = d_{i_r} - \sum_{j=s+1}^{m} a_{i_r j}, \qquad s = 1,2, \; . \; . \; . \; ,m-1 \qquad (1).$$

$$d_{i_r}^{\,m} \; = \; d_{i_r} \qquad (2).$$

If all machines are considered, an overall lower bound, **LB($\overline{\mathrm{A}}$)**, for the minimization of the maximum tardiness can be calculated. This lower bound is such that the

$$LB(\overline{\mathrm{A}}) \;\; = \;\; \max_{s \in j}[LB_s(\overline{\mathrm{A}})]$$

where:

$$LB_s(\overline{\mathrm{A}}) = \max\{\max_{j \in \overline{\mathrm{A}}}(t_{jm} - d_j), \max_{r \in I; i_{rs} \notin \overline{\mathrm{A}}}(t_{\overline{\mathrm{A}}s} + \sum_{p=1; i_{ps} \notin \overline{\mathrm{A}}}^{r} a_{i_{ps}s}$$

$$+ \sum_{j=s+1}^{m} a_{i_{rs}j} - d_{i_{rs}})\} \qquad (3)$$

where $\mathbf{i}_{\mathbf{rs}}, r \in I$ is the Smith sequence of jobs on machine **s** using the S-machine adjusted due dates. $\mathbf{t}_{\overline{\mathbf{A}}\mathbf{s}}$ is the completion time on machine **s** of the last job in the pre-sequence $\overline{\mathrm{A}}$.

This model to minimize maximum tardiness will be utilized as a basis for determining the appropriate machine loading sequence for a GT flow line.

## 4.2 Numerical Example

The following numerical example will illustrate the operation of the model. Consider the flow line scheduling problem of Table 4-1.

TABLE 4-1.

| MACHINE | JOB | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| 1 | 4 | 5 | 6 | 5 | 3 |
| 2 | 3 | 2 | 3 | 4 | 4 |
| 3 | 7 | 1 | 4 | 6 | 3 |
| DUE DATE | 28 | 32 | 43 | 44 | 35 |

The first step is to calculate S-machine adjusted due dates, using equations 1 and 2, yielding the results illustrated in the following section. The $d_{i_r}^{s}$ values, where s=1, are determined to be:

$$d_{i_1}^{1} = 28 - (3+7) = 18$$

$$d_{i_2}^{1} = 32 - (2+1) = 29$$

$$d_{i_3}^{1} = 43 - (3+4) = 36$$

$$d_{i_4}^{1} = 44 - (4+6) = 34$$

$$d_{1_5}^{1} = 35 - (4+3) = 28$$

The $d_{i_r}^{s}$ values for machine 2 (s=2) are calculated as shown below:

$$d_{i_1}^{2} = 28 - 7 = 21$$

$$d_{i_2}^{2} = 32 - 1 = 31$$

$$d_{i_3}^{2} = 43 - 4 = 39$$

$$d_{i_4}^{2} = 44 - 6 = 38$$

$$d_{i_5}^{2} = 35 - 3 = 32$$

The S-machine adjusted due dates for machine 3 ($d_{i_r}^{3}$) are determined by utilizing equation 3, as illustrated below:

$$d_{i_1}^{3} = 28$$

$d_{i_2}^{\,3} = 32$

$d_{i_3}^{\,3} = 43$

$d_{i_4}^{\,3} = 44$

$d_{i_5}^{\,3} = 35$

The S-machine adjusted due dates are utilized to determine the optimal single machine job sequences. Jobs are sequenced according to the nondecreasing value of the S-machine adjusted due dates for each machine. The S-machine orderings are (1, 5, 2, 4, 3), (1, 2, 5, 4, 3) and (1, 2, 5, 3, 4) for s=1, 2 and 3, respectively.

Consider the node with job 1 fixed in the first position. The job order used to determine $LB_1(1)$ is (1, 5, 2, 4, 3), where (5, 2, 4, 3) is the optimal job sequence for the remaining jobs on the first machine. The earliest completion times for the job sequence are determined as shown below:

```
Job 1: 4 + 3 + 7 = 14,
Job 5: 4 + 3 + 4 + 3 = 14,
Job 2: 4 + 3 + 5 + 2 + 1 = 15,
Job 4: 4 + 3 + 5 + 5 + 4 + 6 = 27,
Job 3: 4 + 3 + 5 + 5 + 6 + 3 + 4 = 30.
```

The lower bound on maximum tardiness is now determined for the partial schedule $\overline{A}$, machine = 1, and $i_{rs}$ containing the set of unscheduled jobs (5, 2, 4, 3). The lower bound on maximum tardiness for the unscheduled jobs is calculated as shown below:

$$for\ i_{rs} = 5\ :\ 4 + 3 + (4 + 3) - 35 = -21,$$

$$for\ i_{rs} = 2\ :\ 4 + (3 + 5) + (2 + 1) - 32 = -17,$$

$$for\ i_{rs} = 4\ :\ 4 + (3 + 5 + 5) + (4 + 6) - 44 = -17,$$

$$for\ i_{rs} = 3\ :\ 4 + (3 + 5 + 5 + 6) + (3 + 4) - 43 = -13.$$

Utilizing equation 3, the lower bound on the maximum tardiness, for the set of unscheduled jobs (5, 2, 4, 3), $\overline{A} = (1)$, and s = 1 is determined to be equal to:

$$LB_1(1) = \max\{(14 - 28),\ (-21,\ -17,\ -17,\ -13)\},$$

$$= \max\{(-14),\ (-13)\} = \ -13.$$

The lower bound on maximum tardiness for machine 2 (s=2) with job 1 fixed in the first position (i.e. $\overline{A} = (1)$) is determined next. The job sequence used to determine $LB_2(1)$ is (1, 2, 5, 4, 3), where (2, 5, 4, 3) is the optimal job sequence for the remaining jobs on the second machine. The earliest completion times for the job sequence are determined as shown below:

Job 1 : 4 + 3 + 7 = 14,
Job 2 : 4 + 3 + 2 + 1 = 10,
Job 5 : 4 + 3 + 2 + 4 + 3 = 16,
Job 4 : 4 + 3 + 2 + 4 + 4 + 6 = 23,
Job 3 : 4 + 3 + 2 + 4 + 4 + 3 + 4 = 24.

The lower bound on maximum tardiness is now determined for the partial schedule $\overline{A} = (1)$, machine = 2, and $i_{rs}$ containing the set of unscheduled jobs (2, 5, 4, 3). The lower bound on maximum tardiness for the unscheduled jobs is calculated as shown below:

$$for\ i_{rs} = 2\ :\ 7 + 2 + 1 - 32 = -22,$$

$$for\ i_{rs} = 5\ :\ 7 + (2 + 4) + 3 - 35 = -19,$$

$$for\ i_{rs} = 4\ :\ 7 + (2 + 4 + 4) + 6 - 44 = -21,$$

$$for\ i_{rs} = 3\ :\ 7 + (2 + 4 + 4 + 3) + 4 - 43 = -19.$$

Utilizing equation 3, the lower bound on maximum tardiness for the set of unscheduled jobs (2, 5, 4, 3), $\overline{A}=(1)$ and s=2 is determined to be:

$$LB_2(1) = \max\{(-14),\ (-22,\ -19,\ -21,\ -19)\},$$

$$= \max\{(-14),\ (-19)\} = -14.$$

The lower bound on maximum tardiness for machine 3 (s=3) with job 1 fixed in the first postion (i.e. $\overline{A} = (1)$) is determined in the following section. The job sequence used to determine $LB_3(1)$ is (1, 2, 5, 3, 4), where (2, 5, 3, 4) is the S-machine ordering for the remaining jobs on the third machine. The earliest completion times for the job sequence are determined as shown below:

Job 1 : 4 + 3 + 7 = 14,
Job 2 : 4 + 3 + 7 + 1 = 15,
Job 5 : 4 + 3 + 7 + 1 + 3 = 18,
Job 3 : 4 + 3 + 7 + 1 + 3 + 4 =22,
Job 4 : 4 + 3 + 7 + 1 + 3 + 4 + 6 = 28.

