A Manufacturing Cell Design Tool for the Development and Evaluation of Transfer Lines

By

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B.S. Mechanical Engineering, Tri-State University (1986)

Submitted to the Sloan School of Management and the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degrees of

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Abstract

Manufacturing companies today are constantly striving to reduce manufacturing costs. These companies, especially those who are producing a mature product, are designing elaborate manufacturing systems in an attempt to reduce production costs. Recently these elaborate systems have taken the form of Continuous Non-Buffered Flow Manufacturing systems. This type of manufacturing is represented by one long transfer line containing all the operations, or workstations, required to produce a product. A transfer line of this type is very susceptible to individual workstation performance, because a breakdown of one workstation causes the entire line to stop and production to cease. Due to the high value of strategically placed buffers within long transfer lines, decreasing incremental cost of buffer capacity and the increasing incremental cost to improve workstation efficiencies, the author believes that profitability of most Continuous Non-Buffered Flow Manufacturing systems can be improved through the use of strategically placed buffers.

This thesis discusses the development and implementation of a computer based Manufacturing Cell Design Tool (MCDT) that evaluates the relationships between buffer size, buffer location, isolated workstation efficiency and business profit. The MCDT accomplishes this by providing the designer with rapid financial and operational feedback for each design scenario chosen. By allowing the designer to quickly experiment with numerous design scenarios, the designer obtains a knowledge of the interrelationships among the parameters previously mentioned. The intent of this tool is to utilize rapid feedback to educate the designer as to which variables provide the greatest improvement per dollar invested.

The core evaluation mechanism of the MCDT is its throughput evaluation of each production line configuration chosen. The throughput evaluation is specific to transfer lines; consequently, the design tool is applicable to producers who manufacture high volumes of a standard product. Operationally, the transfer line evaluation mechanism is flexible with respect to the number of machine groups, buffer size between machine groups and individual machine group processing speed.

The MCDT translates calculated throughput into financial values common to the organization. Values for Payback Period, Internal Rate of Return and Net Present Value are calculated based on one of three levels of input which increase in degree of financial accuracy. The first level of input, which represents the least comprehensive data entry, provides the user with an understanding of which production line variables are more important than others for improving profit. The third level of input which is the most comprehensive provides the user with a understanding of how much capital should be expensed to obtain or improve a given workstation, machine group or production line.

The MCDT does not intend to replace the production line designer. Instead the purpose of this tool is to provide information to the designer which allows the designer to perform a better optimization with respect to business objectives. By utilizing common performance metrics, the tool will improve communication speed and accuracy throughout the organization. The tool will also reduce the time required to develop capital appropriation proposals by supplying much of the necessary financial data as standard output from the tool. It is anticipated that the number of design iterations made prior to project approval will also be substantially reduced because the designer will be optimizing with respect to the same metrics that top management will review to approve projects. Based on these predictions, the MCDT will reduce project cycle time and increase the financial benefits received from invested capital.

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List of Symbols

A	Annual payments
b_i	Individual buffer
$\underline{\mathrm{C}}$	Effective cycle time of manufacturing cell
C_g	Cycle time of machine group
$\mathrm{C}_{\mathrm{g,E}}$	Effective cycle time of machine group
c_i	Cycle time of individual workstation within manufacturing cell
CPEY	Cash Position at End of Year
$\underline{\mathrm{E}}$	Transfer line efficiency
E_g	Isolated efficiency of machine group
e_i	Isolated efficiency of individual workstation within manufacturing cell
HMC	Hypothetical Manufacturing Cell
i	Interest rate
IRR	Internal Rate Of Return
IPR	Isolated Production Rate
K	Intermediate calculation variable
M_g	Machine group
m_i	Individual workstation within manufacturing cell
MCDT	Manufacturing Cell Design Tool
MCTF_i	Mean Cycles to Fail individual workstation
MCTR_i	Mean Cycles to Repair individual workstation
MTTF_i	Mean Time to Fail individual workstation
MTTR_i	Mean Time to Repair individual workstation
N	Number of machine groups or number of workstations
NPV	Net Present Value
O	Workstation Reference Number
P_g	Failure rate of machine group
p_i	Failure rate of individual workstation
p_i	Probability of individual workstation failing within next cycle
PLC	Product Labor Cost
PM	Product Margin
PMV	Product Material Value
PPUT	Production Per Unit Time
PV	Product Value
R_g	Repair rate of machine group
r_i	Repair rate of individual workstation
r_i	Probability of individual workstation being repaired within next cycle
S_g	Scrap rate for machine group M_g.
s_i	Scrap rate for workstation m_i.
SAPV	Scrap Adjusted Product Value
T	Payback period
TAPV	Total Adjusted Product Value
TLC	Total Labor Cost
W	Cash outlay of Equipment
WIP	Work In Process
X	Intermediate calculation variable
$\mathrm{x}_{\mathrm{i,g}}$	Probability that if M_g failed that of $\mathrm{m}_{\mathrm{i,g}}$ caused the failure.
$\mathrm{y}_{\mathrm{i,g}}$	Weighted repair probability of m_i within M_g.

List of Subscripts:

Assy	Subassembly system
b	Base
c	Corporate
d	Downstream
E	Effective
f	Inflation
g	Group
i	Isolated
IRR	Internal Rate of Return
N	Last machine group or workstation
s	Simplified
T	End of Payback Period
u	Upstream

1.0 Purpose

1.1 Introduction

This thesis presents work done to develop and implement a computer based Manufacturing Cell Design Tool (MCDT) for use in the design and evaluation of both new and existing manufacturing cells. The computer based tool that was developed is currently being used by the engineers of Johnson & Johnson Medical Inc. to design and improve their manufacturing systems. The intent of this tool is to use common performance metrics throughout the organization and to provide the manufacturing cell designer with rapid financial and operational feedback in terms of these metrics. The specific financial metrics used are: Payback Period, Internal Rate of Return (IRR) and Net Present Value(NPV) while the operational metrics are: throughput per shift, machine group efficiencies and average buffer level. By providing the designer with rapid feedback, the designer will be able to experiment with numerous design scenarios and quickly develop a knowledge of which design parameters drive manufacturing cell efficiency and consequently improve profitability for the business.

Determination of throughput is the core evaluation mechanism of the MCDT. The throughput evaluation method utilized is specific to transfer lines with deterministic processing times and exponentially distributed failure and repair rates. Consequently, the design tool is applicable to most manufacturers who produce high volumes of a standard product through automated processes. The transfer line evaluation is flexible with respect to the number of machines groups, buffer size between machine groups and individual machine group processing speed.

Manufacturing cell throughput is calculated using a Modified Dallery-David-Xie (MDDX) algorithm (Burman 1995) and not simulation. The benefits of the algorithm over simulation is that mean throughput values can be determined in a matter of seconds for a complex manufacturing cell whereas simulation can take several hours. The rapid calculation speed of the algorithm permits the MCDT to quickly feedback information to the designer which in turn allows the tool to more effectively accomplish its purpose of educating the user. The algorithm is also more easily embedded into the design tool. This creates a more user friendly system by not requiring the user to run programs externally to the MCDT.

The purpose of the design tool is not to replace the manufacturing cell designer. Instead the tool's purpose is to provide information to the designer which allows the designer to perform a better optimization with respect to business objectives. This in turn will provide significant profit improvement to the business. Furthermore, the tool will increase communication speed and accuracy throughout the organization by utilizing common performance metrics. The tool will also reduce the time required to develop capital appropriation proposals by supplying much of the necessary financial data as standard output from the tool.

Software demonstrations of the MCDT can be arranged through the MIT, Leaders for Manufacturing Program office.

1.2 Definition of Key Terms

Transfer line:

A transfer line is a linear network of machines or groups of machines each separated by buffer storage areas. A group of machines is comprised of all the machines or workstations, between two subsequent buffer areas where the machines are directly coupled to one another. A single machine between two subsequent buffers represents the smallest possible machine group. All machines within a given machine group typically have identical processing times. The processing times between machine groups may vary. All material flows through every machine and every buffer area exactly once.

Note: In this thesis, the term transfer line and manufacturing cell will be used interchangeably. A transfer line is technically a special configuration of a manufacturing cell.

Payback Period

Number of years and fractions thereof, to repay the money expended on equipment through profits by using the equipment. Primary assumption of calculation is that the time value of money is constant (i.e. interest rate equals zero)

Net Present Value (NPV):

Value of current and future cash flows represented in current dollars. Future cash flows are discounted to today's dollars based on the appropriate interest rate which in turn is based on the appropriate factor of risk for the future cash flow.

Internal Rate of Return (IRR):

Interest rate that reduces the NPV of a project to zero over its economic life. Primary assumptions:

- One interest rate applies to all cash flows in all years.
- Cash flows do not change in sign more than once (i.e. negative initial flow to positive later flows).

Asynchronous Manufacturing:

Groups of machines within a production system operating with different cycle times. Typically asynchronous machine groups are separated by buffers.

Synchronous Manufacturing

Groups of machines within a production system all operating with the same cycle times.

Coupled Machine Groups

Coupling occurs when previous machine groups affect subsequent machine groups and vice versa.

Work In Process (WIP):

All the material within a manufacturing cell at any given point in time.

Throughput Time

The time required for the product to be processed. Time begins when the first operation is performed on the first components used in the product. Time stops when the last operation is performed on the finished product.

Workstation (m_i)

Used to define the points within the manufacturing process at which tasks are performed on the product.

Cycle Time (c_i)

The time taken for a given workstation to perform its task (time/task). In a machine group each workstation will have the same cycle time and this cycle time will equal the index rate of the transfer line within the given machine group.

Isolated Workstation Efficiency (e_i)

The efficiency of a single workstation if the workstation were able to function independently of all previous and subsequent workstations.

Isolated Production Rate (IPR)

Refers to the rate at which isolated workstations, aggregated workstations or machine groups deliver product to the immediate downstream buffer or workstation.

Machine Group (M_g)

Used to define a group of individual workstations (m_i) without intermediate buffers.

Machine Group Cycle Time (C_g)

The cycle time of a machine group. This will equal the cycle time of the individual workstations ($m_{i,g}$) within the group.

Effective Machine Group Cycle Time ($C_{g,E}$)

The cycle time adjusted for scrap. The effective cycle time increases as scrap rate increases.

Machine Group Efficiency (E_g)

The resulting efficiency after a number of isolated workstations have been grouped together in a continuous flow non-buffered system that is isolated from other machine groups.

Transfer Line Efficiency (E)

The resulting efficiency of an entire transfer line. This is calculated using the MDDX algorithm defined in section 2.7.

Starved Workstation

When a workstation can not function because it did not receive a part to process from its immediate upstream workstation. This typically occurs when upstream workstations are in repair.

Blocked Workstation

When a workstation can not function because it could not dispose of the last part it processed. This typically occurs when downstream workstations are in repair.

1.3 Motivation for Project

Since the late 1970's there has been a push within US manufacturing companies to reduce finished goods inventory as well as work in process (WIP). The reduction in WIP has driven many high volume manufacturers to pursue continuous non-buffered asynchronous manufacturing. This type of manufacturing is represented by one long transfer line containing all the workstations required to make a product. All workstations within the line have the same cycle time, and no buffers are present between workstations. In a transfer line of this type, the breakdown of one workstation causes the entire line to stop and consequently production to cease. Continuous Non-Buffered Flow Manufacturing is appropriate when all workstations have an isolated efficiency close to 100%; however, as isolated efficiency decreases, the practicality of this type of manufacturing system decreases.

Example:

In the following example, transfer line efficiencies were determined using the MDDX algorithm, section 2.7.

Transfer line description:
10 aggregated machines groups. Efficiency of each group is 98% (R_g =.05 , P_g =.001)
Effective cycle time of 1 second.

Configuration	Transfer Line Efficiency
Zero buffers	83.3 %
Nine buffers, each with capacity of 1	84.5 %
Nine buffers, each with capacity of 2	85.5 %
Nine buffers, each with capacity of 3	86.4 %
Nine buffers, each with capacity of 4	87.2 %
Nine buffers, each with capacity of 5	87.9 %
Nine buffers, each with capacity of 10	90.4 %
Nine buffers, each with capacity of 20	92.9 %
Nine buffers, each with capacity of 30	94.2 %
Nine buffers, each with capacity of 40	95.0 %
Nine buffers, each with capacity of 50	95.6 %

As is demonstrated in the previous table, buffers add significant benefit with respect to manufacturing cell efficiency, and it is the first unit of buffer that adds the greatest marginal benefit. Unfortunately, it is also the first unit of buffer that adds the greatest marginal cost. After a buffer is created, each additional unit of buffer capacity costs very little up to a discrete point where additional hardware must be purchased. This point of hardware addition is shown in figure 1.1 as a peak in the incremental cost curve for buffer capacity. It is also well known that improving isolated efficiency of a workstation becomes incrementally more expensive as one nears 100% efficiency. This relationship between buffer size/cost and isolated workstation efficiency improvement/cost is shown below in figure 1.1 for a manufacturing cell.

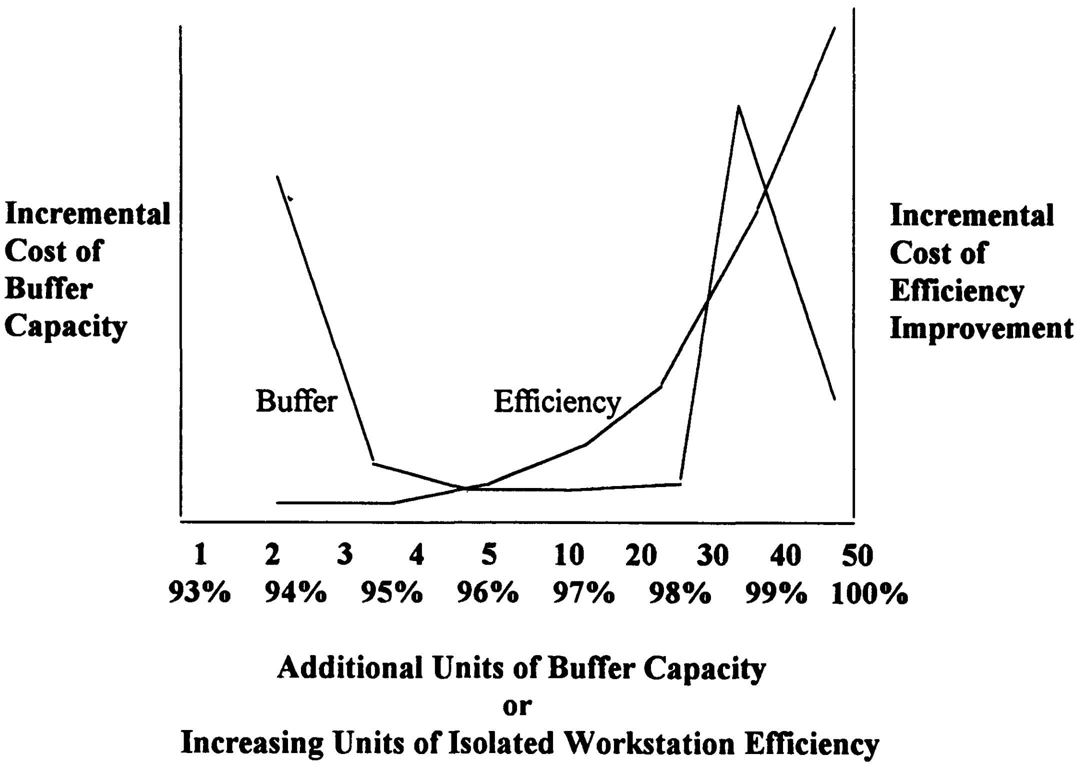


Figure 1.1: Incremental cost of buffers vs. workstation efficiency

Based on this general relationship, it is readily apparent that a optimum combination of buffer size and isolated workstation efficiency exists for all manufacturing cells. The balance between these two variables will depend on the resulting transfer line efficiency that is desired and the incremental costs of workstation efficiency improvement and buffer capacity. In some cases, where the transfer line contains highly efficient isolated workstations and improvement of these workstations is relatively inexpensive, the appropriate buffer size may be zero. However it is the author's belief that most production systems, particularly those which are capacity limited, require strategically placed buffers of size greater than zero, to optimize total profit to the business.

The motivation for this thesis is twofold:

1. To develop a tool that can be used to evaluate the relationships between buffer size, buffer location, isolated workstation efficiency, cost of equipment and total profit to the business.
2. Develop a means by which to effectively transfer this knowledge to the engineers and managers of an organization such that the tool will continue to provide benefits to the organization in the future.

The computer based, Manufacturing Cell Design Tool (MCDT) that was developed meets both objectives. The tool achieves this goal by providing the designer with financial and operational information for each design scenario chosen. By allowing the designer to rapidly experiment with numerous design scenarios, the designer obtains a knowledge of the interrelationships among the parameters previously mentioned. Consequently, the MCDT does not replace the designer, it simply allows the designer to perform her/his job better, by quickly testing different scenarios.

1.4 Production Systems that are Applicable to the Model

The MCDT is applicable to transfer lines with deterministic processing times and exponentially distributed failure and repair times (section 2.1). This type of transfer line is very common and is often characterized by the following:

- Fully automated processes. Direct labor is responsible for maintaining workstations within the manufacturing cell and does not perform actual operations on a regular basis.
- Parts are indexed from workstation to workstation at fixed time intervals.
- To achieve equal cycle times among all coupled workstations, the workstations are either split into a series of several less complex workstations, or identical workstations are placed in parallel.

Examples of such systems:

1. Polaroid Co., Imaging Division: Camera Assembly
2. Johnson & Johnson Medical Inc., Vascular Access Division: Catheter Assembly
3. Ford Motor Co., Romeo Division: Engine Manufacturing
4. Hewlett-Packard, Vancouver Division: Printer Assembly

Automobile car body assembly is an example of a transfer line that typically can not be evaluated by the MCDT without modification to the tool. Automobile car body assembly is commonly performed on a continuously moving transfer line with exponentially distributed processing times. Whenever a transfer line is in continuous motion and operations are performed manually, there is a high probability that the processing times are exponentially distributed rather than deterministic.

1.5 Limitation of Manufacturing Cell Design Tool

1.51 Mean Throughput Analysis

This design tool contains a deficiency in regards to throughput analysis. All throughput calculations are based on mean production values and do not account for variability within a particular period. The field of Manufacturing Systems Analysis is currently studying variability issues. However, at this time, a reliable approach has not yet been determined.