The lower bound on maximum tardiness is now determined for the partial schedule $\overline{A} = (1)$, machine = 3, and $i_{rs}$ containing the set of unscheduled jobs (2, 5, 3, 4). The lower bound on maximum tardiness for the unscheduled jobs is calculated as shown below:

$$for\ i_{rs} = 2\ :\ 14 + 1 - 32 = -17,$$

$$for\ i_{rs} = 5\ :\ 14 + (1 + 3) - 35 = -17,$$

$$for\ i_{rs} = 3\ :\ 14 + (1 + 3 + 4) - 43 = -21,$$

$$for\ i_{rs} = 4\ :\ 14 + (1 + 3 + 4 + 6) - 44 = -16.$$

The lower bound on the maximum tardiness for the set of unscheduled jobs (2, 5, 3, 4), $\overline{A} = (1)$ and s=3 is determined to be:

$$LB_3(1) = \max\{(-14),\ (-17,\ -17,\ -21,\ -16)\} = -14.$$

Next, the overall lower bound on maximum tardiness across machines 1, 2 and 3 with job 1 fixed in the first position (i.e. $\overline{A} = (1)$) is determined to be:

$$LB(1) = \max\{LB_1(1),\ LB_2(1),\ LB_3(1)\}$$

$$= \max\{-13,\ -14,\ -14\} = -13$$

This represents the lower bound for the branch-and-bound node with job 1 fixed in position 1.

The branching procedure continues by placing jobs 2, 3, 4 and 5 in the first position. The lower bound on maximum tardiness, as illustrated previously, is determined for each of these jobs fixed in position 1 of the pre-sequence $\overline{A}$. After the LB(1), LB(2), LB(3), LB(4) and LB(5) are determined, the minimum of these maximum lower bounds is selected for further "branching" and that associated job is fixed in postion 1. The branch-and-bound procedure continues by determining the second job position.

Suppose branching occurs from the node associated with $\overline{A}$ = (1) with LB(1) = -13. Then the next node in the branch-and-bound procedure is to consider job 2 in position 2 and determine the lower bound of maximum tardiness for the pre-sequence $\overline{A}$ = (1-2).

The S-machine ordering used to determine $LB_1$(1-2) is (1, 2, 5, 4, 3), where (5, 4, 3) is the optimal job sequence for the remaining jobs on the first machine. The completion time for job 1 is equal to $4+3+7=14$. Job 2 is completed after $4+5+2+1=12$. Job 5 is completed after 19, job 4 after 27, and job 3 after 30.

The lower bound on maximum tardiness for job sequence (1, 2, 5, 4, 3) for machine 1, is associated with $i_{rs}$=3 having value equal to -13. This lower bound for pre-sequence $\overline{A}$ = (1-2) and s=1 is determined as illustrated below:

$$LB_1(1-2) = \max\{(-14,\ -20),\ (-16,\ -17,\ -13)\},$$

$$= \max\{(-14),\ (-13)\} = \ -13.$$

Next, the lower bound on maximum tardiness for machine 2 (s=2) is calculated with jobs 1 and 2 fixed in the first postions, respectively. The job sequence (1, 2, 5, 4, 3), where (5, 4, 3) is the optimal job sequence for the remaining jobs on the second machine, is used to determine this lower bound. The completion time for job 1 is equal to 4 + 3 + 7 = 14. Job 2 is completed after 9 + 2 + 1 = 12. Job 5 is completed after 11 + 4 + 3 = 18.

The determination of the completion time for $\overline{A}$ = (1-2) on machine 2 (i.e. $t_{\overline{A}2} = 11$) considers the condition where job 2 must wait until job 1 has completed its operation on machine 2 before it can begin processing on machine 2. This interference calculation is a critical operation required by the branch-and-bound procedure. For example, the tardiness calculation for unscheduled job 5 on machine 2 is shown to below:

$$i_{rs} = 5 \; : \; (11 + 4 + 3 - 35) = \; -17.$$

After the lower bounds on maximum tardiness for unscheduled jobs 4 and 3 are determined, the branch-and-bound procedure continues by determining the lower bounds for machine 3 ($LB_3(1-2)$), by utilizing equation 3 and the S-machine job orderings.

The branch-and-bound procedure then fixes jobs 3, 4 and 5 in second job position (i.e. $\overline{A}$ = (1-3), (1-4) and (1-5), respectively) and determines the maximum tardiness bounds for each of these job sequences, as previously illustrated.

The branching procedure continues until all jobs are fixed in a candidate complete job sequence $\overline{A}^*$. All open partial schedules are examined and if no further nodes may be generated with lower bounds less than the maximum tardiness for $\overline{A}^*$, then $\overline{A}^*$ is optimal. However, if a new complete job sequence $\overline{A}'$ is found with a lower value for maximum tardiness, it will become the new sequence $\overline{A}^*$ and the fathoming process continues as discussed above.

# Chapter 5
# Features of the Model

## 5.1 Grouping the Manufacturing Requirements by GT

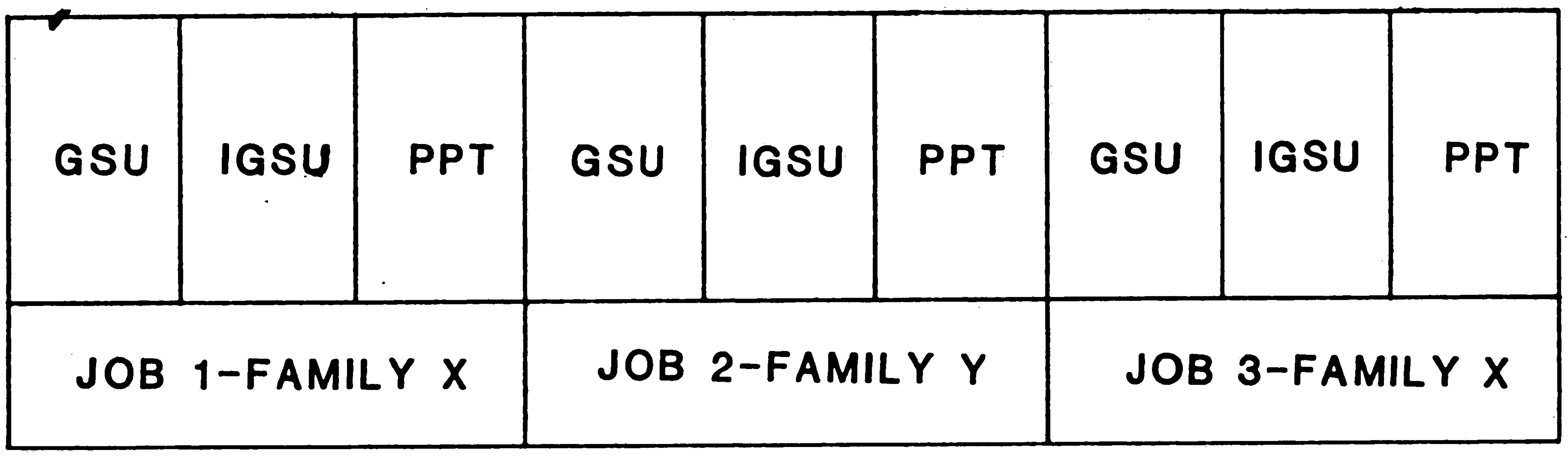
The first step in the model is to combine the manufacturing jobs via the GT families. These grouped jobs are identified by determining those requirements which fall within the GT families and the scheduling horizon of the GT flow line. Adjustments must be made in the planning horizon to allow GT savings without sacrificing customer due dates, as shown previously in Figure 3-4. This balance is a function of manufacturing lead time, raw material availability, end product lead time and due date.

The grouped jobs are ordered in nondecreasing order with respect to due date within groups to identify the earliest due date for a given group. "Group jobs" are then organized according to nondecreasing value of the earliest due date. A calculation is made at this point to determine the savings facilitated by the application of group technology. This will allow a comparison between GT savings and tardiness.

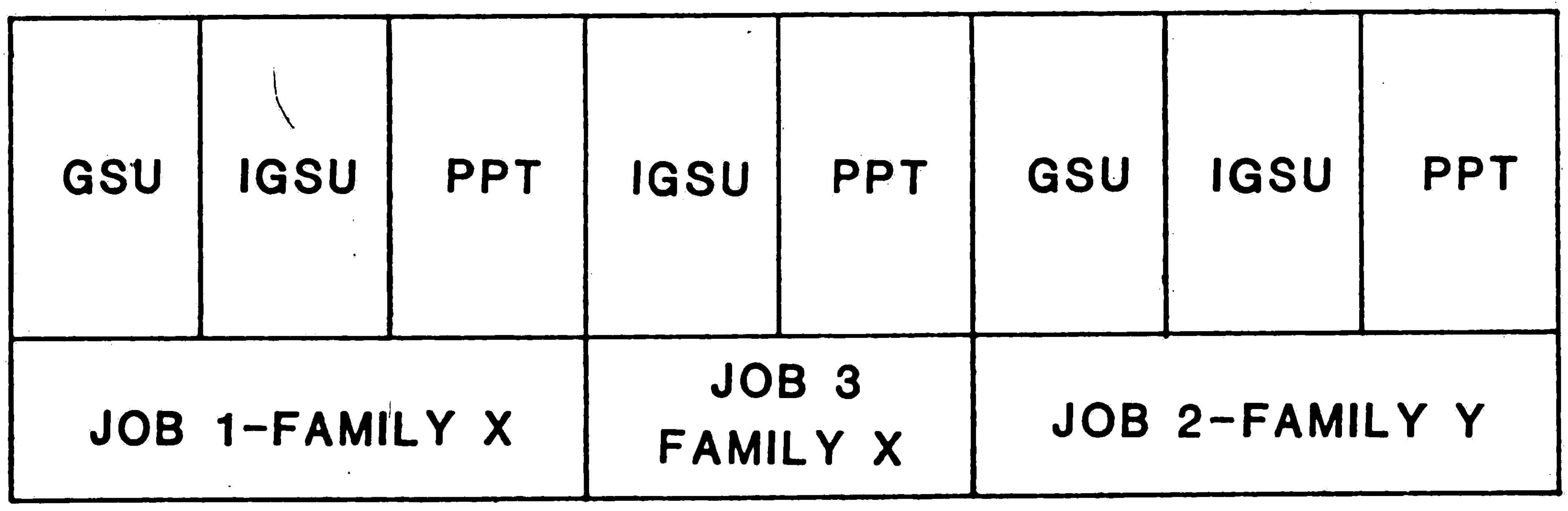
## 5.2 Combining Setup and Piece Production Times for Group Jobs

The next step in the algorithm is to combine the setup and piece production times to determine a total operation time for each operation within each group job.

Operation time is divided into three categories; group setup, intragroup setup and piece production time. Group setup (GSU) is the setup tasks required prior to the production of a particular group (i.e. setup of group tools, setup of inspection equipment, preparation of fixtures, etc). The intragroup setup (IGSU) is the activity required between jobs of the same group (i.e. loading of NC tape, index inserts on tooling, set NC tooling offsets, etc). Piece production time (PPT) is defined as the actual production time required to complete the operation on a particular part. If similiar groups are scheduled consecutively, only one group setup is required as shown in Figure 5-1.



JOBS SCHEDULED WITHOUT GT



COMBINED FAMILY JOBS VIA GT

**Figure 5-1:** Group Savings from Consecutively Scheduled Group Jobs

## 5.3 Determining the GT Based Adjusted Smith Due Dates

The adjusted Smith due dates are determined for each machine in the GT flow line. These due dates represent a proposed array of latest completion times for a single machine utilized by the branch-and-bound procedure for flow line scheduling. To calculate adjusted Smith due dates, subtract the groups' total operation time for all processes following a specific operation from the earliest due date of that particular group job.

## 5.4 Determining the GT Flow Line Schedule

A lower bound for maximum tardiness is computed using the method presented by Townsend. [12,pgs.1016-1019.] GT is incorporated by combining the manufacturing requirements within a given planning horizon for a GT family. The branch-and-bound calculation determines the maximum lower bound for each machine and combination of jobs. The minimum of the maxima is chosen from each of the scheduling alternatives and that job which represents the minumum is fixed in a schedule position. This becomes part of the presequence $\overline{A}$ and is held fixed in the schedule. The branch-and-bound routine continues and fills the next position in a similiar manner. Once all positions in the schedule have been determined, the final job sequence represents the optimum job sequence to minimize maximum tardiness.

## 5.5 Balancing Tardiness and Group Savings

Once a schedule has been determined by the branch-and-bound procedure, a comparison of job lateness to group savings must be made. This comparison will require testing fo the model utilizing actual production data to determine the system performance. If the maximum job tardiness is within the threshold performance requirements then the schedule can be implemented. Otherwise the scheduling time horizon must be reduced (as shown in Figure 3-4) and the entire scheduling process reformulated.

## 5.6 Flowchart of the Model

The following flowchart (shown in Figure 5-2) represents a schematic overview of the algorithm to integrate group technology with scheduling of the GT flow line.

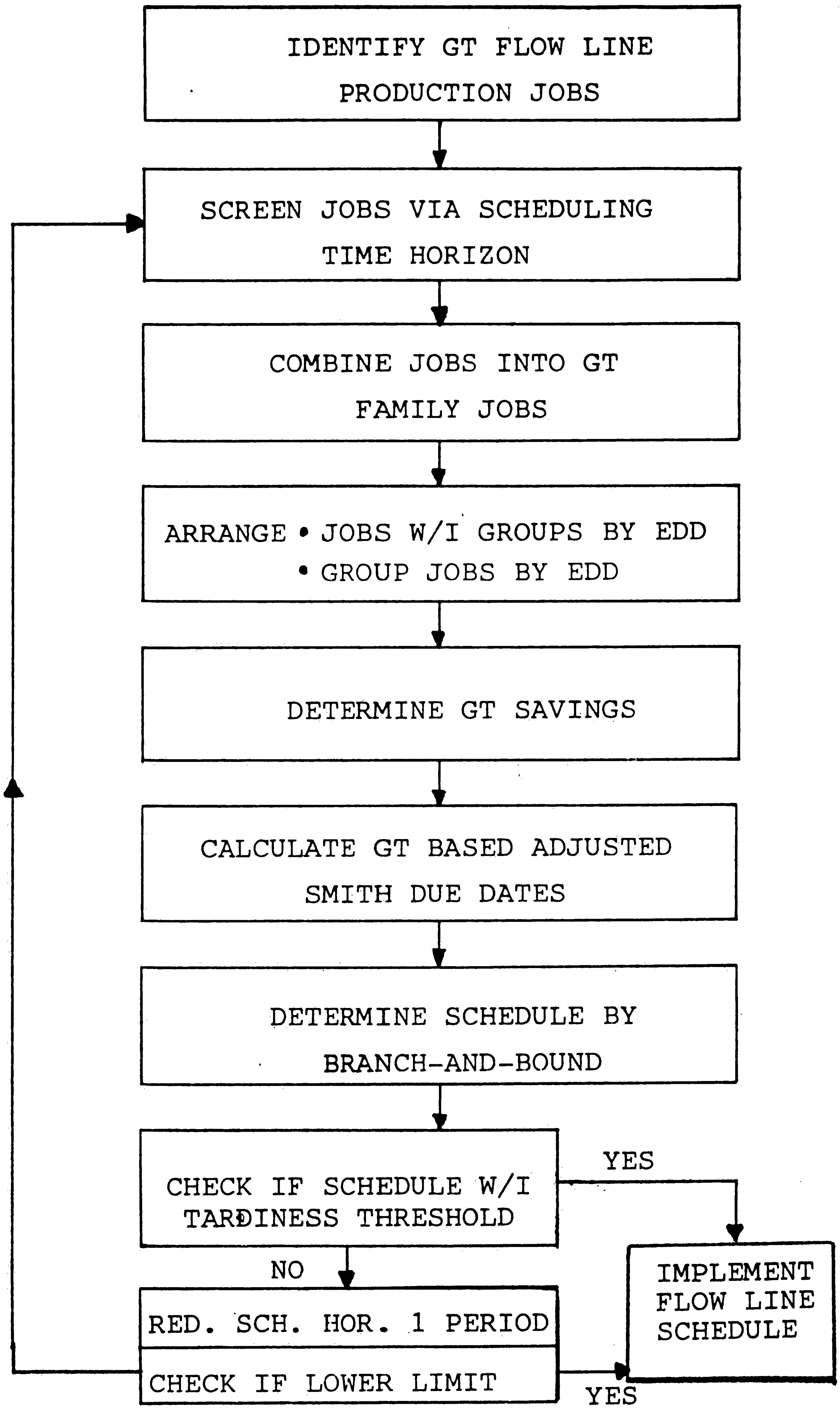
## 5.7 Numerical Example of GT Based Scheduling to Minimize Maximum Tardiness

The following numerical example will illustrate the operation of the GT based flow line scheduling model.