Not accounting for variability does not seriously affect the objectives of the MCDT. This is because the tool evaluates manufacturing cells for yearly production volumes throughout the manufacturing cell's economic life. The accuracy of the tool's output data would be seriously affected if daily production values were necessary for subsequent calculations. This is because daily throughput of production lines typically fluctuates significantly from mean throughput values. The statistical basis for this statement is given below:

Statistical Basis

The tolerance interval that must be defined to obtain a desired confidence level for actual daily production volumes will decrease as the time period increases in length. Changing the time period from one day to one year will result in the tolerance interval being reduced by a factor of $(1 - 1/\sqrt{360})$ or 94.7%. Consequently, on a yearly basis, the predicted production volume and the actual production volume will be very close, even though daily production fluctuates significantly from mean production.

1.52 Simplified Assembly Systems

The Manufacturing Cell Line Design Tool does not access assembly systems in their entirety. Simple systems such as feeder mechanisms and large component subassembly systems must be simplified prior to transfer line analysis. A description of this simplification process will be described in section 2.5.

2.0 Transfer Line Theory

The purpose in describing transfer line theory before describing the Manufacturing Cell Design Tool is because throughput is the basis for all financial calculations made by the design tool, and transfer line theory is the basis for all throughput calculations. For this reason, the author believes it is valuable to understand transfer line theory before becoming exposed to the detailed aspects of the MCDT.

2.1 Theoretical Description of Relevant Terms:

Mean Cycles To Failure ($MCTF_i$)

The mean number of cycles a particular workstation (m_i) performs before it fails.

Mean Time to Failure ($MTTF_i$)

$MTTF_i = MCTF_i * c_i$

Mean Time To Repair ($MTTR_i$)

The mean time it takes to repair a workstation (m_i) after it has failed.

Mean Cycles to Repair ($MCTR_i$)

$MCTR_i = MTTR_i/c_i$

Deterministic Processing Time

A processing time that remains constant over time and possesses zero variability.

The following descriptions of failure and repair probabilities, and failure and repair rates may initially appear rather trivial; however, it is important to differentiate between the two. In many calculations, such as those described in section 2.3, probabilities must be used. If a rate is needed as a final result, the calculated probability can be converted into a rate by dividing by the probability by the workstation cycle time. The MCDT internally performs calculations in a similar fashion. The MCDT uses probabilities for a majority of its calculations and then converts these probabilities into rates solely for input into the MDDX algorithm.

Probability (p_i) of Workstation (m_i) Failing During the Next Cycle

$p_i = 1/\,\mathrm{MCTF}_i$

Any time a workstation is not starved, blocked or under repair, the workstation has a probability (p_i) of failing during the next cycle it operates. The workstation has no memory; therefore, this probability remains the same as each cycle is completed and a new cycle is initiated. The distribution of cycles to failure at a specific point in time is represented by an exponential distribution. For example, the probability of failing during the next cycle is p_i^1 and the probability of failing during the tenth cycle is $(1 - p_i)^9 * p_i$.

Failure Rate (p_i) of Workstation (m_i)

$\mathrm{p}_i = p_i /\, \mathrm{c}_i = 1/\,\mathrm{MTTF}_i$

Any time a workstation is not starved, blocked or under repair, the workstation has a failure rate (p_i) which is applicable during each unit of time it operates.

Probability (r_i) of Workstation (m_i) Being Repaired During the Next Cycle

$r_i = 1/\,\mathrm{MCTR}_i$

The probability (r_i) that if a workstation is under repair that the workstation will be repaired within the next cycle. Again the workstation has no memory; therefore, this probability remains the same as each cycle passes. The distribution of the number of cycles that pass before a workstation is repaired is represented by a exponential distribution.

Repair Rate (r_i) of Workstation (m_i)

$\mathrm{r}_i = r_i /\, \mathrm{c}_i = 1/\,\mathrm{MTTR}_i$

Any time a workstation is not starved, blocked or under repair, the workstation has a failure rate (r_i) which is applicable during each unit of time it operates.

Isolated Workstation Efficiency (e_i)

$e_i = r_i/(p_i+r_i)$

The efficiency of a single workstation if the workstation were never starved or blocked

Isolated Production Rate (IPR)

$IPR = e_i/c_i$	For isolated workstation
$IPR = E_g/C_g$	For isolated machine group
$IPR = \Sigma(e_i/c_i)$	For workstations located in parallel to one another

Aggregated Machine Group Efficiency (E_g)

$E_g = 1/(1+\Sigma(p_{i,g}/r_{i,g}))$

The resulting output efficiency of a machine group is based on the individual workstation performance parameters ($p_{i,g}$ & $r_{i,g,}$). E_g represents the efficiency of a machine group if it were never starved or blocked by other machine groups. As previously defined, workstations within a machine group have no intermediate buffers.

Information in section 2.1 was obtained from Gershwin (1994, 19-132).

2.2 Assumptions of Transfer Line Theory:

1. Failures are operationally dependent and not time dependent. Workstations can only fail if operating. Workstations that are blocked, starved or in repair will have a zero probability of failing during the next unit of time.
2. Repair rates and consequently (r_i) for a given workstation are independent of the repair times of other workstations. The resulting assumption is that once a workstation has failed, the process of repair begins immediately.
3. Workstation failure rates are independent of the states of other workstations. Consequently, the only way workstation failures effect the operability of other workstations is through blockage and starvation.
4. A machine is never simultaneously blocked and starved.

5. Transfer time between workstations within a machine group or between machine groups with buffers of capacity zero, is instantaneous.
6. The first workstation in the first machine group is never starved
7. The last workstation in the last machine group is never blocked
8. All material enters the first workstation of the first machine group of the transfer line, passes through all workstations and buffers exactly once, passes through all workstations and buffers in exactly the same order, and exits the system through the last workstation of the last machine group.
9. All workstations within a machine group will process product at a rate equal to the cycle time of the machine group (C_g) which is equal to the cycle time of the slowest workstation within the machine group ($c_{i,\mathbf{slowest}}$). Therefore, all workstations within a machine group have a cycle time equal to the cycle times of the slowest workstation.
10. Different machine groups may have different cycle times. Note, this flexibility is specific to the Burman MDDX algorithm, section 2.7.
11. Repairs and failures occur at the beginning of a cycle and changes in buffer levels occur at the end of a cycle.

Information in section 2.2 was obtained from Dallery and Gershwin (1992, 8-13).

2.3 Representation of Parallel Workstations:

Any simplification done to a real production system for the purpose of mathematical analysis creates some degree of inaccuracy. Consequently, the simplification process described below will allow the designer to aggregate parallel workstations into an approximately equivalent single workstation for the purpose of throughput analysis. Although this method is a very good approximation, it is not 100% representative of the original system. Similarly, the simplification approaches described in sections 2.4, 2.5 and 2.6 are subject to the same limitations.

Parallel Workstations

The primary purpose of placing workstations in parallel is to obtain an aggregated workstation that has an Isolated Production Rate (IPR) that is approximately equal to the IPR of the adjacent machine groups. Parallel workstations can achieve this objective in one of two ways. First, by placing relatively inefficient workstations in parallel, the aggregated efficiency of the parallel workstation group will be greater than the efficiency of one parallel workstation in isolation provided the cycle time of the aggregated workstation group adheres to the following:

$$1/C_{Aggregated} < 1/C_1 + 1/C_2 + \ldots + 1/C_N$$

Note: $C_1 \ldots C_N$ represents the cycle time of each parallel workstation.

Second, if a workstation is of adequate efficiency to be entered into the transfer line but has a cycle time that is too slow, then identical workstations can be placed in parallel with the original workstation to achieve an aggregated cycle time that is faster than the cycle time of each individual parallel workstation.

$$1/C_{Aggregated} = 1/C_1 + 1/C_2 + \ldots + 1/C_N$$

Note: $C_1 \ldots C_N$ represents the cycle time of each parallel workstation.

Both of the above configurations will now be analyzed. Figure 2.1 graphically represents both configurations.

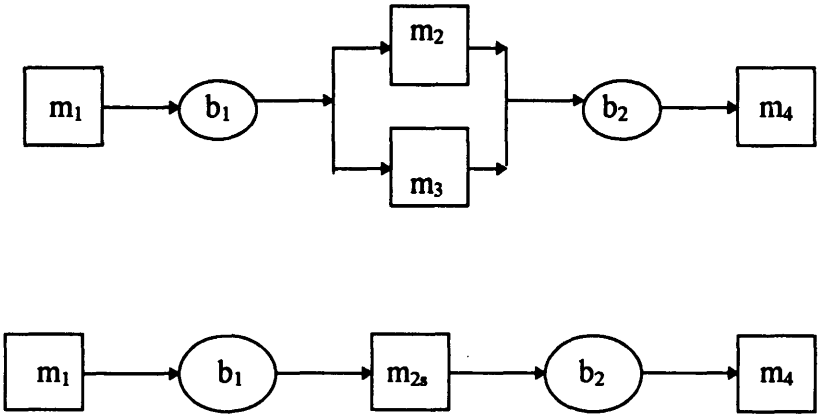


Figure 2.1: Simplification of parallel workstations

First Configuration:

Definition: Cycle time of each parallel workstation is identical to the cycle time of adjacent machine groups. Values for p_i and r_i are identical between parallel workstations. Due to the necessity of delivering parts to and from each parallel workstation, it is most efficient to decouple the group of parallel workstations from adjacent machine groups by placing a buffer on each side of the parallel workstation group.

Combined workstation m_{2s}

- $p_{2,s} = p_2 * p_3$
- $r_{2,s} = [1 - (1 - r_2)*(1 - r_3)]$
- $c_{2,s} = C_g = c_2 = c_3$

For N parallel identical machines:

- $p_{i,s} = p^N$
- $r_{i,s} = [1 - (1 - r)^N]$
- $c_{i,s} = C_g = c_i = c_N$

Note: In the above calculations, probabilities are used as opposed to rates. For throughput evaluation using the MCDT, the resulting probabilities must be converted into rates as described in section 2.1.

Second Configuration:

Definition: Purpose of employing parallel workstations is to achieve an aggregated cycle time that is faster than the cycle time of each parallel workstation and is equal to or less than the cycle time of adjacent machine groups. Values for p_i and r_i are identical between parallel workstations. Due to the necessity of delivering parts to and from each parallel workstation, it is most efficient to decouple the group of parallel workstations from adjacent machine groups by placing a buffer on each side of the parallel workstation group.

Combined workstation m_{2s}

- $p_{2,s} = 2*p_2 = 2*p_3$
- $r_{2,s} = 2*\ r_2 = 2*r_3$
- $1/c_{2,s} = 1/c_2 + 1/c_3$

For N parallel identical machines:

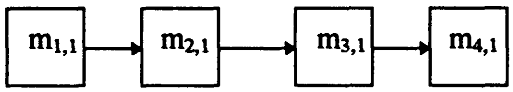
- $p_{i,s} = N*p_i$
- $r_{i,s} = N*r_i$
- $1/c_{i,s} = 1/c_i + \ldots + 1/c_N$

Note: In the above calculations, probabilities are used as opposed to rates. For throughput evaluation using the MCDT, the resulting probabilities must be converted into rates as described in section 2.1.

Information in section 2.3 was obtained from Burman (1995).

2.4 Aggregating Individual Workstations into a Machine Group

The aggregation of sequential workstations that have no intermediate buffers is necessary to gain an understanding of complex transfer lines. The aggregation is also necessary for efficient execution of the MDDX algorithm (section 2.7). Figure 2.2 shows the individual sequential workstations that will be aggregated to form machine group M_1. Figure 2.3 shows a transfer line which consists of several aggregated machine groups similar to M_1 and all separated by intermediate buffers. The MDDX algorithm can evaluate transfer lines in this simplified form.



Non aggregated sequential Workstations

Aggregated Sequential Workstations

Figure 2.2: Aggregation of Sequential Workstations

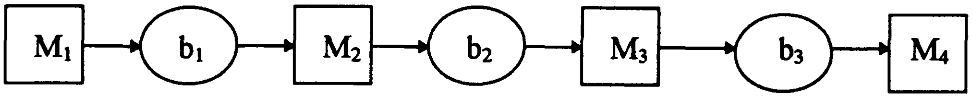


Figure 2.3: Required Transfer Line Configuration for MDDX Algorithm

Efficiency of the aggregated machine group is determined per section 2.1. Prior to executing the MDDX algorithm, it is necessary to determine the aggregated P_g & R_g values for each machine group. Determining P_g & R_g values is accomplished as follows:

- Determine the probability($x_{i,g}$) for each workstation ($m_{i,g}$), that if the machine group (M_g) failed that it failed because of workstation $m_{i,g}$.
  $x_{i,g} = p_{i,g} / \Sigma(p_{i,g})$.
- Multiply each $r_{i,g}$ by $x_{i,g}$ to obtain a weighted repair rate ($y_{i,g}$)
  $y_{i,g} = x_{i,g} * r_{i,g}$
- Sum all $y_{i,g}$ to obtain the aggregated R_g
  $R_g = \Sigma(y_{i,g})$.
- Calculate E_g as described in section 2.1
- Calculate P_g using E_g and R_g
  $P_g = R_g/E_g - R_g$

The values of P_g & R_g for each machine group M_g are used as input to the MDDX algorithm. The cycle time of the machine group equals the cycle time of the individual workstations within the machine group.

Information in section 2.4 was obtained from Burman (1994).

2.5 Simplification of Feeder Systems and Large Component Assembly Systems:

2.51 Feeder Systems

In the evaluation of throughput, feeder systems are not evaluated in their entirety. Figure 2.4 shows a typical part feeder system providing parts for a machine group and figure 2.5 shows this system in simplified form.

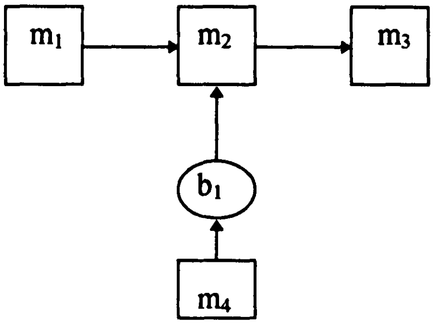


Figure 2.4: Typical feeder system

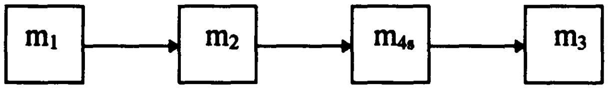


Figure 2.5: Simplified feeder system

The simplification demonstrated above is accomplished by treating workstation m_4 and buffer b_1 as one effective machine (m_{4s} for m_4 simplified). The operating parameters of m_{4s} are obtained in much the same way as a single workstation. In this case the value of p_{4s} is determined by the probability that a part is not available when workstation m_2 needs a part to process. The value for r_{4s} is the probability that when m_4 is in repair and b_1 is empty, that a part will be available for processing by m_2 within the next unit of time. When workstation m_4 and b_1 are simplified to form m_{4s}, the cycle time of the simplified workstation equals the cycle time of the machine group it is entering.

This method is essentially accomplished by observing the very last stage of the assembly system just prior to its entry into the downstream transfer line and ignoring all upstream workstations within the assembly system. This location is observed to determine the probability that a part will not be available for processing by the immediate downstream workstation, and, if it is not available, what the probability is that a part will be available within the next unit of time.

2.52 Large Component Assembly Systems

Large component assembly systems can be handled in the same fashion as described previously; however, the following approach can provide an attractive alternative for simplifying these systems. This second approach is particularly beneficial when designing a new manufacturing cell.

The disadvantage of using this approach is that it is an approximation of the real system. Consequently, the simplified system does not represent the original assembly system with 100% accuracy. The primary difficulty with using this approach is in the aggregation of the assembly system into one representative workstation. Inaccuracy results from the effects of blockage and starvation within the assembly system which are now approximated by the aggregated efficiency of the assembly system. Consequently the total effect of all assembly system blockages and starvations are not propagated throughout the manufacturing cell as is the case in real life.

Figure 2.6 shows a typical assembly system feeding a machine group and figure 2.7 shows this assembly system in simplified form.

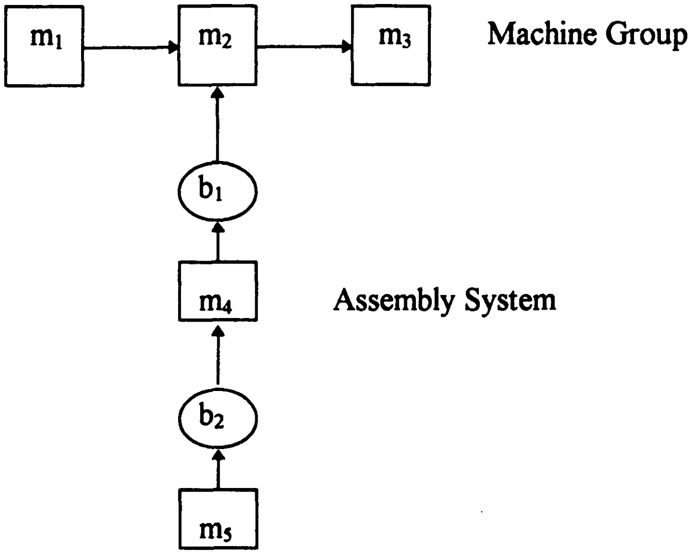


Figure 2.6: Typical assembly system

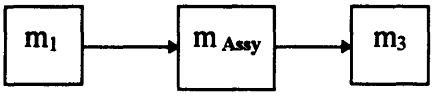


Figure 2.7: Simplified assembly system

The simplification shown above is accomplished by determining the transfer line efficiency for the assembly system, including workstation m_2. This efficiency can be determine by analyzing the assembly system with the MCDT or by using the MDDX algorithm directly. Once the efficiency is known for the assembly system (E_{assy}), it is used to determine, the operational parameters p_{Assy} and r_{Assy}. These parameters are determined as follows:

- Determine the probability($x_{i,Assy}$) for each workstation ($m_{i,Assy}$), that if the Assembly System failed that it failed because of workstation $m_{i,Assy}$.

  $x_{i,Assy} = p_{i,Assy} / \Sigma(p_{i,Assy})$.

- Multiply each $r_{i,Assy}$ by $x_{i,Assy}$ to obtain a weighted repair rate ($y_{i,Assy}$)

  $y_{i,Assy} = x_{i,Assy} * r_{i,Assy}$
- Sum all $y_{i,Assy}$ to obtain the aggregated r_{Assy}

  $r_{Assy} = \Sigma(y_{i,Assy})$.
- Calculate p_{Assy} using E_{Assy} and r_{Assy}

  $p_{Assy} = r_{Assy} / E_{Assy} - r_{Assy}$

Workstation m_2 is then replaced by workstation m_{Assy} in the original machine group. The cycle time for m_{Assy} is the effective cycle time (section 2.6) of the slowest machine group within the assembly system.