Consider the flow line scheduling problem of Table 4-1, in Section 4-2. Suppose the following conditions exist:

1. Jobs 1 and 4 are members of the same part family.
2. Jobs 2 and 3 are members of the same part family.
3. Group setup for all part families and operations is equal to 0.5 time units.
4. Group setup is deducted from each entry in Table 4-1 and the calculations shown in Table 5-1 apply one group setup for each group job.

**Figure 5-2:** GT-Based Min. Max. Tardiness Scheduling of a GT Flow Line



The earliest due date among the production jobs in a group is designated as the due date for the group job. Table 5-1, shown below, illustrates the application of the GT based scheduling procedures to the problem as detailed in Table 4-1.

TABLE 5-1.

| MACHINE | GROUP JOB | | |
|---|---|---|---|
| | 1-4 | 2-3 | 5 |
| 1 | 8.5 | 10.5 | 3 |
| 2 | 6.5 | 4.5 | 4 |
| 3 | 12.5 | 4.5 | 3 |
| DUE DATE | 28 | 32 | 35 |

The combined operation times in Table 5-1 represent the sum of the job operation times and group setup time.

The next step in the model is to calculate the GT based S-machine adjusted due dates using equations 1 and 2.

The $d_{i_r}^{s}$ values, where s=1, are determined to be:

$d_{i_{1-4}}^{1} = 28 - (6.5+12.5) = 9$

$d_{i_{2-3}}^{1} = 32 - (4.5 + 4.5) = 23$

$d_{i_5}^{1} = 35 - (4 + 3) = 28$

The $d_{i_r}^{s}$ values for machine 2 (s=2) are calculated as shown below:

$d_{i_{1-4}}^{2} = 28 - 12.5 = 15.5$

$d_{i_{2-3}}^{2} = 32 - 4.5 = 27.5$

$d_{i_5}^{2} = 35 - 3 = 32$

The $d_i^{s}$ values for machine 3 (s=3) are calculated as shown below:

$d_{i_{1-4}}^{3} = 28$

$d_{i_{2-3}}{}^{3} = 32$

$d_{i_5}{}^{3} = 35$

The GT based S-machine adjusted due dates are used to determine the optimal single machine job sequences. Jobs are sequenced according to nondecreasing value of the GT based S-machine adjusted due dates for each machine. The GT based S-machine job orderings are (1-4, 2-3, 5), (1-4, 2-3, 5) and (1-4, 2-3, 5) for s=1, 2 and 3, respectively.

The branch-and-bound procedure utilizes these GT based S-machine job orderings in the bounding procedure at the initial node where $\overline{A}$ contains no jobs. The next step in the model is to utilize the branch-and-bound model, detailed in Chapter 4, to determine the optimum GT based job sequence.

# Chapter 6

# Developing the Model

## 6.1 Generating the Scheduling Procedure

Fortran code was written to perform the tasks detailed in Chapter 5. These included:

1. Screening the manufacturing requirements for the GT flow line.
2. Identifying manufacturing requirements within a specified scheduling time horizon.
3. Grouping the flow line production jobs within similiar part families.
4. Arranging the production jobs with respect to earliest due date in nondecreasing order within groups.
5. Arranging the group jobs with respect to earliest due date in an nondecreasing order.
6. Combining setup and piece production times for group jobs.
7. Determining the adjusted Smith due dates.
8. Developing the GT flow line job sequence by a branch-and-bound procedure to minimize maximum tardiness.
9. Arranging the production jobs according to the branch-and-bound job sequence.

The steps listed above represent the major tasks required to generate the GT flow line schedule. Ingersoll-Rand's five operation flow line was the test case for development of this model.

## 6.2 Development of the GT Flow Line Simulation

The algorithm results were tested utilizing a simulation model of Ingersoll-Rand's impeller GT flow line. Simulation provides a dynamic tool for testing real systems under various performance criteria. [9,pgs.169-171., 7,pg.281.] The model of the impeller cell was constructed utilizing the discrete modeling capability of SLAM II [8,pgs.222-307.]. The model represented the five operations and setup required for changeover between jobs.

Data input for the program was gathered through examining output records of the cell for two months. The group setup, intragroup setup and piece production times were identified for each of the operations. Production records of cell operators were examined to determine the appropriate probability distributions for performance (i.e. normal, exponential, uniform, etc). This performance criteria and production time data were utilized to test the performance of the model under various scheduling alternatives.

## 6.3 Validation of the Computer Model

Validation is a critical step in any scientific study. The accuracy of all computer code must be ensured to guarantee model precision. Without such a check all results are conjecture.

All modules utilized by the scheduling algorithm were checked versus manual results. Output statements and file data were checked utilizing sample data to certify the accuracy of the results. Each step of the branch-and-bound calculation was manually checked to validate the accuracy of the scheduling computation.

The simulation of the flow line was tested to guarantee model exactness. Sample data and SLAM II utilities for debugging simulation models

[8,pgs.151-152] were employed to output all model activities for manual review. This manual review gave reasonable assurance of the accuracy of the model.

# Chapter 7
# Methods of Comparison

## 7.1 Alternate Scheduling Techniques

Comparison of the GT flow line scheduling results to a variety of scheduling methodologies provides a standard for measurement of model results. The scheduling techniques employed for comparison included:

1. Longest processing time.
2. Shortest processing time.
3. Earliest due date.
4. Least job slack.

Longest processing time (LPT) is a scheduling methodology which ranks jobs for processing in nonincreasing order of processing time. Jobs are then scheduled for machine processing according to this ranked order. The application of this procedure to the flow line required that a total operation time for the flow line be determined for each production job. Jobs were then ranked according to total operation time, without regard to GT family. The simulation then implemented this job order to determine system results of this model.

Shortest processing time (SPT) is a scheduling technique similiar to longest processing time. The difference in the methods is that shortest processing time ranks jobs according to an nondecreasing value of processing time. A total operation time for the flow line for each individual job must be determined. Production jobs are then ranked in an nondecreasing fashion based on total operation times. The schedule was then implemented by the flow line simulation to determine the system performance.

Earliest due date (EDD) is the technique currently applied by Ingersoll-Rand to schedule the impeller flow line. Production jobs are ranked in nondecreasing order based upon their due date. This methodology does not consider the operation times only the job due date. Production jobs were organized according to this nondecreasing value of due date and tested by the flow line simulation.

Least job slack (SLACK) is a scheduling criterion which organizes production jobs in nondecreasing order of job slack. Slack is determined by subtracting the manufacturing lead time and current date from the due date of the job. [4,pgs.203-206.] A positive result of this operation indicates that a certain amount of time (i.e. slack) exists before the job must begin processing in order to avoid being late. Conversely, negative slack indicates that a job will be late. For the purposes of this examination of Ingersoll-Rand's flow line, manufacturing lead time will be replaced by operation time in the determination of slack. This substitution is possible based on the flow line performance. By properly balancing the flow line's operations, work in process has been maintained at a low level causing the manufacturing lead time to approach the sum of the job operation times. Therefore, manufacturing lead time has been replaced by cumulative operation time for this analysis. Slack was calculated for each manufacturing requirement and the jobs were ranked in nondecreasing order of slack for input to the simulation model.

## 7.2 Justification of Comparitive Scheduling Techniques

The selection of LPT, SPT, EDD and SLACK as scheduling rules to compare to the minimization of maxium tardiness model was made due to a number of factors. These rules have proven to be optimal for the single machine case. [1,pgs.18-27,196-197., 11,pgs.200-204.] They have also been utilized to develop dispatching procedures that have proven to be effective and robust in developing schedules in the more general flow and job shop settings. [4,pgs.226-234.]

# Chapter 8
# Analysis of Results

The simulation model of the flow line was tested utilizing the previously detailed scheduling methods. Data for model testing was acquired through analysis of production records for January and February of 1986. The simulation accumulated statistics on a variety of manufacturing performance measures. Critical performance measures monitored by the simulation include:

1. Maximum tardiness.
2. Group technology savings.
3. Average time in the system.
4. Average work in process.
5. Flow line utilization.
6. Average throughput.

The horizontal axis depicted in Figures 8-3, 8-4, 8-5 and 8-6 is "HOURS BETWEEN JOB RELEASES". This denotes the time horizon utilized for releasing production jobs to the flow line.

## 8.1 Maximum Job Tardiness

Each of the scheduling methods determined a job ordering to be processed by the simulation model. Figure 8-1 depicts the maximum job tardiness resulting from the application of each of the scheduling techniques. EDD, LPT, SLACK and the GT scheduling method performed in a similiar manner. SPT did not perform as well as the previously mentioned methods. EDD, LPT, SLACK and the GT scheduling method all scheduled the overdue jobs first. This accounts for the similiar results reported for each of these sequencing methods. Since minimizing tardiness is the primary objective, the use of shortest processing time can be eliminated as a possible scheduling technique.

### 8.2 Group Technology Savings

Savings generated by the groupings of similiar GT family production requirements, is a secondary objective. Although EDD, SPT, LPT and SLACK are not directed to achieving GT savings, unplanned savings did occur. These unplanned grouping were due to a large population of one GT family in the production job sequence. The GT scheduling method performed the best in this category as shown in Figure 8-2. SLACK performed second best, with approximately 20% less GT savings than the GT scheduling method. EDD, the method currently utilized by Ingersoll-Rand for scheduling, exhibited the worst results.

### 8.3 Average Time in the System

Results of the average time in system analysis are shown in Figure 8-3. SPT achieved the most favorable results, with longest processing time having the least favorable results. All other job sequencing procedures (GT scheduling, EDD and SLACK) produced results that were virtually equal to one another. Since SPT organizes jobs in nondecreasing value of total operation time, it is not surprising that SPT would achieve the most favorable results for averge time in the system.

Increasing the time between job releases reduced the average time in the system for all scheduling techniques. Work in process (as shown in Figure 8-4) and queuing time were also reduced, causing the average time in the system to approach the total operation time.