Future improvements to the MCDT could be achieved in this area of feeder and subassembly systems. To accomplish this, a robust version of the current Assembly-Disassembly Dallery-David-Xie algorithm (Gershwin 1994) would need to be developed. Modification to the current MCDT would also be necessary. A MCDT improved in this way would be no more accurate than the current MCDT when using the feeder system approach (2.51). However, the advantages of a MCDT improved in this way is that it would permit detailed evaluation of the assembly system, similar to what was described above for large component assembly systems (2.52), without creating the inaccuracies described.

Information in section 2.5 was obtained from Burman (1994).

2.6 Accounting for Material Scrap

The MDDX algorithm assumes conservation of material throughout the system. This implies that all material that enters the system through the first workstation in the manufacturing cell will be processed and exit the system through the last workstation. Most real manufacturing systems produce scrap at intermediate points within the process, and discharge the scrap as soon as possible to maximize downstream workstation utilization.

This Manufacturing Cell Design Tool makes an approximation to correct for the creation and discharge of scrap from the system. This correction is performed as follows:

- $s_{i,g}$ = Scrap rate for workstation $m_{i,g}$ within its machine group M_g
- S_g = Scrap rate for a machine group M_g
- $S_g = 1 - [(1 - s_{1,g})*(1 - s_{2,g})*......*(1 - s_{i,g})]$
- $C_{g,E} = C_g/(1-S_g)$

Note: All $p_{i,g}$ and $r_{i,g}$ values are calculated based on the actual cycle times of their respective machine groups. Effective cycle times are used only as input to the MDDX algorithm.

2.7 Modified Dallery-David-Xie Algorithm

Many Transfer lines consisting of two machines and one buffer can be easily solved analytically by using the following equation.

$\underline{E} = (1-X*K^b) / [1 + p_1/r_1 - (1 + p_2/r_2)* X*K^b]$

$X = p_2*r_1 / p_1*r_2$

$K = [(p_1 + p_2)*(r_1 + r_2) - p_1*r_2(p_1 + p_2 + r_1 + r_2)] / [(p_1 + p_2)*(r_1 + r_2) - p_2*r_1(p_1 + p_2 + r_1 + r_2)]$

b = buffer capacity

Assumes $C_1 = C_2$

Note: In the above calculations, probabilities are used as opposed to rates.

(Askin 76-77)

However, for transfer lines of greater than two machines exact solutions do not exist. This is because of the very large number of instantaneous product level configurations that are possible throughout the transfer line. The decomposition method is an approach by which a long transfer lines consisting of (N) machines and (N-1) intermediate buffers can be broken down into (N-1) "machine-buffer-machine" (two machine) systems as is shown below in figure 2.8. The decomposition equations first appeared in Gershwin (1987). The first convergence algorithm was developed by Dallery, David and Xie (1988). One of the early algorithms analyzed transfer lines with discrete processing times and exponential failure and repair rates. This algorithm was limited to evaluating transfer lines where all machine groups had the same cycle time. The algorithm embedded in the Manufacturing Cell Design Tool was developed by Mitchell Burman (1995). This algorithm expands on the Dallery, David and Xie algorithm by allowing evaluation of machine groups with different but deterministic cycle time.

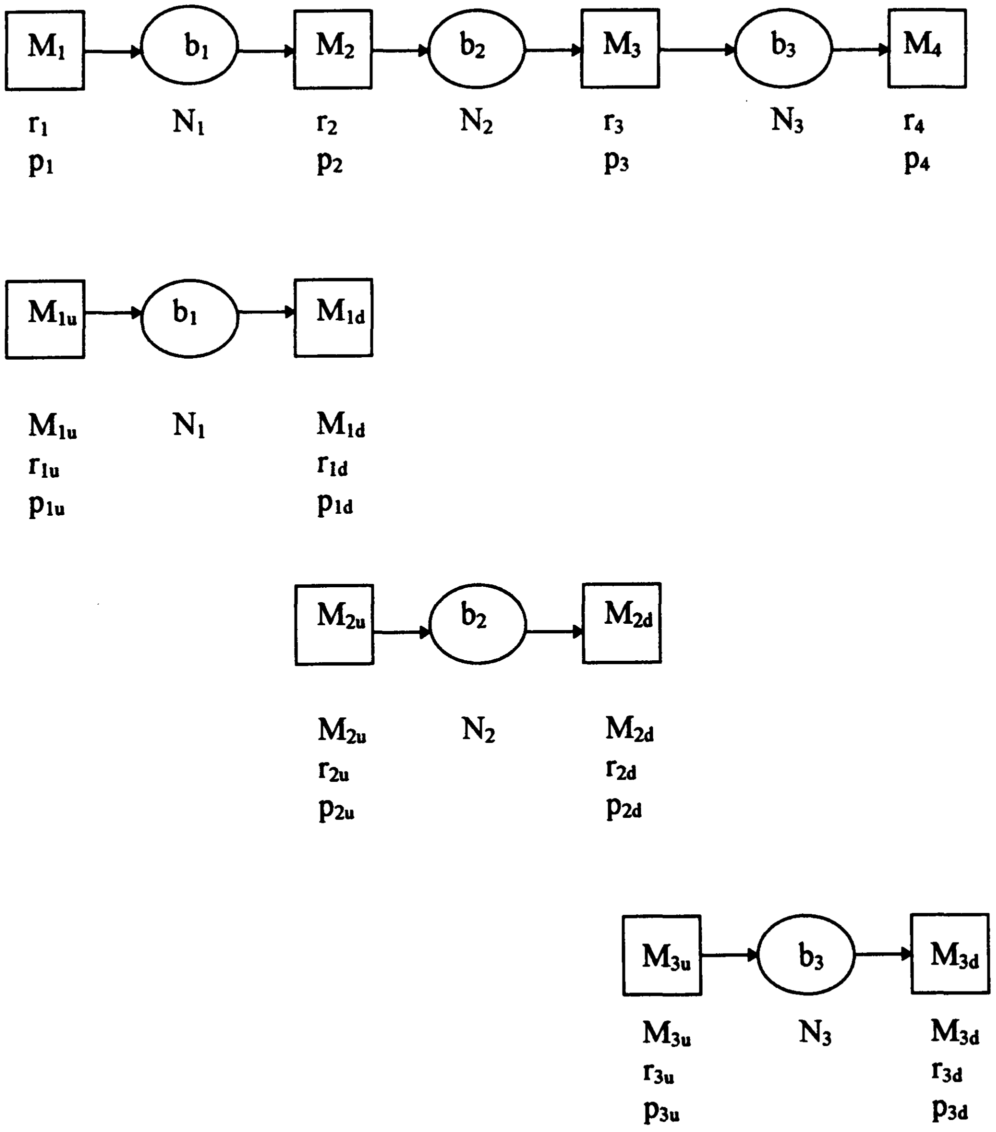


Figure 2.8: Transfer line decomposition method

The general approach for the decomposition method is to evaluate the transfer line in relation to its buffers. Each buffer in each of the decomposed "two machine" transfer lines corresponds to the same buffer in the non decomposed line. Studying the transfer line in this fashion is based on the fact that the flow of product into and out of a buffer is dependent on the aggregated performance of all machines and buffers upstream of the subject buffer (r_{iu} and p_{iu}) as well as the aggregated performance of all machines and buffers downstream of the subject buffer (r_{id} and p_{id}). A buffer can only receive product at the rate at which the upstream transfer line can provide it with product and it can only discharge product at the rate at which the downstream transfer line can accept product. Therefore, by representing the flow of product into and out of buffers, it is possible to represent the flow of the entire transfer line. Referring to figure 2.8, if the aggregated performance of M_1, b_1, M_2, b_2, M_3 were known, it would be possible to solve for transfer line efficiency directly by using the equation shown previously for a two machine line.

The MDDX algorithm begins with the initial data provided for N_i, r_i and p_i and then calculates r_{iu}, p_{iu} and r_{id}, p_{id} for each "two machine" system in the transfer line. The algorithm starts calculating at the beginning of the transfer line and continues to the end. At this point the algorithm will check for convergence of the transfer line efficiency based on each of the (N-1) decomposed two machine systems in the transfer line. If convergence did not occur the algorithm will repeat the process but in reverse, starting at the end of the transfer line and continuing to the front. Convergence will then be checked again. This process will continue until convergence is reached. When this occurs, the long transfer line has been successfully represented by (N-1) "two machine" system with an intermediate buffer.

Modified Dallery-David-Xie Algorithm Output

The MDDX algorithm provides the following three outputs

1. Isolated efficiency of each machine group (E_g)
2. Average buffer levels between each machine group ($\underline{b}_i$)
3. Production Rate per Unit Time (PPUT)

Of these outputs the MCDT primarily uses PPUT. Using PPUT, transfer line efficiency and throughput per time period is calculated as follows:

1. Choose the slowest (longest) cycle time among all the machine groups ($\underline{C} = C_{g,E,slowest}$)
2. Transfer line efficiency = (Production Rate per Unit Time) * (Effective cycle of slowest machine group)

   $\underline{E} = \text{PPUT} * \underline{C}$.
3. Throughput in a time period = (Time period) * (PPUT)

* In the MCDT throughput and transfer line efficiency are automatically calculated.

2.8 Advantages / Disadvantages of Modified Dallery-David-Xie Algorithm

2.81 Advantages of the Modified Dallery-David-Xie Algorithm:

- Can be imbedded in the MCDT and never require the user to have knowledge of its functions.
- Throughput calculations are made in a number of seconds as opposed to hours which is required by simulation.
- The user does not have to learn techniques for building and executing simulation models.
- By simplifying the manufacturing cell into a form that can be analyzed by the algorithm, the user develops initial insight for which operational parameters will have the strongest affect on throughput. The simplifying procedure also reduces the number of operational parameters available to experiment with by elimination of the non significant parameters.

2.82 Disadvantages of the Modified Dallery-David-Xie Algorithm:

- Knowledge of transfer line theory (section 2.0) is necessary to simplify a manufacturing cell into a form that can be analyzed by the algorithm.
- The theory behind the MDDX algorithm is complicated and not easily understood.
- The assumptions listed in section 2.2 are not flexible and must be adhered to for accurate results.
- Throughput variance is not calculated; however, simulation does not readily provide this either.

3.0 Manufacturing Cell Design Tool Description

3.1 Objectives of Tool:

1. To aid the designer in the development of future production systems and in the improvement of existing production systems.
2. To aid managers in making capital appropriations decisions.
3. To shorten the cycle time for manufacturing cell design, manufacturing cell improvement, and financial evaluation/approval of manufacturing systems.

Financial outputs of MCDT:

Based on the broad applications for the design tool and the interrelations of input parameters, the author deemed NPV to be the most relevant metric for evaluating improvement or degradation of a manufacturing cell's performance. In the academic financial community, NPV is without question the most accurate financial metric to use for evaluating potential projects (Stuart Myers). The unit of NPV (dollars) also has a near universal meaning throughout an organization whereas metrics such as manufacturing cell efficiency are more abstract and connote a different meaning to different people.

To aid in implementation of the MCDT it became necessary to include two additional financial metrics; Payback Period and IRR. Both metrics are used extensively by Johnson and Johnson Medical Inc., are more familiar to its design engineers, and require slightly less input. In spite of the inaccuracies associated with these two metrics the author felt it more beneficial to fully implement a tool that accomplishes most of what is possible as opposed to developing a tool that accomplishes 100% of what is possible but is never implemented. The MCDT actually accomplishes both implementation and accuracy by providing the additional metrics as well as NPV.

Operational outputs of MCDT:

The MCDT also provides average steady state throughput per shift, aggregated machine group efficiencies, average buffer levels, and manufacturing cell efficiency as standard output for all analysis levels. The reason for providing this additional information as output is to aid the design engineer in optimizing the profitability of the manufacturing cell. The additional data help the designer by providing information on the location of bottlenecks within the manufacturing cell.

The basis for developing an interactive design tool as opposed to writing a report or creating a turnkey solution is the following:

1. The degree of implemented success is directly related to the degree of involvement by the user in the design, improvement or evaluation process.
2. If the user is to be an integral part of the process then it is necessary to educate the user with respect to the effects and interrelations of manufacturing cell design parameters on business profitability. Such parameters include buffer size, buffer location, isolated workstation efficiency, cycle time, capital cost, installation and startup cost, and changeover time.
3. Interactive educational methods are superior to non interactive methods. Consequently, a mechanism that allows the user to experiment with numerous manufacturing cell scenarios and provides rapid feedback to the user for each scenario chosen, will allow the user to learn at the greatest rate.
4. It is better to implement 80% of the solution than it is to solve 100% of the problem and fail to implement it.

3.2 Input and Output Options:

Based on the assumption that the MCDT will have users at several levels within an organization, the tool was designed to allow users the option to choose the degree of output accuracy desired. High output accuracy requires detailed input data whereas lower output accuracy requires less input data as well as less input detail. By providing this option, different individuals can use the tool for different purposes and only have to enter data in relation to the level of accuracy necessary for their purpose.

The design tool provides three possible levels of input detail as well as several simplifying options within each level.

Level #1 Least input detail. Output is Payback Period, throughput per shift and operational information. This level is primarily intended to be used by design engineers who are in the initial stages of a new manufacturing cell design. The benefit of this output is primarily in its relative value and not its absolute value. Through experimentation with different manufacturing cell configurations, the designer can determine an approximate layout for a manufacturing cell and determine what parameters have the greatest potential impact on business profit.

Level #2 Medium input detail. Output is Payback Period, IRR, throughput per shift and operational information. This level is intended to be used in the later stages of a new manufacturing cell design, improvement of an existing manufacturing cell, and financial evaluations requiring medium accuracy.

Level #3 Maximum input detail. Output is Payback Period, IRR, NPV, throughput per shift and operational information. This level is intended to be used in the final stages of either a new manufacturing cell design or improvement to an existing cell. Financial evaluations at this level are very comprehensive and can provide direct input to large capital appropriation requests.

Essentially, as the input becomes less detailed, the output becomes less accurate in absolute terms. If a designer is primarily concerned with locating the few parameters in a design that provide the most leverage for profit improvement, then level #1 is appropriate. However, if a designer needs to determine how much capital should be expended to improve the efficiency of a particular piece of equipment, then level #3 should be used.

3.3 How the MCDT Adds Value

The purpose of the MCDT is not to replace the manufacturing cell designer or anyone else within the organization. Instead, its purpose is to provide rapid information feedback to help these people perform their jobs better. The tool provides information to the designers which allows the designer to perform optimizations with respect to the business objectives as opposed to optimizing with respect to a metric that is relevant only to the designer's particular department. The tool will increase communication speed and accuracy throughout the organization by utilizing common performance metrics. The tool will also reduce the time required to develop capital appropriation proposals by supplying much of the necessary financial data as standard output from the tool. It is anticipated that the number of design iterations made prior to project approval will also be substantially reduced because the designer will be optimizing with respect to the same metrics that top management will review to approve projects. Based on these predictions, the MCDT will reduce project cycle time and increase the financial benefits received from invested capital.

3.4 General Procedure for Using MCDT

The general sequential procedure of data entry and execution of the MCDT is described in the following section. A graphical representation of this procedure is shown in appendix 1.

3.41 Default Input

Prior to initial execution of the MCDT for a new analysis, default data can be entered. Default values are not required to conduct an analysis as these values can be manually entered while executing the tool. A list of defaults is provided in appendix 2. This list is comprehensive and includes all the possible default values for the three input levels. Consequently, a level #3 analysis, can be conducted without all the default values entered whereas a level #1 analysis will require most of these values. Default values can be changed at the beginning of any analysis by a person with appropriate password authority. Each analysis level allows users the option to use particular default values at designated stages within the program. The more default values used within an analysis, the less accurate the output will be. For this reason, the user must be aware of their ultimate goal when using the tool. If the goal is to locate the few parameters in a design that provide the most leverage for profit improvement then extensive use of the default values is fine. However, if the goal is to determine how much capital should be expended to improve the efficiency of a particular piece of equipment, then very few default values should be used. It is the default options that are available within each analysis level that create a continuous scale of increasing analysis accuracy among all levels.

3.42 Operational Data Entry File

As with default inputs, Operational Data Entry takes place prior to initial execution of the MCDT for a new analysis. Operational data is entered into a large data file that contains operational data for other manufacturing cells as well. Appendix 3 provides an example of a Operational Data Entry File. The data entered at this stage consists of the following:

List of Base Workstations

This is a single list for all manufacturing cells stored within the Operational Data Entry File. The list can be added to but not deleted from. Each Base Workstation contains a reference number, description, $c_{b,i}$, $MTTF_{b,i}$, $MCTF_{b,i}$, $MTTR_{b,i}$, $MCTR_{b,i}$. $MCTF_{b,i}$ and $MCTR_{b,i}$ are automatically calculated. The purpose of the Base Workstation list is to provide the user with a group of familiar workstations to compare with less familiar workstations in order to obtain $MTTF_i$, $MCTF_i$, $MTTR_i$, $MCTR_i$. for the less familiar workstations.

At this stage a basic point must be described about the relationship between $MTTF_i$, $MCTF_i$ and c_i and the relationship between $MTTR_i$, $MCTR_i$ and c_i. MCTF is assumed to be constant for a given workstation over a particular range of cycle times. This point is concurrent with Transfer Theory Assumption #1 in section 2.2 where failures are assumed to be operationally dependent. The result of this point is that a particular workstation requires an average number of cycles, not time, to fail. If the workstation is cycled 1% faster, it will take the same number of cycles to fail but the MTTF will be reduced by 1%.

Repairs on the other hand are time dependent. When an workstation fails, it requires a certain MTTR which is independent of the workstation's cycle time. If the workstation is cycled 1% faster, it will take the same time to repair, but the MCTR will increase by 1%.

Average Cycle Time ($\underline{C}$)

Average cycle time for the entire manufacturing cell is entered prior to entering individual operational data. This cycle time is used for only intermediate calculation and therefore does not have to be extremely accurate.

Workstation Description and Reference Number

All workstations within the manufacturing cell must be entered in the order in which the workstations process the product. For each workstation, a description of the operation performed is entered along with a reference number which relates the subject workstation to the first workstation in the process. Automatic inspection stations are entered as well.

$MCTF_i$ and $MTTF_i$

This information can be obtained in a combination of two ways: relative data entry and/or known data entry.

Relative data entry compares individual unfamiliar workstations with a list of Base Workstations. For a given unfamiliar workstation, a Base Workstation is chosen and a difficulty multiplier entered. The difficulty multiplier specifies a percentage that the Base Workstation's $MCTF_{b,i}$ must be increased or decreased by to obtain the $MCTF_i$ for the unfamiliar workstation. $MCTF_i$ is then multiplied by $\underline{C}$ to obtain $MTTF_i$.

For known data entry, a value for $MTTF_i$ and c_i is entered directly for individual workstations. $MTTF_i$ is then divided by c_i to obtain $MCTF_i$.