**Figure 8-1:** MAXIMUM JOB TARDINESS

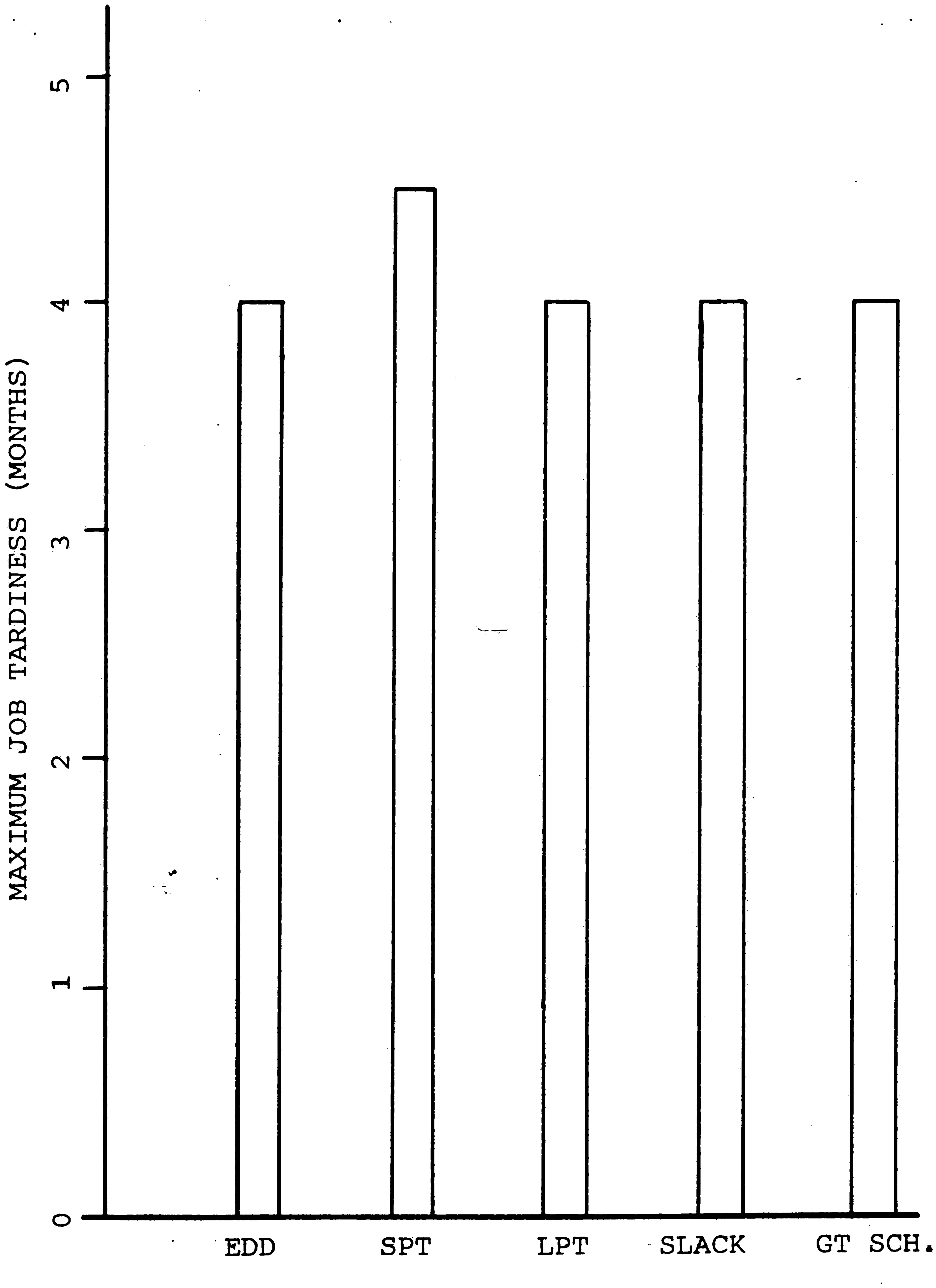


Figure 8-2: GT SAVINGS/PRODUCTION JOB

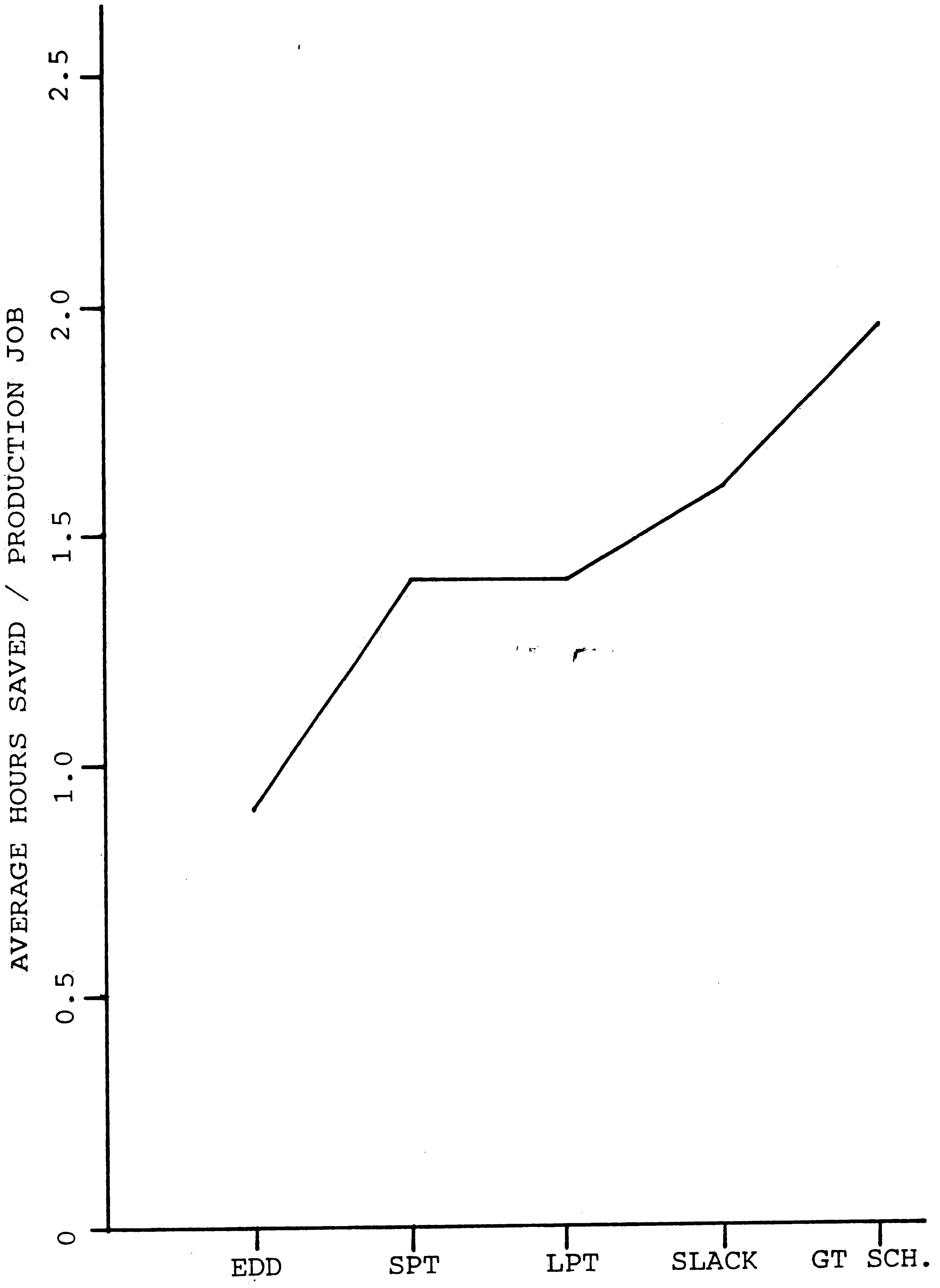
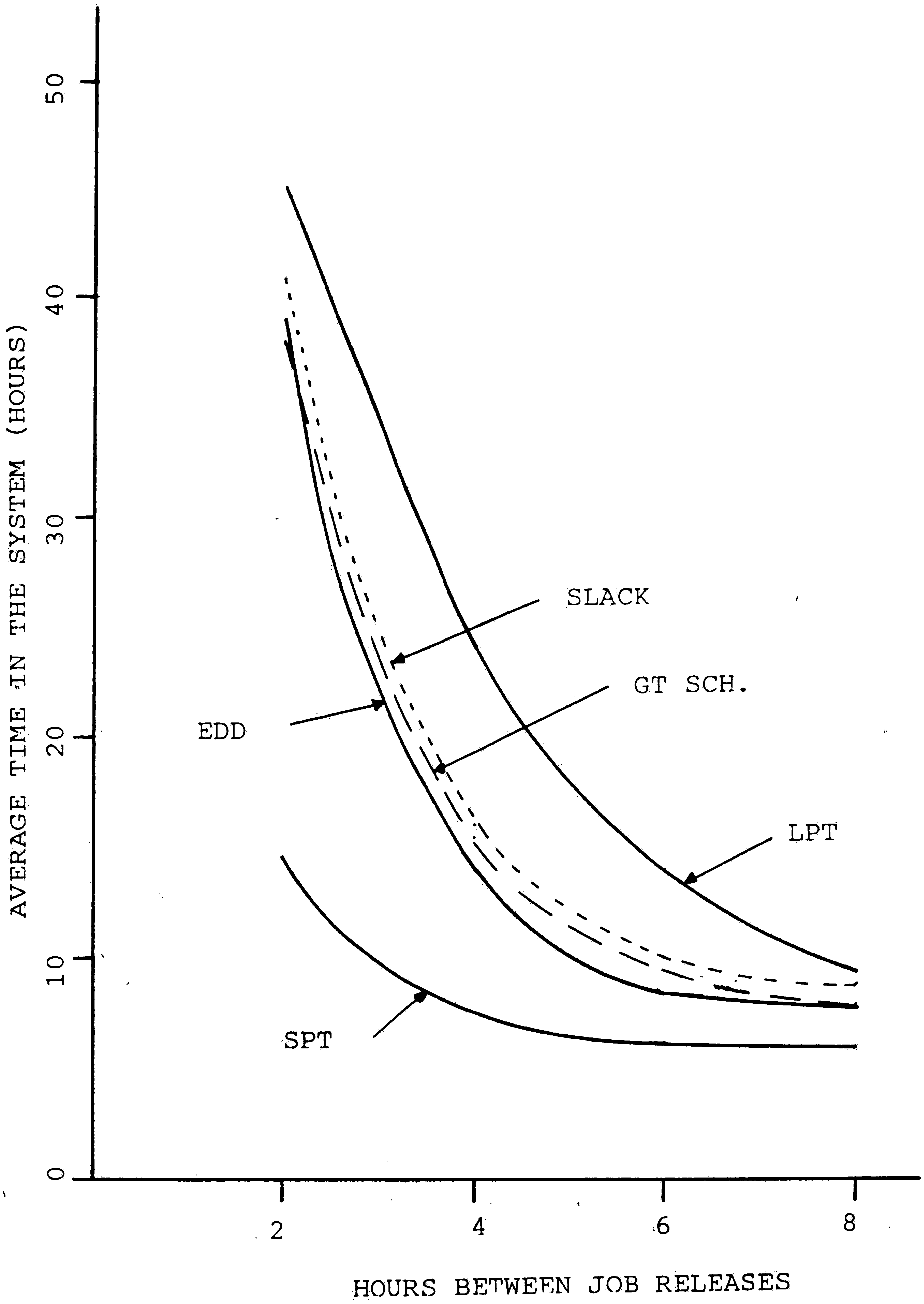


**Figure 8-3:** AVERAGE TIME in the SYSTEM



## 8.4 Average Work in Process

Average work in process results are depicted in Figure 8-4. SPT preformed the best. GT scheduling, EDD, LPT and SLACK produced results that were virtually equal to one another. Average work in process was reduced for all scheduling methods as the time between job releases increased. This was an obvious result of reduced production units entering the system per unit time.

## 8.5 Flow Line Utilization

Utilization for the flow line is shown in Figure 8-5. GT scheduling, EDD, LPT and SLACK produced results that were virtually equal to one another. SPT exhibited the worst performance. As expected, utilization decreased for all scheduling techniques as the time between job releases increased. Utilization is directly related to work in process which exhibited similiar results.

## 8.6 Average Throughput

Throughput is depicted in Figure 8-6. LPT exhibited the worst performance. EDD, SPT, SLACK and GT scheduling produced results that were virtually equal to one another. Reducing the time between job releases improved the performance of all scheduling techniques. This result, of reducing the job release interval, correlates to the increased work in process (shown in Figure 8-4). With the reduced job release interval machine utilization and average throughput are improved, at the cost of increased work in process.

**Figure 8-4:** AVERAGE WORK in PROCESS

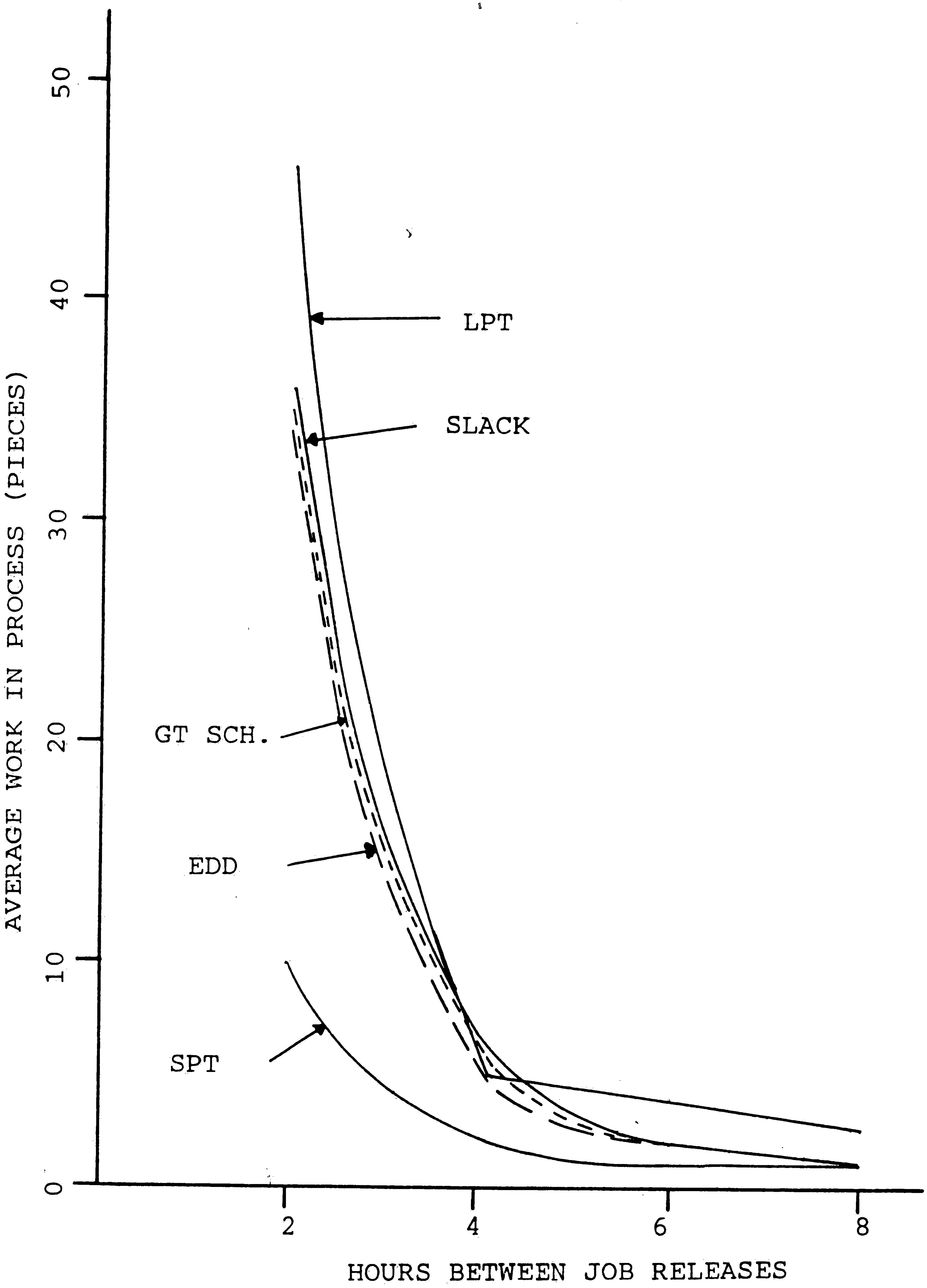


**Figure 8-5:** FLOW LINE UTILIZATION

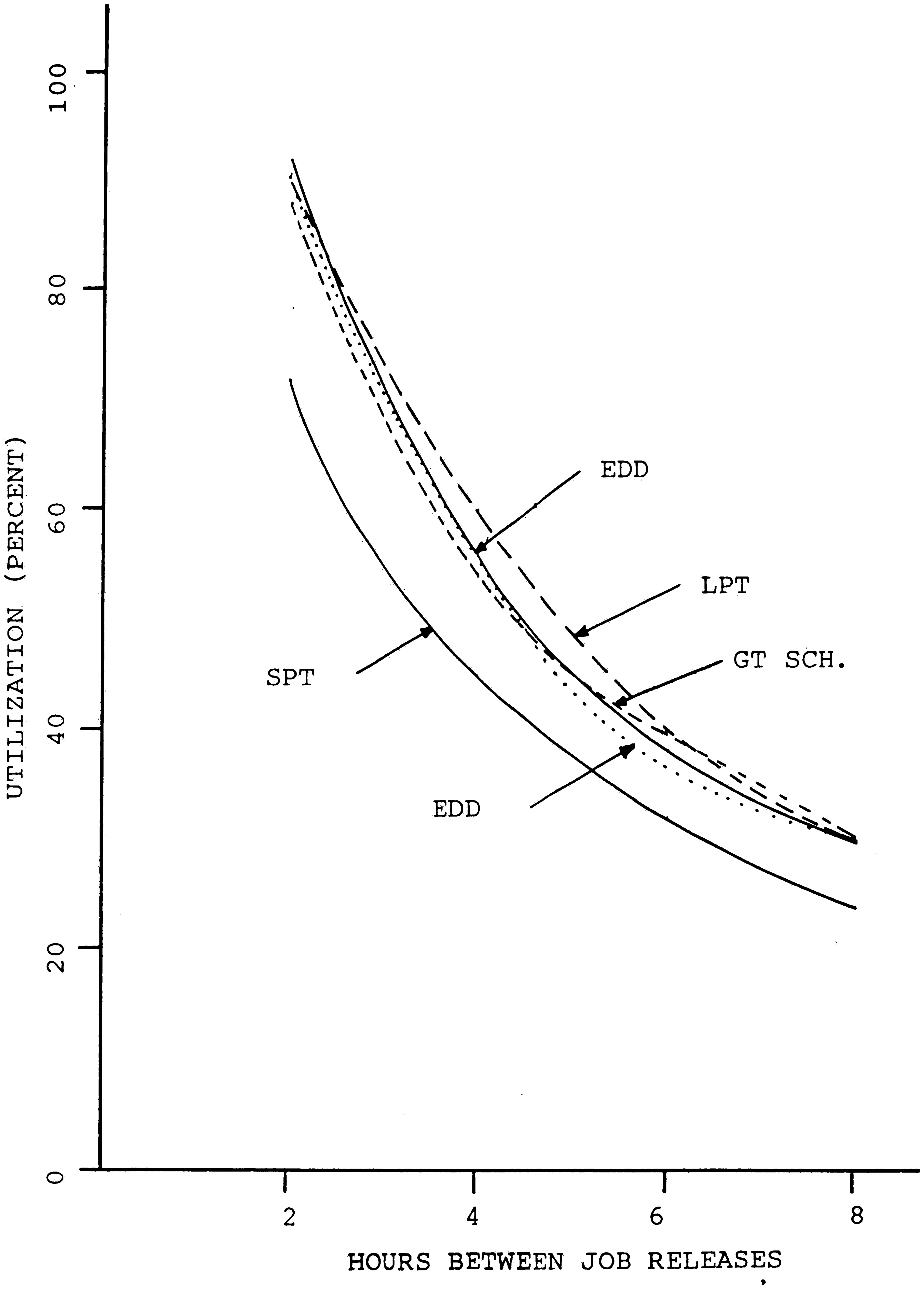
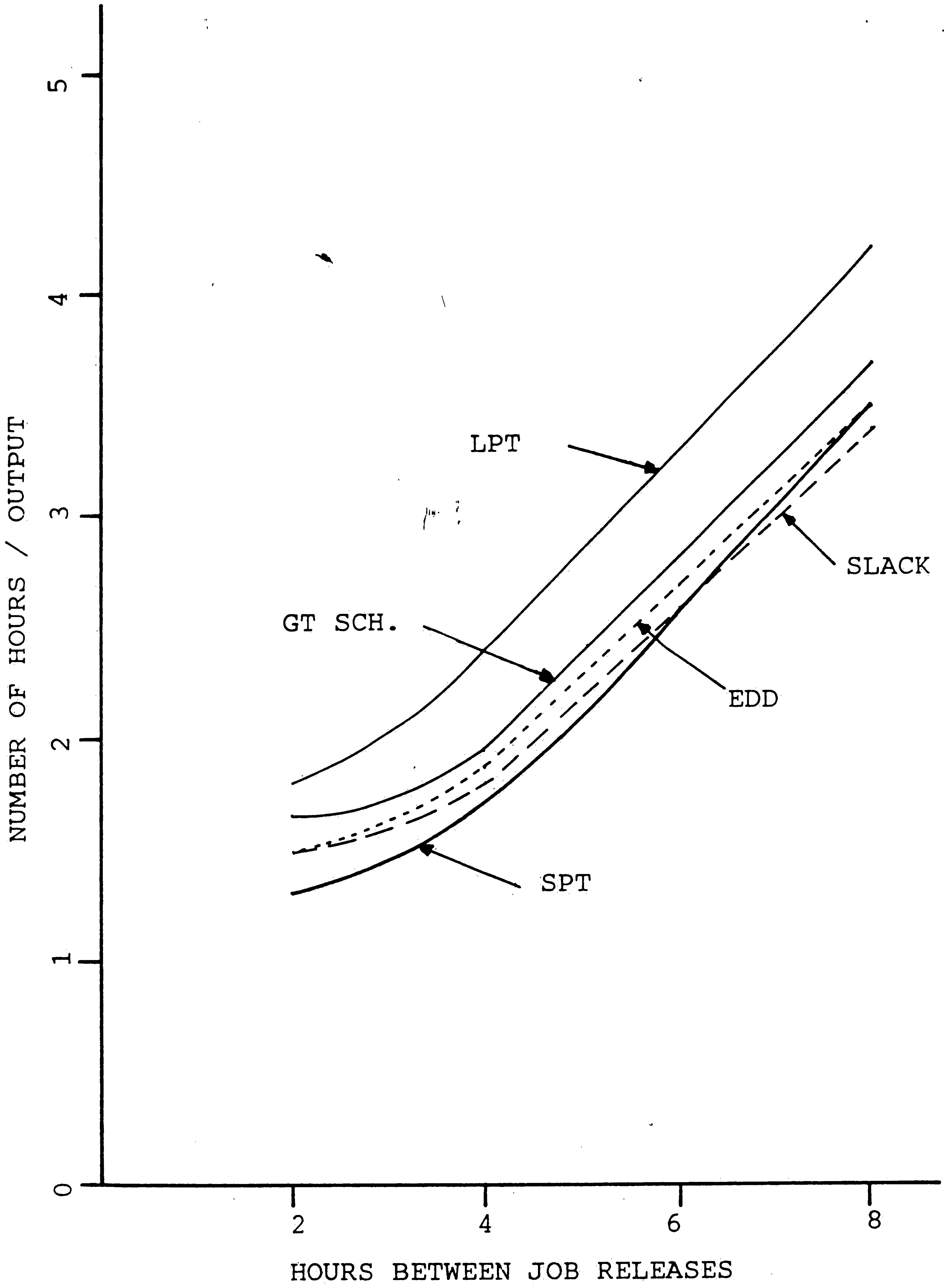