A “drag and drop” function is available to copy various workstations within a manufacturing cell as well as copying from one manufacturing cell to another. When this copy function is used, it copies $MCTF_i$ and not $MTTF_i$ or c_i. $MTTF_i$ is recalculated based on either an entered value for c_i or the average value of $\underline{C}$.

$MCTR_i$ and $MTTR_i$

This information can be obtained in a combination of two ways: relative data entry and/or known data entry.

Relative data entry compares individual unfamiliar workstations with the list of Base Workstations. For a given unfamiliar workstation, a Base Workstation is chosen and a difficulty multiplier entered. The difficulty multiplier specifies a percentage that the Base Workstation’s $MTTR_{b,i}$ must be increased or decreased by to obtain the $MTTR_i$ for the unfamiliar workstation. $MTTR_i$ is then divided by $\underline{C}$ to obtain $MCTR_i$.

For known data entry, a value for $MTTR_i$ and c_i is entered directly for individual workstations. $MTTR_i$ is then divided by c_i to obtain $MCTR_i$.

A “drag and drop” function is available to copy various workstations within a manufacturing cell as well as from one manufacturing cell to another. When this copy function is used, it copies $MTTR_i$ and not $MCTR_i$ or c_i. $MCTR_i$ is recalculated based on either an entered value for c_i or the average value of $\underline{C}$.

Generic Load and Unload Workstations:

The purpose of Generic Load and Unload workstations is to account for the necessity of additional workstations whenever a buffer is added to a manufacturing cell. Every time a continuous process is divided by an in-line buffer, an additional unload workstation is necessary to unload product into the buffer and a load workstation is necessary to load product to the next workstation.

Whenever a new manufacturing cell is defined in the Operational Data Entry File, the MCDT requires the user to define Generic Load and Unload workstations prior to exiting the file. These workstations are defined in a similar fashion to the other workstations within the manufacturing cell.

Product Scrap Rates

The user specifies the product scrap rates in relation to workstations within the process where scrap is detected (typically inspection stations). These values are to be entered as the percent defective. For example a 10% scrap rate will be entered as .10. If these rates are not known, rates can be obtained again from the accounting cost sheets.

Note: $MCTF_i$, $MTTF_i$, $MCTR_i$, $MTTR_i$, and Product Scrap Rates can also be entered for the transitional period after a changeover and before steady state performance is achieved. This transitional period will typically have lower values for $MCTF_i$, and $MTTF_i$ and may have higher values for $MCTR_i$, $MTTR_i$ and Product Scrap Rate. The user can choose whether to enter these values in a similar fashion to what was done for steady state operation or can apply a scaling factor (entered or default) which will determine transitional performance directly from steady state performance.

Material Scrap Costs

Accounting estimates for material value at points within the manufacturing process are entered in relation to the representative workstation. These values and the correct point within the manufacturing process are given on accounting cost sheets. The values entered represent the sum of material cost, previous manufacturing cell labor, and previous manufacturing cell variable burden. Note: if a level #1 analysis is being conducted, this data is not necessary. This data is used to calculate the cost of manufacturing the product; in a Level #1 analysis, this calculation is not performed.

3.43 Choice of Analysis level

Specify the level at which the current analysis is to be conducted. Section 3.2 describes the differences between the three possible levels.

3.44 General Input

Financial and Scheduling

Appendix 4 show the required financial and scheduling inputs for each analysis level. Each level contains certain variables that require input while other variables may utilize a default value. It is readily observed from the appendix that a significant percentage of level #1 input can utilize default values whereas the percentage for level #3 is much less. This increase in input detail is consistent with the intended purpose of a level #3 analysis as described previously.

Sales Volume Prediction

The designer has the option to choose capacity limited production, demand limited production or a combination of the two. Capacity limited sales assume every unit produced is sold no matter how great the yearly throughput. Demand limited production on the other hand assumes that excess capacity exists; consequently, production should not be run 3 shifts/day, 365 days/year.

Options for Sales Volume Predictions:

Capacity limited production: Excessively high sales volumes are automatically entered for each year of the production line's life.

Demand Limited Production: Sales volume for each year are entered manually.

Combination of Capacity and Demand Limited Production: Manually enter excessively high sales volumes for the capacity limited years and realistic volumes for demand limited years.

Appendix 5 provides an example of each option above.

Profit Margin Behavior Over Time

The behavior of profit margin over time is important for determining the profitability of a manufacturing cell over its expected life. Again, there are three input options: manual, constant percentage per year, or default.

Manual: the percent increase or decrease in margin is entered for each year of the manufacturing cell's life.

Constant Percentage: A percentage is entered by the user which is used to automatically scale actual margins in each successive year.

Default: Essentially the same as "Constant Percent" except the percentage used for scaling is a default value.

Appendix 6 provides an example for each option above. Notice that the resulting margin is calculated for each year.

Burden Behavior Over Time

The behavior of burden over time is important for determining the profitability of a manufacturing cell over its expected life. The options for entering this information are identical to those described previously for Margin behavior Over Time and are shown in appendix 7.

3.45 Design Scenario Input

Different configurations of the manufacturing cell can be evaluated at this point within the execution of the MCDT. The parameters that can be varied at this stage of the execution include: number of machine groups, distribution of workstations within machine groups, buffer size between machine groups, and cycle time of each machine group. The input sequence proceeds as follows:

1. Choose the number of machine groups (maximum of 10).

   When this is entered, the MCDT performs an initial distribution of the workstations within each machine group. This distribution is performed to equalize the aggregated efficiencies of each machine group and is based on steady state operational performance.
2. Manually alter the workstation distribution using a "drag and drop" procedure.
3. The following financial data is entered:

   Equipment Cost: Levels #1, #2, #3
   Installation Cost Levels #1, #2, #3
   Startup Cost Levels #1, #2, #3
   Total Labor Cost: Levels #2, #3
   Salvage Value: Levels #1, #2, #3 (default option also available for all levels)
4. Combinations of buffer size and machine group cycle times:

   After the previous data is entered, the user can perform up to ten configuration iterations. Within each iteration, the user can specify different values for buffer capacity and cycle time for each machine groups. If more than ten scenarios are desired for a particular configuration, the user can execute the first set and simply repeat the above data entry process.

Financial and operational output data is written to a separate file. The output data for each iteration performed is provided in a form similar to that shown in appendix 8. Each combination of buffer size and machine group cycle time is associated with the relevant financial output for the analysis level performed as well as steady state throughput per shift, average buffer levels and machine group efficiencies. The output also contains the previously entered input information such that a given iteration can be performed again.

Extensive financial and cash flow calculations (appendix 9) are temporarily saved in a separate file for the last iteration executed. If this information is needed for a previous iteration, the user must rerun the analysis with the desired scenario as the last iteration.

As previously mentioned, analysis is limited to ten iterations at a time When additional iterations or different machine groupings are desired, it is not necessary to rerun the program from the beginning. Instead, the user has the ability to run numerous loops of the input process previously described in this section (3.44 & 3.45).

3.5 How the MCDT Performs Evaluations

In this section, I will relate the general sequence of data entry (section 3.4) with the relevant transfer theory calculations (section 2.0) and the financial calculations that are performed on the resulting information. This section will provide an understanding of the sequence in which data is used, how it is used, and the financial assumptions made to obtain MCDT output.

3.51 Calculation of product margin

As mentioned in section 3.4 this input is only relevant for level #2 and level #3 analyses. Margin is entered manually for level #1 analyses.

The Operational Data Entry File (section 3.42) provides scrap rate and product material value for individual workstations within the manufacturing cell. This information is combined with total labor cost per part (section 3.44) to calculate the total product value at a point within the manufacturing cell. Note: in these calculations it is assumed that each workstation listed in the Operational Data Entry File contributes equally to total labor cost for the manufacturing cell. For each workstation that has a scrap rate assigned to it, the MCDT will calculate the total product value at that point in the manufacturing cell and then adjust this value to account for the average scrap rate at that workstation. Total product value at the end of the manufacturing cell is simply the total product value at the last workstation after being adjusted for scrap rate. Total product value is then added to the cost of subsequent operations (section 3.41). This sum is then subtracted from product sale price to obtain product margin. All calculations mentioned are automatically performed by the MCDT but are shown below for informational purposes.

1. Product material value at a particular workstation (PMV_i):

   This is simply the material value entered in the Operational Data Entry File.

2. Product labor content at a particular workstation (PLC_i):

   TLC = Total labor content of manufacturing cell

   O_i = Workstation reference number

   O_T = Total number of workstations within manufacturing cell

   $PLC_i = TLC * O_i / O_T$

3. Product value at a particular workstation (PV_i):

   $PV_i = (PLC_i - PLC_{(i-1)}) + (PMV_i - PMV_{(i-1)}) + SPAV_{(i-1)})$

4. Scrap adjusted product value at a particular workstation ($SAPV_i$):

   $SAPV_i = PV_i * (s_i + 1)$

5. Total adjusted product value (TAPV):

   This is simply the $SAPV_{(\text{Last Workstation})}$.

6. Product Margin (PM):

   PM = (sale price of product) - (cost of follow on operations) - (TAPV)

The margin per part is calculated for both steady state operation and the period after changeover before steady state operation is achieved. The value of margin used in subsequent financial calculations is a weighted average of the two margin values and is based on the amount of time spent in each operational mode.

3.52 Sequence of Transfer Line Calculations

As mentioned in section 2.7, the purpose of the transfer line calculations is to determine a value for PPUT which is converted to a throughput rate and ultimately into financial values.

All calculations discussed below are automatically performed by the MCDT but are described here for informational purposes.

1. $MTTF_i$, $MCTF_i$, $MTTR_i$, $MCTR_i$, c_i, and $\underline{C}$ provided in the Operational Data Entry File are used to obtain p_i and r_i values for each workstation (section 2.1). Values for p_i and r_i are determined for both steady state and transitional period after changeover.
2. Individual workstations are then allocated into a user specified number of machine groups. The workstation allocations are performed to minimize the difference in steady state machine group efficiencies (E_g) between machine groups (section 3.45).
3. Each time the manufacturing cell is divided into an additional machine group, a "generic" unload workstation is added to the previous machine group and a "generic" load workstation is added to the latter machine group. The addition of these workstations is necessary to represent the movement of product into and out of an in-line buffer. The "generic" load and unload workstations are defined in the Operational Data Entry file for each manufacturing cell.
4. The user then manually alters the initial groupings as necessary to achieve a functional manufacturing cell.
5. The user enters the data shown in section 3.45 -3 & -4
6. Based on the new machine group cycle times, p_i's, and E_g's are recalculated for both steady state and transitional period after changeover.
7. Effective cycle times for both steady state and transitional period after changeover are calculated for each machine group (sections 2.6). These effective cycle times, based on the material scrap rates entered in the Operational Data Entry File, are used in the MDDX algorithm. Note, these effective cycle times are not used to recalculate p_i and E_g.
8. The MDDX algorithm is executed. A single execution performs both steady state and transitional period manufacturing cell efficiency calculations for each input iteration defined (section 3.45-4)

9. Throughput rates are calculated for both steady state and transitional period after changeover (section 2.7). Subsequent financial calculations are based on a weighted average of the two throughput rates which are in turn determined by the fractional time spent in each operational mode.
10. Steady state throughput per shift, individual machine group efficiencies, and average buffer levels are calculated from the MDDX algorithm output and are provided as standard operational output for the design tool.
11. Yearly throughput is the product of the weighted average throughput rate and the time per year the cell operates.

3.53 Financial Calculations

Appendix 9 shows the financial spread sheet that can be obtained for the last iteration performed. All financial calculations discussed below are automatically performed by the MCDT but are described here for informational purposes. These calculations are based on the following:

Financial Assumptions:

1. Installation costs are amortized over the economic life of the manufacturing cell.
2. Startup costs affect yearly cash flow and are not amortized over the economic life of the manufacturing cell.
3. Economic life for financial evaluation is equal to the accounting life of the manufacturing cell.
4. Capital depreciation is performed per standard "Straight Line" methods with the exception of first year depreciation which is based on the "Half Year" convention.
5. Accounting values for "Net Sales", "Variable Manufacturing and Distribution", "Other Direct Costs of Sales", and "Total Working Capital" are accounted for in "Product Margin."
6. "Operating Expenses" and " Component Improvement" are accounted for through "Burden", and "Burden Increase per Year."
7. NPV and IRR calculations include a credit for salvage value.

8. Salvage value will include the fair market value of retired equipment that is suitable for use in another manufacturing cell, i.e, equipment that is flexible enough to be used for other applications.

Financial Spread Sheet Calculations:

3.531 Income Generated

1. Net Income

   Each year during the accounting life of the manufacturing cell, the yearly throughput rate is compared to the predicted sales volume and the smaller of the two values is taken (appendix 5). This value is then multiplied by the product profit margin for that year to obtain Net Income for that year.

2. Depreciation

   As stated in the assumptions, depreciation is performed per straight line methods over the accounting life of the manufacturing cell. The only exception to this is that depreciation in the first year is one half the depreciation in subsequent years.

3. Burden

   Each year during the accounting life of the manufacturing cell, the yearly burden is calculated based on the previous year's burden and the percent increase in burden for the year calculating (appendix 7).

4. Installation

   Installation cost pertains to all costs associated with physically installing a new manufacturing cell in the plant. As stated in the assumptions, the installation cost is amortized over the accounting life of the manufacturing cell.

5. Startup Cost

   Startup costs pertain to all costs associated with improving a new piece of equipment until it reaches its steady state performance efficiency. These costs include, but are not limited to: startup engineering labor, decreased labor productivity elsewhere in the plant, and equipment redesign. As stated in the assumptions, the startup costs are not amortized over the accounting life of the manufacturing cell, instead they are taken as a debit in the year occurring

6. Taxes

   Taxes are calculated based on the sum of Items #1 through #4.

7. Income After Taxes

   This is simply the sum for items #1 through #4 less taxes.

3.532 Cash Outlay for Equipment

This is simply the capital expensed to design and acquire the manufacturing cell. Note: this value is used only in calculation of Payback Period. IRR and NPV utilize Annual Payback for Equipment in place of cash outlay for equipment.

3.533 Annual Payback for Equipment

Determination of Annual Payments

$A = [P*(i_c*(i_c+1)^T)] / [(i_c+1)^T - 1]$

$A \equiv$ Annual payments

$P \equiv$ Cash Outlay for Equipment

$i_c \equiv$ Corporate cost of capital (NPV calculation), or i_{IRR} (IRR calculation)

$T \equiv$ Length of Payback Period in years

The value for Annual Payments will be applied to each year of the Payback Period

3.534 Payback Period Calculation

1. Cash Position at End of Year (CPEY)

   Income After Taxes (3.531 -6) is combined with Cash Outlay for Equipment in each year of the manufacturing cell's accounting life.

2. Cumulative Cash Position

   This is simply the running sum of CPEY for current year and all previous years.

3. Payback Period Calculation

   The number of years and fractions thereof for the Cumulative Cash Position to reach a value of zero. Note: Payback Period does not account for the time value of money.

3.535 IRR Calculation

1. Cash Position at End of Year

   Income After Taxes (3.531-6) is combined with Annual Payback for Equipment (based on i_{IRR}) in each year of the manufacturing cell's accounting life.

2. IRR Calculation

   Cash Position at End of Year (CPEY) year is discounted by an i_{IRR} interest rate such that the cumulative discounted cash flow for at the end of the manufacturing cell's accounting life is zero.

$$0 = CPEY_1/(i_{IRR}+1)^1 + CPEY_2/(i_{IRR}+1)^2 + ...+CPEY_T/(i_{IRR}+1)^T$$

Note: multiple values for IRR will occur if the sign of CPEY changes more that once during the accounting life of the manufacturing cell.

3.536 NPV Calculation

1. Cash Position at End of Year

   Income After Taxes (3.531-6) is combined with Annual Payback for Equipment (based on i_c).in each year of the manufacturing cell's accounting.

2. NPV Calculation

   CPEY is discounted by an inflationary interest rate (i_f). Discounted CPEYs for all years of the manufacturing cell's accounting life are summed to obtain NPV.

$$NPV = CPEY_1/(i_f+1)^1 + CPEY_2/(i_f+1)^2 + \ldots\ldots\ldots + CPEY_T/(i_f+1)^T$$

4.0 Example - Design of a Hypothetical Manufacturing Cell

The following example has been constructed to demonstrate how the MCDT can be used to design a new manufacturing cell. All properties of the manufacturing cell are hypothetical. Any resemblance to a known manufacturing cell or company is purely coincidental. The purpose of providing this example is to demonstrate a common situation experienced by many manufacturing cell designers and to describe how the MCDT can significantly improve the manufacturing cell design process and consequently its resulting profitability.

4.1 Description of Workstations and Product

Product:

This manufacturer produces several types of toys, specifically those toys which have high volume demand. The production line that is being developed will produce a radio controlled race car. The car has several subtle design variations, all of which will be produced, and can be produced on the planned production line with minor tooling change outs. This car, as with past products produced by the company, will have a very high demand. Yearly demand is anticipated to be 2 million per year and remaining constant over the next four years. The product will also be relatively inexpensive with a $20 retail price. Marginal production costs are less than half the retail price.

Workstations:

The Hypothetical Manufacturing Cell (HMC) contains 81 workstations of which 22 are for inspection, and 8 are for loading and unloading parts to and from buffers. The cycle time of 6 workstations differ significantly from that of the other workstations. The production sequence is fixed and can not be altered. Several workstations must process the product without time delay from previous workstation; therefore, it is not possible to place a buffer between these workstations. All workstations are similar in function and method to other workstations currently in use within the plant. Many of these workstations are actually identical to other workstations within the plant. Appendix 10A & 10B provides descriptive information for all workstations and buffers as well as their intended processing sequence prior to MCDT evaluation. Appendix 11 provides a graphical layout of a critical portion of the manufacturing cell. By examining this layout, the reader should develop an understanding for how the total manufacturing cell functions.

Due to the anticipated high production volume, this product as with past products, will be produced on dedicated machinery in a transfer line configuration. Based on the company's risk averse management policies, planned production capacity will be less that expected demand. Therefore, the production system is likely to be capacity limited throughout its life due to insufficient capacity sizing and the probable "band wagon" effect on product demand.

4.2 Evaluation Difficulties Facing Organization

The manufacturing organization is very skilled technically and has the advantage of a well qualified and very cooperative direct labor force. Over the past ten years, many changes have taken place within this facility. The organization has transitioned from a batch manufacturer to cellular manufacturer and is currently striving to achieve continuous non-buffered flow production. Due to this transition in manufacturing methods, incorporation of continuous improvement techniques, and statistical process control, the company has improved yields by 20% and has reduced WIP by over 75%. The manufacturing cell that will be designed for the race car will account for approximately 5% of this product's anticipated WIP if designed per current methods.

4.21 Cultural Belief that Zero Buffers are Optimum

As this organization has transitioned from batch to cellular manufacturing, it has developed a belief that production buffers are non productive and thus should be eliminated. This belief has been confirmed as production volumes, yields, and customer responsiveness have increased/improved due to the eliminated of buffers. Process bottlenecks also became apparent when buffers were reduced; consequently, these bottlenecks were fixed and process efficiency was improved. As a result, a majority of the organization holds the belief that continuous non-buffered flow manufacturing systems are optimum and should be striven for when developing new manufacturing cells.

4.22 Equipment Startup Cost Are Not Well Understood

When the cost tracking system was developed for this company, it was based on the premise that all production lines within the plant and all plant employees were fixed costs. Based on this view, it was unnecessary to track direct and indirect labor for each manufacturing line over its life. In essence, all labor was overhead. The result of this cost tracking system is that when a new manufacturing cell is brought into the plant, the only cost that is recognized is the capital cost of the equipment and its physical installation. The costs associated with startup operations such as additional engineering and direct labor as well as decreased productivity elsewhere in the plant are unknown. These costs may seem insignificant at first glance; however, per recent studies provided in "Dynamic Manufacturing" (Hayes) these costs can be two to three times the capital cost of purchasing and installing the manufacturing cell.

4.23 Moderate Internal Knowledge of Process Optimization Techniques

Process optimization techniques such as those described in section 2.0 are not well understood. Benefits of small in-line buffers and their ability to partially decouple manufacturing systems are not currently recognized. Furthermore simulation modeling has not been utilized to obtain an understanding of various production alternatives. The organization has designed production cells in the past based on rules of thumb and common sense. The following examples will provide an understanding of the techniques currently employed:

1. Long transfer lines containing up to 40 workstations are arranged in series with no intermediate buffers. Their purpose for this configuration is to reduce WIP, decrease throughput time, and expose bottleneck workstations

2. Cycle times of machine groups are arranged from faster cycle times at the beginning of the transfer line to slower cycle times at the end of the transfer line. The basis for this is that the production process is optimized if the downstream workstations are never starved for product.

3. Machine group efficiencies are arranged from higher efficiencies at the beginning of the transfer line to lower efficiencies at the end of the transfer line. The basis for this is that the production process is optimized if the downstream machine groups are never starved for product.

4.24 Tradeoffs between Isolated workstation efficiency and cost

Currently two manufacturing cells within the plant have approached the desired system of "Continuous Non-Buffered Manufacturing." These two cells represent a difficulty that the organization faces with existing manufacturing cells as well as cells currently being developed. Because of the great complexity of a given manufacturing cell and the interrelations of numerous parameters, engineers and managers do not have a sound understanding of the incremental financial benefits that can be obtained by incrementally improving a specific workstation's efficiency. The engineers and managers are aware of the workstations that seem to be constraining production; however, they do not know within a factor of ten what it is worth to improve the constraining workstation.

4.3 Data Collection

In order to utilize the MCDT it is necessary to obtain individual workstation performance information as described in section 2.1. The data collection process can be difficult but is critical to the analysis, particularly if a Level #3 analysis is to be conducted. With the proposed manufacturing cell incorporating similar workstations to existing manufacturing cells, it is possible to obtain real data for these workstations. Data should also be collected on other workstations within the plant to develop performance information for Base Workstations (section 3.42). The workstations chosen as Base Workstations should be familiar to all designers such that these workstations can be used to estimate the performance of new workstations.

4.31 Data Acquisition System

Several methods for obtaining performance data directly from a manufacturing cell exist; however, it is most efficient if the data can be collected electronically. Data acquisition systems can be developed and connected directly to the computer controller of an individual machine group if the controller incorporates very specific sensors that detect all possible failure modes. If the controller does not possess this degree of accuracy, it is necessary to develop a data acquisition system that utilizes input commands from the operators. If this second method is used, it is necessary to make the data entry as simple as possible to avoid recording errors and/or operators failing to record workstation failures.

4.32 Verification of Exponential Properties

After data collection is complete, the individual workstation $MTTF_i$ and $MTTR_i$ should be evaluated to assure they are exponentially distributed. As described in section 1.4, most processes that incorporate a high degree of automation with deterministic cycle times will conform to this requirement. If the data fails to resemble an exponential distribution, but exhibits the characteristics described in section 1.4, it is possible that errors have occurred during the data collection process.

4.4 Simplifying Assumptions made to Manufacturing Cell

As stated in section 2.3, 2.4 and 2.5, the existing manufacturing cell must be simplified for the primary purpose of obtaining a representative system that can be evaluated using the MDDX algorithm. Simplification of the system is also beneficial to the designer. Through the process of simplification, the designer obtains a better understanding of the operational parameters that have the greatest effect on improving manufacturing cell performance.

4.41 Feeder Systems

All feeder systems within the main assembly system and the subassembly system must be simplified as described in section 2.51. Values of $p_{i,s}$ and $r_{i,s}$ can be obtained for each feeder system by simply observing the last stage of the feeder system just prior to it's entry into the downstream transfer line. This location is observed to determine the probability that a part will not be available for processing by the immediate downstream workstation, and, if the product is not available, what the probability is that it will be available within the next unit of time. Once $p_{i,s}$ and $r_{i,s}$ are known for a particular feeder system, the feeder system is treated as an additional workstation within the transfer line as is shown in figure 2.5. Appendices 10A & 10B provide values of $p_{i,s}$ and $r_{i,s}$ for each feeder system present.

4.42 Assembly Systems

As described in section 2.52, assembly systems can be treated in the same manner as feeder systems; however, in this example, the Drive Motor assembly system will be aggregated into a single workstation. In doing this, workstations #25 and #24 will be aggregated with the rest of the assembly system to form one, approximately equivalent, workstation. Refer to appendix 12 for an example of the procedure used.

4.43 Parallel Workstations

The two sets of parallel workstations present in the manufacturing cell were each aggregated into a single equivalent workstation per section 2.3, configuration #2.

Appendix 13 represents the workstations in appendix 10 after aggregation and other simplifying assumptions have been applied to get the manufacturing cell into an appropriate configuration to be analyzed by the MCDT.

4.5 General Optimization Techniques

Countless optimization techniques and methods exist; however, for many the difficulty in using the technique is great and the resulting benefit is small. The following methods or rules of thumb, have a significant effect on manufacturing cell performance and are relatively easy to understand. These rules of thumb should be kept in mind while using the MCDT. By doing so, the designer will greatly reduce the number of design scenarios run, and therefore, obtain an optimum manufacturing cell configuration more quickly.

4.51 Purpose of Buffers

Buffers allow the efficiency of a manufacturing cell to approach its maximum efficiency. The maximum efficiency of a manufacturing cell is the efficiency of the worst performing machine group within the manufacturing cell. Buffers add value by allowing the worst performing machine group to operate a greater percentage of the time for which it is capable of operating. In other words, buffers improve efficiency by reducing the amount of time the worst performing machine group is starved or blocked by other machine groups. As stated in section 1.3, the marginal benefit of buffer capacity is greatest for the first unit of buffer and decreases for each additional unit of buffer capacity. Appendix 14 provides a graphical representation of this relationship for a ten machine, nine buffer transfer line.

4.52 Buffer Size

The buffer should be large enough to accommodate the average disturbance of upstream and downstream machine groups. Essentially, if the average repair time for a two machine production line is equal to one hundred machine cycles, then the buffer placed between these two machines should have a capacity of approximately one hundred parts.

4.53 Buffer Placement

A buffer adds very little value if it is placed between two machine groups, which when combined as one aggregated group, have an efficiency that is greater than the worst performing machine group in the manufacturing cell. Buffers only add value if they permit the worst performing machine group to operate a greater percentage of the time for which it is capable.

4.54 Number of Buffers

<u>If</u> the cost of buffer capacity is dependent only on the total number of units and is independent of the number of individual buffers, then manufacturing cell profitability is greatest when several small buffers are used instead of one large buffer. By using many small buffers, the efficiency of the worst performing machine group is being maximized and consequently the

efficiency of the manufacturing cell is maximized. This is also a logical extension of the principal of diminishing returns to buffer size (section 4.51.)

4.55 Machine Group Efficiencies

If all machine groups within a manufacturing cell have equal cycle times, then workstations should be allocated to machine groups such that each machine group has approximately the same aggregated efficiency. This is because the efficiency of the manufacturing cell is at best equal to the efficiency of the worst performing machine group. By making all machine groups approximately equal, the efficiency of the worst performing machine group is maximized. The MCDT automatically accomplishes this through machine group efficiency balancing (section 3.45).

4.56 Different Machine Group Cycle Times and the Creation of Scrap

When machine groups within a manufacturing cell have different cycle times and produce scrap, it is important to take these factors into account when configuring the manufacturing cell. The creation of scrap by a machine group increases the effective cycle time of that machine group as is observed by a downstream machine group (section 2.6). Consequently, when considering a large manufacturing cell, machine group M_2 should have a cycle time close to the effective cycle time of machine group M_1. The cycle time of machine group M_3 should be approximately equal to the effective cycle time of M_2. This process is continued for all machine groups within the manufacturing cell.

4.57 Adding Successive Workstations to a Machine Group

The marginal performance degradation that is experienced when a workstation is added to a machine group is greatest for the first workstation added and decreases for each successive workstation that is added (appendix 15).

4.58 Reversibility Principal of Manufacturing Cells

To illustrate this principal, consider a manufacturing cell composed of several machine groups each separated by a buffer of finite size. Also assume that no scrap is created. This manufacturing cell is configured such that each sequential machine group starting with the first machine group is less efficient and cycles slower than its preceding machine group. The result of this configuration is that the average buffer level of all buffers within the manufacturing cell will approach the maximum capacity of those buffers.

Now invert the distribution of machine group cycle times and efficiencies such that the first machine group now has the same efficiency and cycle time as the last machine group previously had. Now the manufacturing cell is configured such that each sequential machine group starting with the first machine group is more efficient and cycles faster than its proceeding machine group. No other changes are made. In this new configuration, the throughput will be exactly the same as was accomplished with the first system. The only difference is that in the new system the average buffer level of all buffers is close to zero.

Based on this principal, manufacturing cells can be designed with buffers which provide the benefit of decoupling and therefore improve efficiency, but do not add WIP to the manufacturing process.

4.6 Modeling and Improving the Hypothetical Manufacturing Cell (HMC)

The following information describes the analysis of both the original HMC and the redesigned configuration. Both analyses utilize the MCDT to perform the evaluations.

4.61 Model Assumptions

The following assumptions and simplifications were incorporated into this analysis.

- The workstation immediately upstream of a buffer will discharge all defective parts at that point in the process.

- The workstation immediately upstream of a buffer will also perform the "Generic Loading" of parts into the buffer.
- The workstation immediately downstream of a buffer will perform the "Generic Unloading" of parts from the buffer.
- "Generic Load" and "Generic Unload" workstations are capable of cycling as fast as the fastest machine group within the manufacturing cell.
- A scale factor of 1.5 was applied to the steady state performance of all workstations to obtain a performance value for these workstations during the transitional period following changeover.
- Each additional buffer costs $200,000 and has a capacity 25 units. Buffer capacity increases are in steps of 25, each at a cost of $200,000.

4.62 Non Configuration Specific Input Data

- All financial and operational default parameters used are provided in appendix 16. The default value for "Product Margin" was not utilized because level #2 & #3 analyses calculate "Product Margin" internally.
- The manufacturing cell was assumed to be capacity limited for its entire life.
- All other financial input data utilized in both analyses is provided in Appendices 17 & 18 and 23 & 24.

4.63 Results

4.631 Analysis of Original Hypothetical Manufacturing Cell (HMC)

The configuration analyzed for the original HMC is shown in appendices 10A, 10B, 12, and 13 and or described in sections 4.1 and 4.4. This configuration incorporates four buffers each with a capacity of ten. The reason buffers were present at all in the original configuration was because of the parallel wire solder workstations. If parallel workstations were not present, the HMC would have been design with no buffers.

Appendices 17, 18 and 19 provide the operational and financial output for this analysis.

The following is a brief summary of the results:

1. Capital outlay for equipment and installation: $6.4 million.
2. Throughput per year: $1.21 million.
3. Demand per year: $2 million.
4. Payback period: 1.24 years on a four year project.
5. Project NPV: $17.68 million.
6. Effective cycle time of slowest machine group during steady state operation: 15.99 sec.
7. Three machine groups. Efficiencies for each group: 72.9%, 85.75%, and 86.59% respectively. Of these groups, the efficiency of the first and last can be improved through strategic buffer placement.

Caution should be taken when comparing the efficiencies of different machine groups when the machine groups have different cycle times. A low efficiency machine group with a fast cycle time may produce more product than a efficient machine group with a slow cycle time. It is for this reason that machine group performance is defined as the number of units that a machine group can produce within a given period of time. In the above example, the machine group with an efficiency of 85.75% is actually rather good because it has an effective cycle time of 10.1 seconds as opposed to the machine groups before and after it which have effective cycle times of 15.99 and 15.44 seconds respectively.

Production per unit time (PPUT) for a machine group:
PPUT = (Time Period) * (Machine group efficiency)/(Effective cycle time of group)

4.632 Redesigned Hypothetical Manufacturing Cell

Improvement of the HMC starts with improving the Drive Motor Subassembly System. Adding one buffer of capacity 25 following the "Install Right Endcap" improves line balance, improves effective cycle time and consequently improves the aggregated assembly system efficiency. Comparative data for the new versus original subassembly system are given below:

Original subassembly system:

Steady state efficiency = 88.67%
Changeover efficiency = 81.75%
Effective cycle time (SS) = 14.67 sec
Throughput per shift . = 1583 (if unconstrained by downstream workstations)

New subassembly system:

Steady state efficiency = 91.58%
Changeover efficiency = 88.12%
Effective cycle time (SS) = 13.95 sec
Throughput per shift = 1757 (if unconstrained by downstream workstations)

Appendices 20 and 21 show the configuration for the new subassembly system and its aggregated properties respectively.

The configuration of the primary line, analyzed for the new HMC, is shown in appendix 22. This system incorporates three buffers of capacity 25, in addition to the two buffers that were previously utilized for the parallel wire solder workstation.

Appendices 23, 24 and 25 provide the operational and financial output for this analysis. Appendix 24 also provides output for each of the six buffer size iterations conducted for this analysis. For each buffer size iterations, an individual buffer was reduced to a capacity of zero while maintaining all other buffers at their original capacities. This was done to verify that each buffer contributed more to NPV than it cost. If a buffer was found not to be profitable by this process, another "Analysis Loop" (appendix 1) would be run to obtain the exact profit increase that would be realized by elimination of the buffer. Running a second Analysis Loop allows input values for the number of machine groups and capital costs to be reentered for the new configuration. As can be observed by studying the different iterations, buffer #1 is the least beneficial of all the buffers; however, buffer #1 increases net NPV by roughly $210,000 ($26,660,000 - $26,250,000 - buffer cost). Although this is the least useful buffer, it still contributes twice its cost to net profit.

The following is a brief summary of this analysis:

1. Capital outlay for equipment and installation: $7.2 million.
2. Throughput per year: $1.54 million (27.2% improvement).
3. Demand per year: $2 million.
4. Payback period: 1.02 years on a four year project.
5. Project NPV: $26.66 million (50.8% improvement).
6. Six machine groups. Efficiencies for each group: 89.76%, 89.58%, 89.91%, 85.75%, 91.94%, and 93.41% respectively.
7. Effective cycle time of slowest machine group during steady state operation: 15.29 sec.

Appendix 26 presents the comparative information described above in tabular form.

4.7 Summary

The preceding example demonstrates how strategically placed buffers can significantly improve the efficiency and consequently, profitability of a manufacturing cell. The example also demonstrates how the MCDT can be used to quickly determine strategic buffer locations as well as proper buffer capacities.

Although the preceding example provided insight into the design of a new manufacturing cell, the MCDT can also be used to improve the performance of a existing manufacturing cells. In an existing manufacturing cell, the MCDT would be used to evaluate the benefit of improving individual workstation efficiencies and increasing/decreasing existing buffer capacities. Any operational change that has a positive effect on NPV (when accounting for the cost of the operational change) should be pursued.

5.0 Conclusion

Through use of the MCDT, a designer can quickly evaluate the difficult tradeoffs between buffer placement, buffer capacity, isolated workstation efficiency, incremental improvement of workstation efficiency, capital expenditures, and profit. These types of tradeoff analyses are traditionally very difficult and time consuming to conduct. Consequently, they are seldom done and the production problems are never solved. It is for this reason that critical bottleneck workstations are often modified with bailing wire and duct tape. This is done either because the engineers and managers involved are either unaware that the processes are bottlenecks, or they do not know, within several factors of ten, how much capital should be dedicated to repairing or improving the workstations in question. It is this same lack of tradeoff knowledge that allows new manufacturing cells to be designed without one or two minutes of buffer inventory at four of five locations throughout the manufacturing system. As shown by the preceding example, these relatively small buffers, when located properly, can increase production by as much as 27% and profit by 51%. However, these buffers are eliminated in the organization's quest for achieving "World Class Manufacturing" (Hayes) systems even though a week or more of idle in-process inventory may be maintained elsewhere within the overall manufacturing system.

To successfully use the MCDT and obtain its potential benefits, a designer must have moderate knowledge of the process optimization theory incorporated in the tool (section 2.0) as well as general process optimization techniques (section 4.5.) Without this knowledge, a designer may develop an efficient manufacturing cell configuration by trial and error. However, the number of iterations required to do so will be rather large and the designer may not incorporate the new configuration because they will not understand why the configuration is efficient. A knowledgeable user, on the other hand, can quickly use the MCDT to focus on the critical parameters of manufacturing cell design that contribute to efficiency and profit.

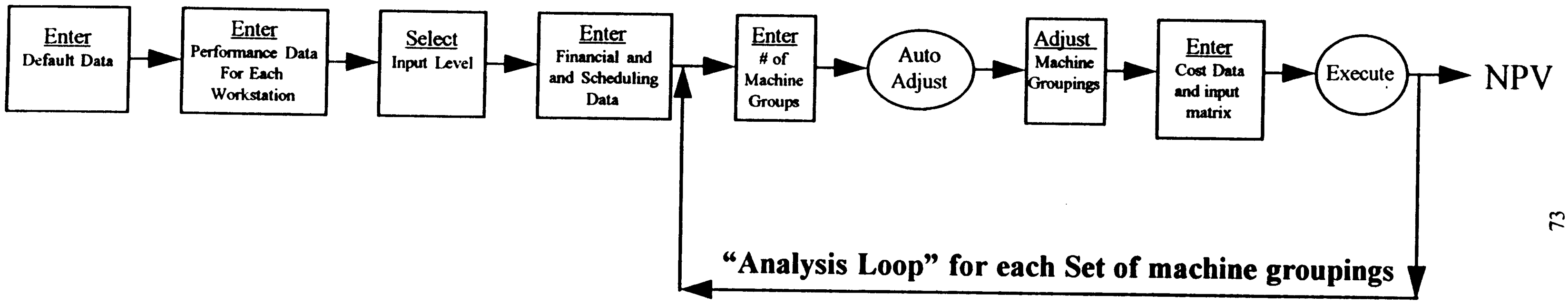
Whether the MCDT is used to design new manufacturing cells or improve existing manufacturing cells, the primary benefits of using the tool are to employ common performance metrics throughout the organization and to provide the manufacturing cell designer with rapid financial and operational feedback in terms of these metrics. By providing a knowledgeable designer with this feedback, the designer will be able to efficiently experiment with numerous design scenarios and quickly develop a knowledge of which design parameters drive manufacturing cell efficiency and consequently improve business profit. The designer can then optimize the manufacturing cell design with respect to NPV which in turn optimizes the design form a business perspective.