**Figure 8-6:** AVERAGE THROUGHPUT



# Chapter 9
# Conclusion

## 9.1 Summary

Results of the simulation indicate that the proposed GT scheduling technique may provide a feasible scheduling method for the flow line. Comparison of simulation results demonstrated that the GT scheduling methodology performed as well as EDD, SPT, LPT and SLACK scheduling techniques in accomplishing the primary objective of minimizing maximum tardiness. GT scheduling also attained the highest amount of group technology savings. Other performance measures, (i.e. average time in the system, averge work in process, flow line utilization and average throughput) monitored by the simulation model, indicated that GT scheduling performed on a competitive basis with the other scheduling techniques.

Varying the scheduling time horizon is a feature of the model which allows the user to determine the balance of GT savings and job tardiness. Unlike Period Batch Control or other single cycle scheduling techniques, the GT scheduling method maintains system performance within the threshold limit of tardiness. The threshold limit is a function of the flow line performance (i.e. average throughput, mean time between failures, etc.) and other factors (i.e. average job size, total operation time, etc.) Therefore, application of the GT scheduling technique to a flow line necessitates an analysis of flow line performance by actual observation and simulation modeling prior to model implementation.

In summary, the proposed GT scheduling method provides a possible scheduling technique to balance maximum tardiness with group technology savings for a flow line. Application of this technique for flow line scheduling may result in production cost savings, while maintaining the integrity of the production job due dates.

## 9.2 Future Research

Model testing of the GT scheduling procedure demonstrates that the stated objectives of minimizing maximum tardiness and integrating group technology for a flow line have been achieved. Examination of results indicates a number of important factors that provide a basis for future research.

Among them, the grouping of GT family jobs by MRP may not provide accurate capacity planning for GT families. A method proposed by Hax and Meal [10,pgs.574-588.] provides an aggregate planning method for part family production requirements. This planning technique provides the capacity planning function for part families based upon forecasted and actual production requirements. This hierarchial planning system would provide capacity planning information for the flow line. Knowledge of anticipated production activity levels for GT families could be utilized by the GT scheduling technique. This information could assist the GT scheduling method in determining the scheduling time horizon, manpower requirements, maintenance schedule, etc., which could improve the performance of the flow line.

Modification of the branch-and-bound procedure to provide a stopping rule, based upon $\epsilon$-optimality criterion, for the branch-and-bound procedure would reduce computer processing time. This modification may prove to be extremely beneficial for cases requiring the scheduling of a large amount of group jobs. Proper selection of the stopping criterion could dramatically reduce required

CPU time while not significantly affecting schedule optimality.

Modification of the model to allow the splitting of group jobs may improve the model performance. This change could reduce the maximum tardiness, while causing only a slight reduction in the group technology savings.

The previously detailed changes have the potential to improve the production scheduling model proposed by this thesis. These topics provide a basis for future research and enhancement of the model.

# REFERENCES

[1] **Baker, Kenneth R.**
*Introduction to Sequencing and Scheduling.*
John Wiley & Sons, New York, 1974.

[2] Groover, Mikell P.
*Automation, Production Systems and Computer-Aided Manufacturing.*
Prentice-Hall, Englewood Cliffs, New Jersey, 1980.

[3] Groover, Mikell P. and Zimmers, Emory W.
*CAD/CAM COMPUTER-AIDED DESIGN AND MANUFACTURING.*
Prentice-Hall, Englewood Cliffs, New Jersey, 1984.

[4] Halevi, Gideon.
*THE ROLE OF COMPUTERS IN MANUFACTURING PROCESSES.*
John Wiley & Sons, New York, 1980.

[5] Ham, Inyong., Hitomi, Katsundo and Teruhiko,Yoshida.
*Group Technology Applications to Production Management.*
Kluwer-Nijhoff Publishing, Boston, 1985.

[6] Hyer, Nancy Lea and Wemmerlou, Urban.
MRP/GT: A Framework for Production Planning and Control of Cellular Manufacturing.
*Decision Sciences* 13(4):681-701, October, 1982.

[7] Lin, Lee-Eng Shirley and Lu, C.Y. Joseph.
The Scheduling Problem in Random Flexible Manufacturing Systems.
In *Flexible Manufacturing Systems Operations Research Models and Applications*, pages 278-283. ORSA/TIMS, Ann Arbor, Michigan, August, 1984.

[8] Pritsker, A. Alan B. and Pegden, Claude Dennis.
*Introduction to Simulation and Slam.*
John Wiley & Sons, New York, 1979.

[9] Schriber, Thomas J.
The Use of GPSS/H in Modeling a Typical Flexible Manufacturing System.
In *Flexible Manufacturing Systems Operations Research Models and Applications*, pages 168-182. ORSA/TIMS, Ann Arbor, Michigan, August, 1984.

[10] Silver, Edward A. and Peterson, Rein.
*Decision Systems for Inventory Management and Production Planning.*
John Wiley & Sons, New York, 1985.

[11] Smith, Milton L. and Seidmann, Abraham.
Due Date Selection Procedures For Job-Shop Simulation.
*Computers & Industrial Engineering* 7(3):199-207, 1983.

[12] Townsend, W.
Sequencing n Jobs On m Machines To Minimize Maximum Tardiness: A Branch-and-Bound Solution.
*Management Science* 23(9):1016-1019, May, 1977.

# Vita

The author is the son of Richard, Sr. and Dawn Titus of Wilkes-Barre, Pennsylvania. He was born in Nanticoke, Pennsylvania on June 21, 1959. His high school education at Hanover Area was completed in 1977. Mr. Titus graduated from Lehigh University in 1981 with a Bachelor of Science Degree in Industrial Engineering.

Since graduation Mr. Titus has been employed by the Ingersoll-Rand Company located in Phillipsburg, New Jersey. His current position is Supervisor of Manufacturing Engineering Systems.

He is married to the former Lisa Dippre and they reside in Bethlehem, Pennsylvania.