When performing a preliminary design for a manufacturing cell, a designer should not forego using the MCDT on the grounds that only rough operational and financial data is available. In this situation a "Level #1" analysis can be conducted. As discussed in section 3.2, the output from a "Level #1" analysis is not useful in itself. However, its value on a relative basis, when comparing results to other iterations of the same analysis, is very useful. By comparing these results versus the input parameters and manufacturing cell configurations that were employed, the designer can quickly determine which design parameters have the greatest leverage for improving manufacturing cell performance.

The most important component of the MCDT is the design engineer. The basic intention of the MCDT is to enhance the skills of the designer and thereby allow the designer to perform his/her job better. In this way, the value of the design tool to the organization is increased by the skills of the designer. Using the tool in this way also increases the likelihood of it being utilized on a continual basis, both now and in the future. This is because the designer will continue to be responsible for the design. The MCDT aids the designer in developing an efficient/profitable design in a timely manner. By incorporating the tool into an organization in this way, the tool will not be viewed as a replacement for the design engineer, instead, the design engineer will use and improve the tool over time as the needs of the organization change.

Appendix #1

MCDT Data Entry and Execution Flow Chart



Appendix 2

Default Parameters

	Level #1	Level #2	Level #3
1	Changeover Operational Scale Factor	Same As Level #1	Same As Level #1 & #2
2	Number Shifts Worked per Week	Same As Level #1	Same As Level #1 & #2
3	Number of Weekss Worked per Year	Same As Level #1	Same As Level #1 & #2
4	Number of Hours Worked per Shifts Minus Shift Change and General Maintainence	Same As Level #1	Same As Level #1 & #2
5	Number Changeovers per Year	Same As Level #1	Same As Level #1 & #2
6	Average Time for Changeover	Same As Level #1	Same As Level #1 & #2
7	Time After Changeover to Obtain Steady State (SS) Operation	Same As Level #1	Same As Level #1 & #2
8	Fixed Burden for Last Year	Same As Level #1	**Not a Default**
9	Income Tax Rate	Same As Level #1	Same As Level #1 & #2
10	Product Margin	**Not Relevant for Level #2**	**Not Relevant for Level #3**
11	Margin Percent Increase per Year	Same As Level #1	Same As Level #1 & #2
12	Burden Percent Increase per Year	Same As Level #1	Same As Level #1 & #2
13		Sell Price of Catheter	Same As Level #2
14		Cost of Follow on Operations	Same As Level #2

Appendix 3

Operational Data Entry File

Steady State & Changeover Data

Work-Station Number		Description	Cycle Time (sec)	Material Value of Assembly ($)	Steady State MTTF (sec)	Steady State MCTF	Steady State MTTR (sec)	Steady State MCTR	Steady State Scrap Rate (%)	Change-Over MTTF (sec)	Change-Over MCTF	Change-Over MTTR (sec)	Change-Over MCTR	Change-Over Scrap Rate (%)
1			##.#	##.##	#####	#####	####	####	#.##%	#####	#####	####	####	#.##%
2			##.#	##.##	#####	#####	####	####	#.##%	#####	#####	####	####	#.##%
3			##.#	##.##	#####	#####	####	####	#.##%	#####	#####	####	####	#.##%
4			##.#	##.##	#####	#####	####	####	#.##%	#####	#####	####	####	#.##%
5			##.#	##.##	#####	#####	####	####	#.##%	#####	#####	####	####	#.##%
6			##.#	##.##	#####	#####	####	####	#.##%	#####	#####	####	####	#.##%

Appendix 4

Financial and Scheduling Data Entry

	Level #1	Level #2	Level #3
Required Data Entry			
1	Maximum Payback Period	**Not Relevant for Level #2**	**Not Relevant for Level #3**
2		Corporate Loan Payback Period	Same As Level #2
3		Manufacturing Cell Accounting Life	Same As Level #2
4			Fixed Burden for Last Year
5			Inflationary Interst Rate
6			Corporate Cost of Capital
Default Options			
1	Changeover Operational Scale Factor	Same As Level #1	Same As Level #1 & #2
2	Number Shifts Worked per Week	Same As Level #1	Same As Level #1 & #2
3	Number of Weeks Worked per Year	Same As Level #1	Same As Level #1 & #2
4	Number of Hours Worked per Shift Minus Shift Change and General Maintainence	Same As Level #1	Same As Level #1 & #2
5	Number Changeovers per Year	Same As Level #1	Same As Level #1 & #2
6	Average Time for Changeover	Same As Level #1	Same As Level #1 & #2
7	Time After Changeover to Obtain Steady State (SS) Operation	Same As Level #1	Same As Level #1 & #2
8	Fixed Burden for Last Year	Same As Level #1	**Not a Default**
9	Income Tax Rate	Same As Level #1	Same As Level #1 & #2
10	Product Margin	**Not Relevant for Level #2**	**Not Relevant for Level #3**
11	Margin Percent Increase per Year	Same As Level #1	Same As Level #1 & #2
12	Burden Percent Increase per Year	Same As Level #1	Same As Level #1 & #2
13		Sell Price of Catheter	Same As Level #2
14		Cost of Follow on Operations	Same As Level #2

Appendix 5

Sales Demand Per Year ($ Million)

Year	Amount (Million)
1995	0
1996	0
1997	0
1998	0
*	
*	
*	

Note:

1) For demand limited production, simply enter demand values for each year
2) For capacity limited production, the MCDT will arbitrarily choose an unobtainable demand for each year.

Appendix 6

Product Profit Margin vs. Year ($)

Year	Amount
1995	12.94
1996	13.58
1997	14.26
1998	14.98
*	
*	
*	

Note:

1) The initial product margin values are calculated by the MCDT.
2) To alter values, simply enter a new value.

Appendix 7

Fixed Burden vs. Year ($ Million)					
	Year	**Amount**			
	1995	4.40			
	1996	4.84			
	1997	5.32			
	1998	5.86			
	*				
	*				
	*				
	Note:				
	1) The initial burden values are calculated by the MCDT.				
	2) To alter values, simply enter a new value.				

Appendix 8

Output: Loop #1

Number of Machine Groups	5	(for example)
Capital Cost	###	
Install. Cost	###	
Startup Costs	###	
First Workstation in Each Machine Group	1, 9, 16, 22, 29	(for example)

Machine Group Efficiencies and Average Buffer Level (## %, ##)

	Iterations									
Group #	1		2		3		4		5	
1	## %	##	## %	##	## %	##	## %	##	## %	##
2	## %	##	## %	##	## %	##	## %	##	## %	##
3	## %	##	## %	##	## %	##	## %	##	## %	##
4	## %	##	## %	##	## %	##	## %	##	## %	##
5	## %	##	## %	##	## %	##	## %	##	## %	##
T-put/Shft	###		###		###		###		###	
Financial Output										
Payback	##		##		##		##		##	
IRR	##		##		##		##		##	
NPV	##		##		##		##		##	

Output: Loop #2

Number of Machine Groups	4	(for example)
Capital Cost	###	
Install. Cost	###	
Startup Costs	###	
First Workstation in Each Machine Group	1, 12, 26, 35	(for example)

Machine Group Efficiencies and Average Buffer Level (## %, ##)

	Iterations									
Group #	1		2		3		4		5	
1	## %	##	## %	##	## %	##	## %	##	## %	##
2	## %	##	## %	##	## %	##	## %	##	## %	##
3	## %	##	## %	##	## %	##	## %	##	## %	##
4	## %	##	## %	##	## %	##	## %	##	## %	##
T-put/Shft	###		###		###		###		###	
Financial Output										
Payback	##		##		##		##		##	
IRR	##		##		##		##		##	
NPV	##		##		##		##		##	

Appendix 9

		1995	1996	1997	1998
Income Generated					
	Net Income	19.88	20.88	21.92	23.02
	Depreciation	-0.85	-1.70	-1.70	-1.70
	Burden	-4.40	-4.84	-5.32	-5.86
	Startup Costs	-4.00			
	sum	10.63	14.34	14.90	15.46
	less tax	-4.15	-5.59	-5.81	-6.03
	Income after tax	6.49	8.75	9.09	9.43
Cash outlay for Equip.		-7.20	0.00	0.00	0.00
Payback for Equip					
	NPV calculation	-4.45	-4.45	0.00	0.00
	IRR calculation	-10.48	-10.48	0.00	0.00
Payback					
	Cash pos. end of yr	0.14	10.45	10.79	11.13
	Cumulative cash position	0.14	10.58	21.37	32.50
	Payback Period (Yrs)	1.02			
NPV					
	Cash pos. end of yr	2.89	6.00	10.79	11.13
	Cumulative cash position	2.89	8.88	19.67	30.80
	NPV of cash flows	2.75	5.44	9.32	9.16
	NPV	26.66			
IRR					
	IRR	123.25%			

Appendix 10A

Model Car Transfer Assembly Line							Issolated	Material	Issolate
Work-Station Number	Description	Cycle Time (sec)	MTTF (sec)	MTTR (sec)	MCTF	MCTR	Station Scrap Rat (%)	Value of Assembly ($)	Station efficiency (%)
1	Blow-off Fixture	13	10000	30	769.2	2.3	0.0	0.00	99.70%
2	Inspect Fixture	13	150000	200	11538.5	15.4	0.0	0.00	99.87%
3	Mold Frame	13	3000	120	230.8	9.2	0.0	0.20	96.15%
4	Transfer Frame	13	3000	60	230.8	4.6	1.5	0.20	98.04%
5	Inspect Frame	13	50000	200	3846.2	15.4	0.5	0.20	99.60%
6	Attach Rear Wheel Mounts	13	6000	40	461.5	3.1	1.0	0.25	99.34%
7	Attach Front Wheel Mounts	13	12000	40	923.1	3.1	0.5	0.30	99.67%
8	Inspect Wheel Mounts	13	50000	200	3846.2	15.4	0.0	0.30	99.60%
9	Rear Wheel Feeder System	13	5000	100	384.6	7.7	0.0	0.30	98.04%
10	Install Rear Wheel Assembly	13	10000	60	769.2	4.6	1.2	0.40	99.40%
11	Inspect Rear Wheel Assembly	13	50000	200	3846.2	15.4	0.0	0.40	99.60%
12	Steering Bar Feeder System	13	5000	40	384.6	3.1	0.0	0.40	99.21%
13	Steering Bar Assembly	13	5000	50	384.6	3.8	1.1	0.45	99.01%
14	Inspect Steering Bar	13	50000	100	3846.2	7.7	0.0	0.45	99.80%
15	Front Right Wheel Feeder System	13	10000	90	769.2	6.9	0.0	0.45	99.11%
16	Install Front Right Wheel	13	5000	90	384.6	6.9	1.0	0.50	98.23%
17	Inspect Front Right Wheel	13	50000	150	3846.2	11.5	0.0	0.50	99.70%
18	Front Left Wheel Feeder System	13	10000	90	769.2	6.9	0.0	0.50	99.11%
19	Install Front Left Wheel	13	5000	90	384.6	6.9	1.0	0.55	98.23%
20	Inspect Front Left Wheel	13	50000	150	3846.2	11.5	0.0	0.55	99.70%
21	Steering Motor Feeder System	13	5000	60	384.6	4.6	0.0	0.55	98.81%
22	Install Steering Motor	13	7000	100	538.5	7.7	0.6	0.90	98.59%
23	Inspect Steering Motor Assembly	13	30000	200	2307.7	15.4	0.2	0.90	99.34%
24	Drive Motor Assembly System	unknown	unknown	unknown	unknown	unknown	unknown	unknown	unknown
25	Install Drive Motor	13	5000	120	384.6	9.2	0.5	1.90	97.66%
26	Inspect Drive Motor Assembly	13	50000	50	3846.2	3.8	0.0	1.90	99.90%
27	Radio Control Feeder System	13	40000	200	3076.9	15.4	0.0	1.90	99.50%
28	Install Radio Control	13	8000	90	615.4	6.9	0.5	2.90	98.89%
	Discharge Defective Assemblies	10	50000	90	5000.0	9.0	0.0	2.90	99.82%
	Buffer => capacity of 10								
	Unload Assembly form Buffer	10	25000	40	2500.0	4.0	0.0	3.00	99.84%
29*	Solder RC Wires to Steering Motor	30	30000	1800	1000.0	60.0	0.5	2.95	94.34%
30*	Inspect Wire Attachment	30	50000	200	1666.7	6.7	0.0	2.95	99.60%
31*	Solder RC Wires to Drive Motor	30	30000	1800	1000.0	60.0	0.5	3.00	94.34%
32*	Inspect Wire Attachment	30	50000	200	1666.7	6.7	0.0	3.00	99.60%
	Discharge Defective Assemblies	10	50000	90	5000.0	9.0	0.0	3.00	99.82%
	Buffer => capacity of 10								
	Unload Assembly form Buffer	10	25000	40	2500.0	4.0	0.0	3.00	99.84%
33	Rear Seat Feeder System	15	8000	90	533.3	6.0	0.0	3.00	98.89%
34	Install Rear Seat	15	12000	90	800.0	6.0	0.6	3.10	99.26%
35	Inspect Rear Seat	15	50000	200	3333.3	13.3	0.2	3.10	99.60%
36	Front Seat Feeders System	15	8000	90	533.3	6.0	0.0	3.10	98.89%
37	Install Front Seat	15	12000	90	800.0	6.0	0.5	3.20	99.26%
38	Inspect Front Seat	15	50000	200	3333.3	13.3	0.1	3.20	99.60%
39	Car Shell Feeder System	15	4000	120	266.7	8.0	0.0	3.20	97.09%
40	Install Car Shell	15	8000	70	533.3	4.7	0.5	3.40	99.13%
41	Attachment Screw #1 Feeder System	15	20000	30	1333.3	2.0	0.0	3.40	99.85%
42	Transfer and Tighten Screw	15	10000	60	666.7	4.0	0.0	3.42	99.40%
43	Attachment Screw #2 Feeder System	15	20000	30	1333.3	2.0	0.0	3.42	99.85%
44	Transfer and Tighten Screw	15	10000	60	666.7	4.0	0.0	3.44	99.40%
45	Inspect Car Shell Installation	15	75000	175	5000.0	11.7	1.0	3.44	99.77%
46	Clean	15	50000	300	3333.3	20.0	0.0	3.44	99.40%
47	Apply Decal #1	15	20000	150	1333.3	10.0	0.0	3.45	99.26%
48	Apply Decal #2	15	20000	150	1333.3	10.0	0.0	3.46	99.26%
49	Apply Decal #3	15	20000	150	1333.3	10.0	0.0	3.47	99.26%
50	Apply Decal #4	15	20000	150	1333.3	10.0	0.0	3.48	99.26%
51	Final Inspection	15	30000	200	2000.0	13.3	0.0	3.48	99.34%
52	Discharge Good Cars	15	50000	150	3333.3	10.0	0.0	3.48	99.70%
53	Discharge Defective Cars	15	50000	150	3333.3	10.0	0.0	3.48	99.70%
54	Inspect Empty Pallet	15	50000	150	3333.3	10.0	0.0	3.48	99.70%

Note:

1) Workstations 29, 30, 31 & 32 have three identical lines operating in parallel

2) Total labor for car assembly less subassemblies = $1.00

Appendix 10B

Drive Motor Sub Assembly System

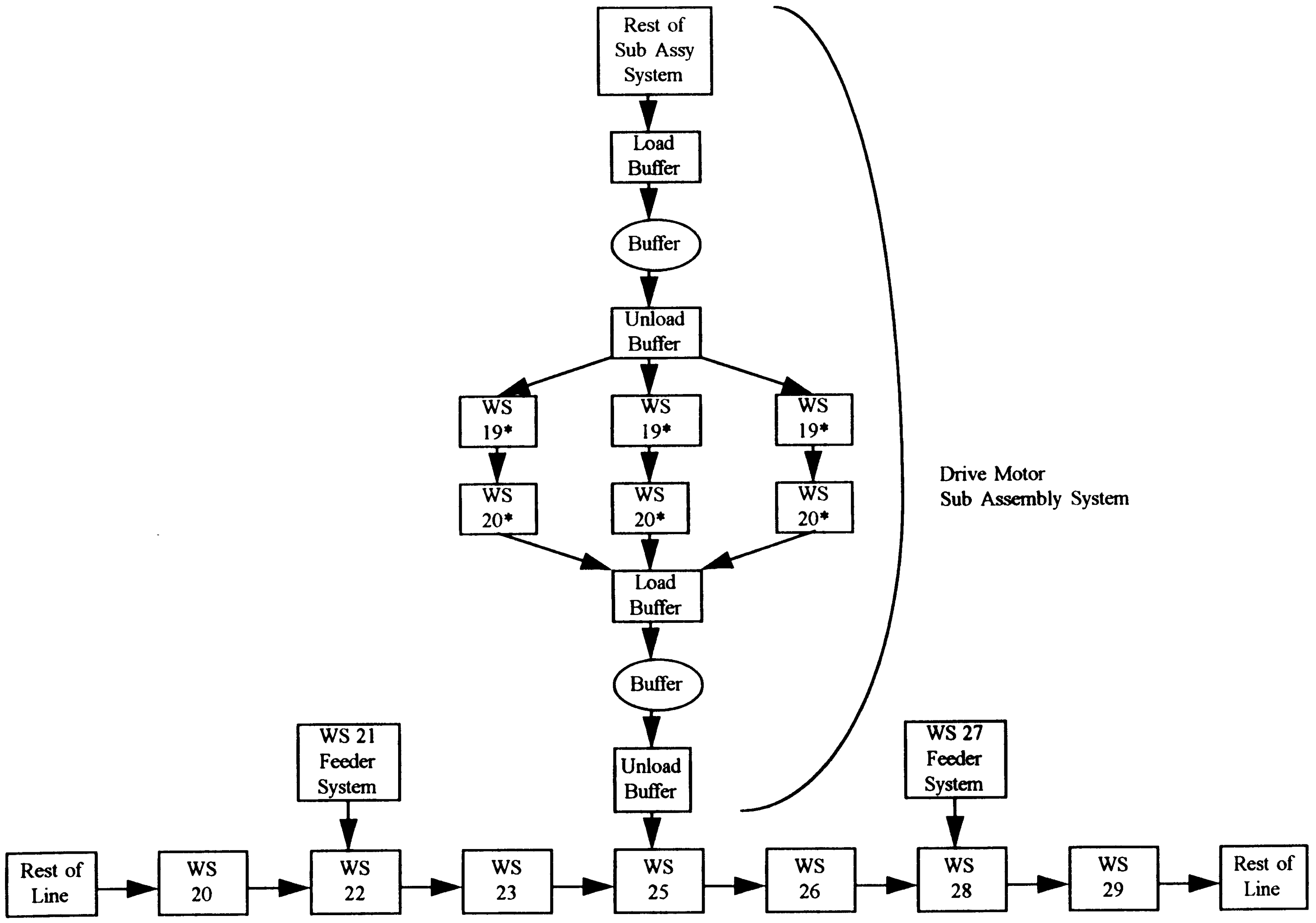
What was actually Analyzed

Work-Station Number	Description	Cycle Time (sec)	MTTF	MTTR	MCTF	MCTR	Station Scrap Rate %	Value of Assembly $	Issolate Station efficiency
1 SA	Inspect Pallet	11	20000	100	1818.2	9.1	0.0	0.00	99.50%
2 SA	Housing Feeder System	11	5000	100	454.5	9.1	0.0	0.00	98.04%
3 SA	Transfer Housing	11	5000	60	454.5	5.5	1.0	0.05	98.81%
4 SA	Inspect Housing	11	150000	1000	13636.4	90.9	0.5	0.05	99.34%
5 SA	Armature Feeder System	11	10000	150	909.1	13.6	0.0	0.05	98.52%
6 SA	Install Armature	11	20000	100	1818.2	9.1	2.0	0.25	99.50%
7 SA	Inspect	11	50000	200	4545.5	18.2	0.5	0.25	99.60%
8 SA	Left Endcap Feeder System	13	5000	60	384.6	4.6	0.0	0.25	98.81%
9 SA	Install Left Endcap	13	10000	100	769.2	7.7	1.0	0.30	99.01%
10 SA	Right Endcap Feeder System	13	50000	60	3846.2	4.6	0.0	0.30	99.88%
11 SA	Install Right Endcap	13	15000	100	1153.8	7.7	1.0	0.35	99.34%
12 SA	Inspect Endcaps	13	50000	200	3846.2	15.4	0.5	0.35	99.60%
13 SA	Casing Feeder System	13	6000	50	461.5	3.8	0.0	0.35	99.17%
14 SA	Install Casing	13	8000	80	615.4	6.2	2.0	0.40	99.01%
15 SA	Inspect Casing	13	150000	200	11538.5	15.4	0.5	0.40	99.87%
16 SA	Power Pack Feeder System	13	30000	150	2307.7	11.5	0.0	0.40	99.50%
17 SA	Install Power Pack	13	10000	60	769.2	4.6	2.5	0.65	99.40%
18 SA	Inspect Power Pack Installation	13	50000	200	3846.2	15.4	0.5	0.65	99.60%
	Discharge Defective Assemblies	10	50000	90	5000.0	9.0	0.0	0.65	99.82%
	Buffer => capacity of 10								
	Unload Assembly form Buffer	10	25000	40	2500.0	4.0	0.0	0.25	99.84%
19* SA	Solder Power Pack Wires to Motor	30	30000	1800	1000.0	60.0	0.5	0.70	94.34%
20* SA	Inspect Wire Attachment	30	100000	200	3333.3	6.7	0.0	0.70	99.80%
	Discharge Defective Assemblies	10	50000	90	5000.0	9.0	0.0	0.70	99.82%
	Buffer => capacity of 10								
	Unload Assembly form Buffer	10	25000	40	2500.0	4.0	0.0	0.25	99.84%

Note:

1) Workstations 19 & 20 have three identical lines operating in parallel
2) Total Labor for subassembly = $0.20
3) SA indicates Sub Assembly operation.

Appendix #11


Rest of
Sub Assy
System
Load
Buffer
Buffer
Unload
Buffer
WS
19*
WS
19*
WS
19*
WS
20*
WS
20*
WS
20*
Load
Buffer
Buffer
Unload
Buffer
Drive Motor
Sub Assembly System
WS 21
Feeder
System
WS 27
Feeder
System
Rest of
Line
WS
20
WS
22
WS
23
WS
25
WS
26
WS
28
WS
29
Rest of
Line

Appendix 12

Drive Motor Sub Assembly System

Changeover Scale Factor Used = 1.5

Work-Station Number	Description	MTTF	MTTR	Steady State p	Steady State r	Steady State representive r	Change over p	Change over r	Change over representive r
1 SA	Inspect Pallet	20000	100	0.00005	0.01000	0.000194	0.00008	0.01000	0.000194
2 SA	Housing Feeder System	5000	100	0.00020	0.01000	0.000777	0.00030	0.01000	0.000777
3 SA	Transfer Housing	5000	60	0.00020	0.01667	0.001295	0.00030	0.01667	0.001295
4 SA	Inspect Housing	150000	1000	0.00001	0.00100	0.000003	0.00001	0.00100	0.000003
5 SA	Armature Feeder System	10000	150	0.00010	0.00667	0.000259	0.00015	0.00667	0.000259
6 SA	Install Armature	20000	100	0.00005	0.01000	0.000194	0.00008	0.01000	0.000194
7 SA	Inspect	50000	200	0.00002	0.00500	0.000039	0.00003	0.00500	0.000039
8 SA	Left Endcap Feeder System	5000	60	0.00020	0.01667	0.001295	0.00030	0.01667	0.001295
9 SA	Install Left Endcap	10000	100	0.00010	0.01000	0.000388	0.00015	0.01000	0.000388
10 SA	Right Endcap feeder System	50000	60	0.00002	0.01667	0.000129	0.00003	0.01667	0.000129
11 SA	Install Right Endcap	15000	100	0.00007	0.01000	0.000259	0.00010	0.01000	0.000259
12 SA	Inspect Endcaps	50000	200	0.00002	0.00500	0.000039	0.00003	0.00500	0.000039
13 SA	Casing Feeder System	6000	50	0.00017	0.02000	0.001295	0.00025	0.02000	0.001295
14 SA	Install Casing	8000	80	0.00013	0.01250	0.000607	0.00019	0.01250	0.000607
15 SA	Inspect Casing	150000	200	0.00001	0.00500	0.000013	0.00001	0.00500	0.000013
16 SA	Power Pack Feeder System	30000	150	0.00003	0.00667	0.000086	0.00005	0.00667	0.000086
17 SA	Install Power Pack	10000	60	0.00010	0.01667	0.000647	0.00015	0.01667	0.000647
18 SA	Inspect Power Pack Installation	50000	200	0.00002	0.00500	0.000039	0.00003	0.00500	0.000039
	Discharge Defective Assemblies	50000	90	0.00002	0.01111	0.000086	0.00003	0.01111	0.000086
	Unload Assembly form Buffer	25000	40	0.00004	0.02500	0.000388	0.00006	0.02500	0.000388
19* to 20*	Aggregated Solder and Inspect	1300	100	0.00077	0.01000	0.002988	0.00115	0.01000	0.002988
	Discharge Defective Assemblies	50000	90	0.00002	0.01111	0.000086	0.00003	0.01111	0.000086
	Unload Assembly form Buffer	25000	40	0.00004	0.02500	0.000388	0.00006	0.02500	0.000388
25	Install Drive Motor	5000	120	0.00020	0.00833	0.000647	0.00030	0.00833	0.000647
			sum =	0.00257		0.012144	0.00386		0.012144

How to alter the main assembly transfer line

1) There will be no "Drive Motor Assembly System" (Oper. #24) from the original assembly system

2) Workstation "Install Drive Motor" (Oper. #25) will be replaced by the aggregated assembly system

3) Operational parameters for this aggregated operation are given below

4) Material value of part at aggregated station = value given by Manufacturing Cell Design Tool or calculated per section 3.51.

5) Scrap rate for the aggregated station is zero

6) Cycle time for the aggregated assembly system will be the slowest effective cycle time of the subassembly system.
This value is obtained form sheet #2 of the Manufacturing Cell Design Tool output.
Some slight errors start to occur at this point, because the effective cycle time after changeover will be greater due to increase scrap; however, only one cycle time can be entered for the aggregated subassembly operation.

88.67% Steady State Line Efficiency from **sheet #2 of Manufacturing Cell Design Tool output**

81.75% Changeover Line Efficiency from **sheet #5 of Manufacturing Cell Design Tool output**

Steady State Aggregated Assembly System Operational Parameters:

r= 0.012144 MTTR= 82

p= 0.001552 MTTF= 644

Changeover Aggregated Assembly System Operational Parameters:

r= 0.01214 MTTR= 82

p= 0.002711 MTTF= 369

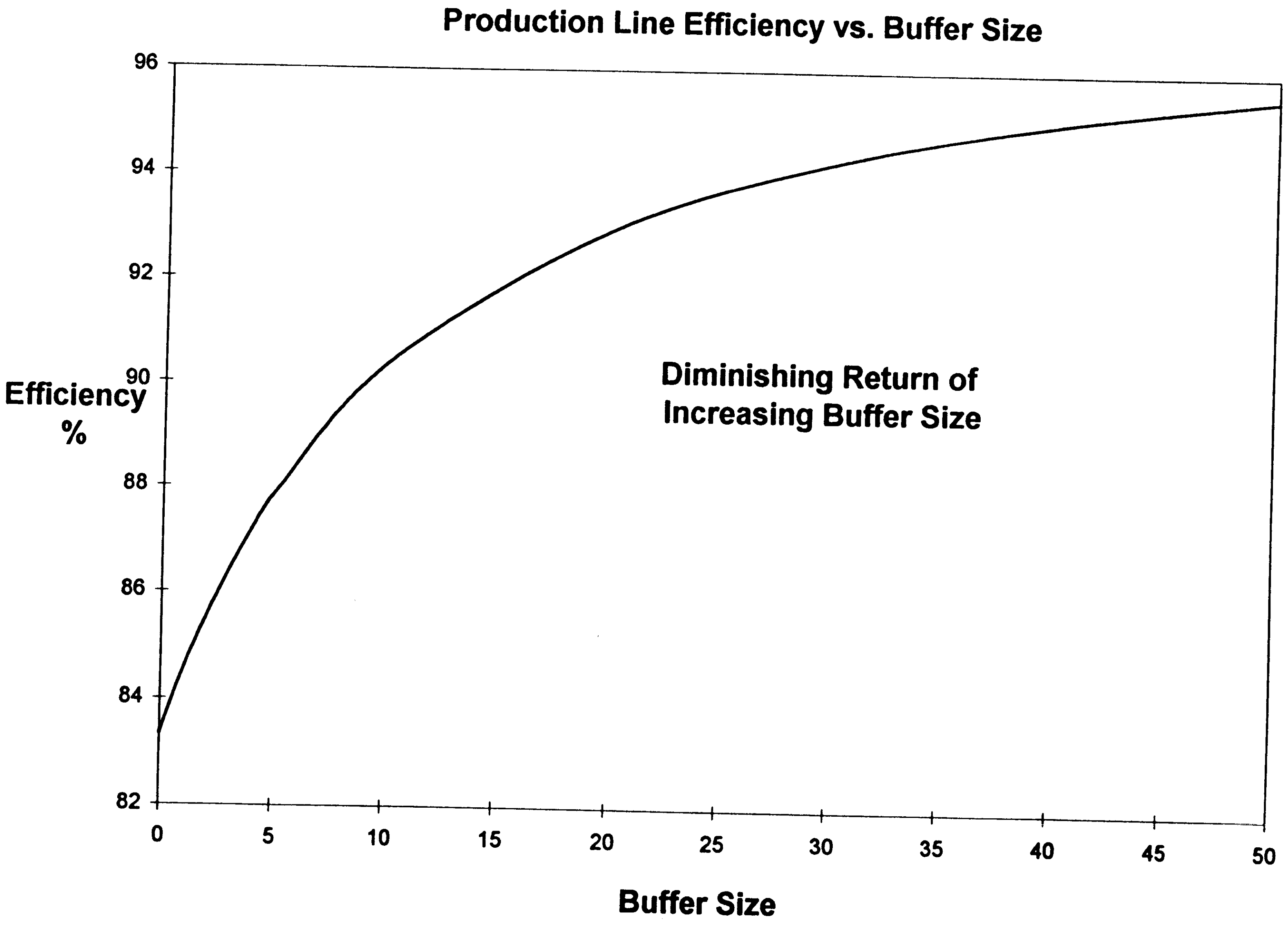
Note:

If a scale factor was not used to estimate changeover performace, the aggregated r value for the period after changeover would have been different from the steady state value.

Appendix 13

Model Car Manufacturing Cell With Aggregated Subassemblyy										
Work- Station Number		Description	Cycle Time (sec	MTTF (sec)	MTTR (sec)	MCTF	MCTR	Issolated Station Scrap Rat (%)	Material Value of Assembly ($)	Issolate Station efficiency (%)
1		Blow-off Fixture	13	10000	30	769.2	2.3	0.0	0.00	99.70%
2		Inspect Fixture	13	150000	200	11538.5	15.4	0.0	0.00	99.87%
3		Mold Frame	13	3000	120	230.8	9.2	0.0	0.20	96.15%
4		Transfer Frame	13	3000	60	230.8	4.6	1.5	0.20	98.04%
5		Inspect Frame	13	50000	200	3846.2	15.4	0.5	0.20	99.60%
6		Attach Rear Wheel Mounts	13	6000	40	461.5	3.1	1.0	0.25	99.34%
7		Attach Front Wheel Mounts	13	12000	40	923.1	3.1	0.5	0.30	99.67%
8		Inspect Wheel Mounts	13	50000	200	3846.2	15.4	0.0	0.30	99.60%
9		Rear Wheel Feeder System	13	5000	100	384.6	7.7	0.0	0.30	98.04%
10		Install Rear Wheel Assembly	13	10000	60	769.2	4.6	1.2	0.40	99.40%
11		Inspect Rear Wheel Assembly	13	50000	200	3846.2	15.4	0.0	0.40	99.60%
12		Steering Bar Feeder System	13	5000	40	384.6	3.1	0.0	0.40	99.21%
13		Steering Bar Assembly	13	5000	50	384.6	3.8	1.1	0.45	99.01%
14		Inspect Steering Bar	13	50000	100	3846.2	7.7	0.0	0.45	99.80%
15		Front Right Wheel Feeder System	13	10000	90	769.2	6.9	0.0	0.45	99.11%
16		Install Front Right Wheel	13	5000	90	384.6	6.9	1.0	0.50	98.23%
17		Inspect Front Right Wheel	13	50000	150	3846.2	11.5	0.0	0.50	99.70%
18		Front Left Wheel Feeder System	13	10000	90	769.2	6.9	0.0	0.50	99.11%
19		Install Front Left Wheel	13	5000	90	384.6	6.9	1.0	0.55	98.23%
20		Inspect Front Left Wheel	13	50000	150	3846.2	11.5	0.0	0.55	99.70%
21		Steering Motor Feeder System	13	5000	60	384.6	4.6	0.0	0.55	98.81%
22		Install Steering Motor	13	7000	100	538.5	7.7	0.6	0.90	98.59%
23		Inspect Steering Motor Assembly	13	30000	200	2307.7	15.4	0.2	0.90	99.34%
24 & 25		**Aggrigated Motor S-Assy**	14.67	644	82	43.9	5.6	0.0	1.90	88.71%
26		Inspect Drive Motor Assembly	13	50000	50	3846.2	3.8	0.0	1.90	99.90%
27		Radio Control Feeder System	13	40000	200	3076.9	15.4	0.0	1.90	99.50%
28		Install Radio Control	13	8000	90	615.4	6.9	0.5	2.90	98.89%
		Discharge Defective Assemblies	10	50000	90	5000.0	9.0	0.0	2.90	99.82%
		Buffer => capacity of 10								
		Unload Assembly form Buffer	10	25000	40	2500.0	4.0	0.0	3.00	99.84%
29 to 32		Aggregated Wire Solder	10	860	140	86.0	14.0	1.0	3.00	86.00%
		Discharge Defective Assemblies	10	50000	90	5000.0	9.0	0.0	3.00	99.82%
		Buffer => capacity of 10								
		Unload Assembly form Buffer	10	25000	40	2500.0	4.0	0.0	3.00	99.84%
33		Rear Seat Feeder System	15	8000	90	533.3	6.0	0.0	3.00	98.89%
34		Install Rear Seat	15	12000	90	800.0	6.0	0.6	3.10	99.26%
35		Inspect Rear Seat	15	50000	200	3333.3	13.3	0.2	3.10	99.60%
36		Front Seat Feeders System	15	8000	90	533.3	6.0	0.0	3.10	98.89%
37		Install Front Seat	15	12000	90	800.0	6.0	0.5	3.20	99.26%
38		Inspect Front Seat	15	50000	200	3333.3	13.3	0.1	3.20	99.60%
39		Car Shell Feeder System	15	4000	120	266.7	8.0	0.0	3.20	97.09%
40		Install Car Shell	15	8000	70	533.3	4.7	0.5	3.40	99.13%
41		Attachment Screw #1 Feeder System	15	20000	30	1333.3	2.0	0.0	3.40	99.85%
42		Transfer and Tighten Screw	15	10000	60	666.7	4.0	0.0	3.42	99.40%
43		Attachment Screw #2 Feeder System	15	20000	30	1333.3	2.0	0.0	3.42	99.85%
44		Transfer and Tighten Screw	15	10000	60	666.7	4.0	0.0	3.44	99.40%
45		Inspect Car Shell Installation	15	75000	175	5000.0	11.7	1.0	3.44	99.77%
46		Clean	15	50000	300	3333.3	20.0	0.0	3.44	99.40%
47		Apply Decal #1	15	20000	150	1333.3	10.0	0.0	3.45	99.26%
48		Apply Decal #2	15	20000	150	1333.3	10.0	0.0	3.46	99.26%
49		Apply Decal #3	15	20000	150	1333.3	10.0	0.0	3.47	99.26%
50		Apply Decal #4	15	20000	150	1333.3	10.0	0.0	3.48	99.26%
51		Final Inspection	15	30000	200	2000.0	13.3	0.0	3.48	99.34%
52		Discharge Good Cars (not generic)	15	50000	150	3333.3	10.0	0.0	3.48	99.70%
53		Discharge Defective Cars	15	50000	150	3333.3	10.0	0.0	3.48	99.70%
54		Inspect Empty Pallet	15	50000	150	3333.3	10.0	0.0	3.48	99.70%

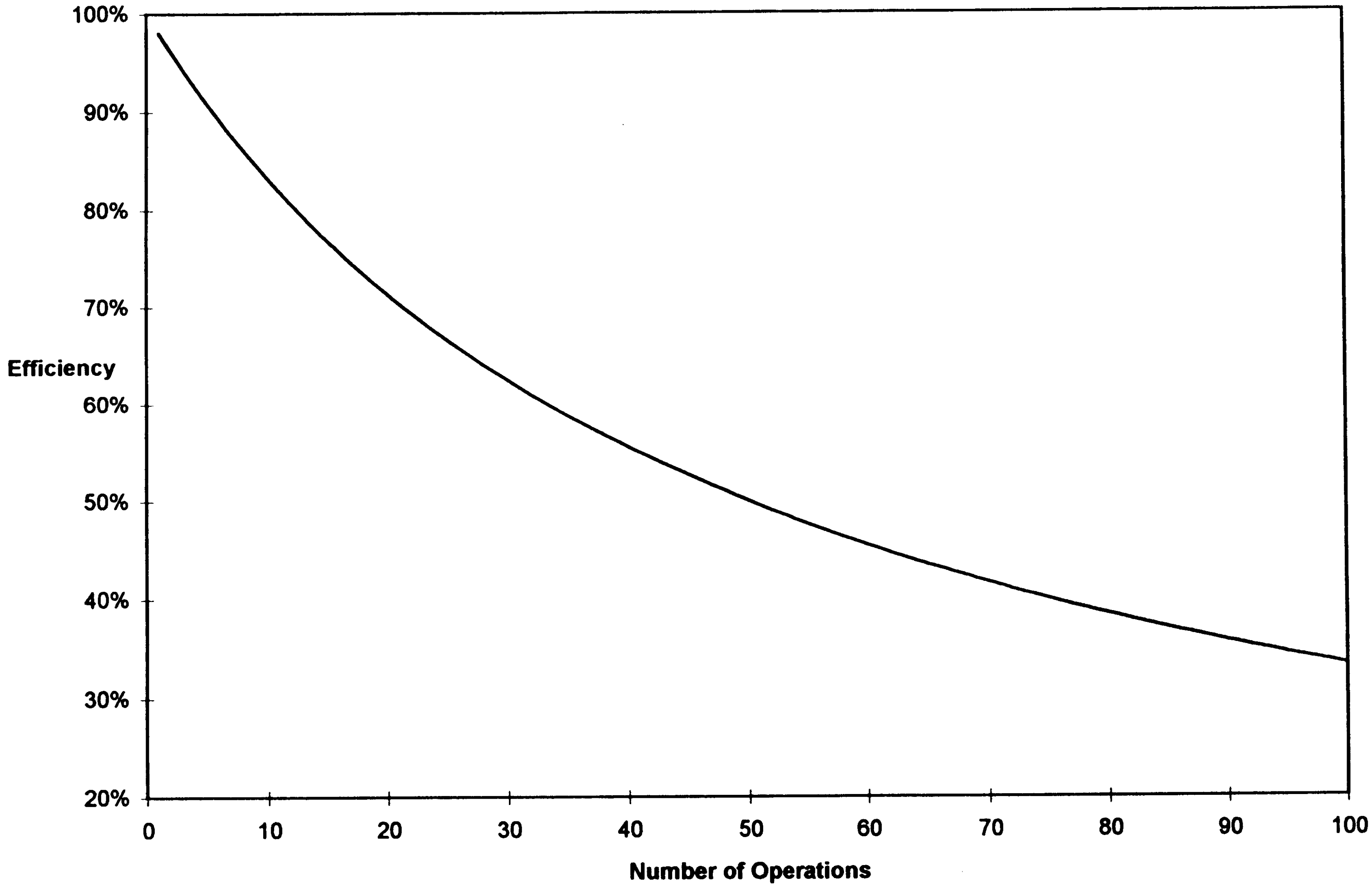
Appendix 14



Production Line Efficiency vs. Buffer Size

Appendix 15

Line Efficiency vs. Number of Workstations



Appendix 16

Manufacturing Cell Design Tool	
Financial and Operational Default Parameters	
Shifts worked per week:	20.00
Weeks worked per year:	50.00
Hours worked per shift minus shift change and general maintenance:	7.50
Changeovers per year:	100.00
Average time to perform changeover (Hrs.):	0.50
Changeover operational scale factor:	1.50
Time to obtain steady state after changeover (Hrs.):	2.00
Fixed burden for last year ($MM):	4.00
Income tax rate:	39%
Product Margin ($):	7.50
Projected product margin increase per year:	5%
Projected burden increase per year:	10%

Appendix 17

Loop Process #	**1**			
Number of Machine Groups				**3**
Equipment Cost, MM				**6.0**
Install. Cost, MM				**0.4**
Startup Costs, MM				**4.0**
First Workstation in Each Machine Group				**1, 29, 33**
Data format: Buffer size, Actual cycle time				
	Iterations			
Group #	1			
1	10	14.67		
2	10	10		
3	0	15		
T-put/shift	1213.88			
Payback	1.236			
IRR	0.963576			
NPV	17.68008			

Appendix 18

Loop Process #		**1**			
Number of Machine Groups				**3**	
Equipment Cost, MM				**6.0**	
Install. Cost, MM				**0.4**	
Startup Costs, MM				**4.0**	
First Workstation in Each Machine Group				**1, 29, 33**	
Data format: Machine group efficiency, Average buffer level					
	Iterations				
Group #	1				
1	72.90%	0.94			
2	85.75%	2.70			
3	86.59%				
T-put/shift	1213.88				
Payback	1.236				
IRR	0.963576				
NPV	17.68008				

Appendix 19

		1995	1996	1997	1998
Income Generated					
	Net Income	15.70	16.49	17.31	18.18
	Depreciation	-0.75	-1.50	-1.50	-1.50
	Burden	-4.40	-4.84	-5.32	-5.86
	Startup Costs	-4.00			
	sum	6.55	10.15	10.49	10.82
	less tax	-2.56	-3.96	-4.09	-4.22
	Income after tax	4.00	6.19	6.40	6.60
Cash outlay for Equip.		-6.40	0.00	0.00	0.00
Payback for Equip					
	NPV calculation	-3.93	-3.93	0.00	0.00
	IRR calculation	-7.81	-7.81	0.00	0.00
Payback					
	Cash pos. end of yr	-1.65	7.69	7.90	8.10
	Cumulative cash position	-1.65	6.04	13.93	22.04
	Payback Period (Yrs)	1.24			
NPV					
	Cash pos. end of yr	0.82	3.76	7.90	8.10
	Cumulative cash position	0.82	4.58	12.48	20.58
	NPV of cash flows	0.78	3.41	6.82	6.66
	NPV	17.68			
IRR					
	IRR	96.38%			

Appendix 20

Drive Motor Sub Assembly System										
	What was actually Analyzed									
Work-Station Number		Description	Cycle Time (sec)	MTTF	MTTR	MCTF	MCTR	Station Scrap Rate %	Value of Assembly $	Issolate Station efficiency
1 SA		Inspect Pallet	11	20000	100	1818.2	9.1	0.0	0.00	99.50%
2 SA		Housing Feeder System	11	5000	100	454.5	9.1	0.0	0.00	98.04%
3 SA		Transfer Housing	11	5000	60	454.5	5.5	1.0	0.05	98.81%
4 SA		Inspect Housing	11	150000	1000	13636.4	90.9	0.5	0.05	99.34%
5 SA		Armature Feeder System	11	10000	150	909.1	13.6	0.0	0.05	98.52%
6 SA		Install Armature	11	20000	100	1818.2	9.1	2.0	0.25	99.50%
7 SA		Inspect	11	50000	200	4545.5	18.2	0.5	0.25	99.60%
8 SA		Left Endcap Feeder System	13	5000	60	384.6	4.6	0.0	0.25	98.81%
9 SA		Install Left Endcap	13	10000	100	769.2	7.7	1.0	0.30	99.01%
10 SA		Right Endcap Feeder System	13	50000	60	3846.2	4.6	0.0	0.30	99.88%
11 SA		Install Right Endcap	13	15000	100	1153.8	7.7	1.0	0.35	99.34%
		Discharge Defective Assemblies	10	50000	90	5000.0	9.0	0.0	0.65	99.82%
		Buffer => capacity of 25								
		Unload Assembly form Buffer	10	25000	40	2500.0	4.0	0.0	0.25	99.84%
12 SA		Inspect Endcaps	13	50000	200	3846.2	15.4	0.5	0.35	99.60%
13 SA		Casing Feeder System	13	6000	50	461.5	3.8	0.0	0.35	99.17%
14 SA		Install Casing	13	8000	80	615.4	6.2	2.0	0.40	99.01%
15 SA		Inspect Casing	13	150000	200	11538.5	15.4	0.5	0.40	99.87%
16 SA		Power Pack Feeder System	13	30000	150	2307.7	11.5	0.0	0.40	99.50%
17 SA		Install Power Pack	13	10000	60	769.2	4.6	2.5	0.65	99.40%
18 SA		Inspect Power Pack Installation	13	50000	200	3846.2	15.4	0.5	0.65	99.60%
		Discharge Defective Assemblies	10	50000	90	5000.0	9.0	0.0	0.65	99.82%
		Buffer => capacity of 10								
		Unload Assembly form Buffer	10	25000	40	2500.0	4.0	0.0	0.25	99.84%
19* SA		Solder Power Pack Wires to Motor	30	30000	1800	1000.0	60.0	0.5	0.70	94.34%
20* SA		Inspect Wire Attachment	30	100000	200	3333.3	6.7	0.0	0.70	99.80%
		Discharge Defective Assemblies	10	50000	90	5000.0	9.0	0.0	0.70	99.82%
		Buffer => capacity of 10								
		Unload Assembly form Buffer	10	25000	40	2500.0	4.0	0.0	0.25	99.84%
25		Install Drive Motor	13	5000	120	384.6	9.2	0.5	1.90	97.66%
	Note:									
		1) Workstations 21 & 22 have three identical lines operating in parallel								
		2) Total Labor for subassembly = $0.20								
		3) SA indicates Sub Assembly operation.								

Appendix 21

Drive Motor Sub Assembly System									
	Changeover Scale Factor Used =	1.5							
						Steady			Change
Work-				Steady	Steady	State	Change	Change	over
Station				State	State	representive	over	over	representive
Number	Description	MTTF	MTTR	p	r	r	p	r	r
1 SA	Inspect Pallet	20000	100	0.00005	0.01000	0.000190	0.00008	0.01000	0.000190
2 SA	Housing Feeder System	5000	100	0.00020	0.01000	0.000759	0.00030	0.01000	0.000759
3 SA	Transfer Housing	5000	60	0.00020	0.01667	0.001265	0.00030	0.01667	0.001265
4 SA	Inspect Housing	150000	1000	0.00001	0.00100	0.000003	0.00001	0.00100	0.000003
5 SA	Armature Feeder System	10000	150	0.00010	0.00667	0.000253	0.00015	0.00667	0.000253
6 SA	Install Armature	20000	100	0.00005	0.01000	0.000190	0.00008	0.01000	0.000190
7 SA	Inspect	50000	200	0.00002	0.00500	0.000038	0.00003	0.00500	0.000038
8 SA	Left Endcap Feeder System	5000	60	0.00020	0.01667	0.001265	0.00030	0.01667	0.001265
9 SA	Install Left Endcap	10000	100	0.00010	0.01000	0.000380	0.00015	0.01000	0.000380
10 SA	Right Endcap feeder System	50000	60	0.00002	0.01667	0.000127	0.00003	0.01667	0.000127
11 SA	Install Right Endcap	15000	100	0.00007	0.01000	0.000253	0.00010	0.01000	0.000253
	Discharge Defective Assemblies	50000	90	0.00002	0.01111	0.000084	0.00003	0.01111	0.000084
	Unload Assembly form Buffer	25000	40	0.00004	0.02500	0.000380	0.00006	0.02500	0.000380
12 SA	Inspect Endcaps	50000	200	0.00002	0.00500	0.000038	0.00003	0.00500	0.000038
13 SA	Casing Feeder System	6000	50	0.00017	0.02000	0.001265	0.00025	0.02000	0.001265
14 SA	Install Casing	8000	80	0.00013	0.01250	0.000593	0.00019	0.01250	0.000593
15 SA	Inspect Casing	150000	200	0.00001	0.00500	0.000013	0.00001	0.00500	0.000013
16 SA	Power Pack Feeder System	30000	150	0.00003	0.00667	0.000084	0.00005	0.00667	0.000084
17 SA	Install Power Pack	10000	60	0.00010	0.01667	0.000633	0.00015	0.01667	0.000633
18 SA	Inspect Power Pack Installation	50000	200	0.00002	0.00500	0.000038	0.00003	0.00500	0.000038
	Discharge Defective Assemblies	50000	90	0.00002	0.01111	0.000084	0.00003	0.01111	0.000084
	Unload Assembly form Buffer	25000	40	0.00004	0.02500	0.000380	0.00006	0.02500	0.000380
19* & 20*	Aggregated Solder and Inspect	1300	100	0.00077	0.01000	0.002920	0.00115	0.01000	0.002920
	Discharge Defective Assemblies	50000	90	0.00002	0.01111	0.000084	0.00003	0.01111	0.000084
	Unload Assembly form Buffer	25000	40	0.00004	0.02500	0.000380	0.00006	0.02500	0.000380
25	Install Drive Motor	5000	120	0.00020	0.00833	0.000633	0.00030	0.00833	0.000633
			sum =	0.00263		0.012331	0.00395		0.012331
		91.58%	Steady State Line Efficiency from **sheet #2 of Manufacturing Cell Design Tool output**						
		88.12%	Changeover Line Efficiency from **sheet #5 of Manufacturing Cell Design Tool output**						
		Steady State Aggregated Assembly System Operational Parameters:							
		r=	0.012331	MTTR=	81				
		p=	0.001135	MTTF=	881				
		Changeover Aggregated Assembly System Operational Parameters:							
		r=	0.01233	MTTR=	81				
		p=	0.001662	MTTF=	602				
		Note:							
		If a scale factor was not used to estimate changeover performace, the aggregated r value							
		for the period after changeover would have been different from the steady state value.							

Appendix 22

Model Car Manufacturing Cell With Aggregated Subassemblyy

Work-Station Number	Description	Cycle Time (sec)	MTTF (sec)	MTTR (sec)	MCTF	MCTR	Issolated Station Scrap Rat (%)	Material Value of Assembly ($)	Issolate Station efficiency (%)
1	Blow-off Fixture	13	10000	30	769.2	2.3	0.0	0.00	99.70%
2	Inspect Fixture	13	150000	200	11538.5	15.4	0.0	0.00	99.87%
3	Mold Frame	13	3000	120	230.8	9.2	0.0	0.20	96.15%
4	Transfer Frame	13	3000	60	230.8	4.6	1.5	0.20	98.04%
5	Inspect Frame	13	50000	200	3846.2	15.4	0.5	0.20	99.60%
6	Attach Rear Wheel Mounts	13	6000	40	461.5	3.1	1.0	0.25	99.34%
7	Attach Front Wheel Mounts	13	12000	40	923.1	3.1	0.5	0.30	99.67%
8	Inspect Wheel Mounts	13	50000	200	3846.2	15.4	0.0	0.30	99.60%
9	Rear Wheel **Feeder System**	13	5000	100	384.6	7.7	0.0	0.30	98.04%
10	Install Rear Wheel Assembly	13	10000	60	769.2	4.6	1.2	0.40	99.40%
11	Inspect Rear Wheel Assembly	13	50000	200	3846.2	15.4	0.0	0.40	99.60%
	Generic Discharge/Buffer Load Operatio	10	50000	90	5000.0	9.0	0.0	0.00	99.82%
	Buffer => capacity of 25								
	Generic Buffer Unload Operation	10	25000	40	2500.0	4.0	0.0	0.00	99.84%
12	Steering Bar **Feeder System**	13	5000	40	384.6	3.1	0.0	0.40	99.21%
13	Steering Bar Assembly	13	5000	50	384.6	3.8	1.1	0.45	99.01%
14	Inspect Steering Bar	13	50000	100	3846.2	7.7	0.0	0.45	99.80%
15	Front Right Wheel **Feeder System**	13	10000	90	769.2	6.9	0.0	0.45	99.11%
16	Install Front Right Wheel	13	5000	90	384.6	6.9	1.0	0.50	98.23%
17	Inspect Front Right Wheel	13	50000	150	3846.2	11.5	0.0	0.50	99.70%
18	Front Left Wheel **Feeder System**	13	10000	90	769.2	6.9	0.0	0.50	99.11%
19	Install Front Left Wheel	13	5000	90	384.6	6.9	1.0	0.55	98.23%
20	Inspect Front Left Wheel	13	50000	150	3846.2	11.5	0.0	0.55	99.70%
21	Steering Motor **Feeder System**	13	5000	60	384.6	4.6	0.0	0.55	98.81%
22	Install Steering Motor	13	7000	100	538.5	7.7	0.6	0.90	98.59%
23	Inspect Steering Motor Assembly	13	30000	200	2307.7	15.4	0.2	0.90	99.34%
	Generic Discharge/Buffer Load Operatio	10	50000	90	5000.0	9.0	0.0	0.00	99.82%
	Buffer => capacity of 25								
	Generic Buffer Unload Operation	10	25000	40	2500.0	4.0	0.0	0.00	99.84%
24 & 25	**Aggrigated Motor S-Assy**	13.95	895	82	64.2	5.9	0.0	1.90	91.61%
26	Inspect Drive Motor Assembly	13	50000	50	3846.2	3.8	0.0	1.90	99.90%
27	Radio Control **Feeder System**	13	40000	200	3076.9	15.4	0.0	1.90	99.50%
28	Install Radio Control	13	8000	90	615.4	6.9	0.5	2.90	98.89%
	Discharge Defective Assemblies	10	50000	90	5000.0	9.0	0.0	2.90	99.82%
	Buffer => capacity of 10								
29 to 32	**After Aggregation**	10	860	140	86.0	14.0	1.0	3.00	86.00%
	Buffer => capacity of 10								
	Unload Assembly form Buffer	10	25000	40	2500.0	4.0	0.0	3.00	99.84%
33	Rear Seat **Feeder System**	15	8000	90	533.3	6.0	0.0	3.00	98.89%
34	Install Rear Seat	15	12000	90	800.0	6.0	0.6	3.10	99.26%
35	Inspect Rear Seat	15	50000	200	3333.3	13.3	0.2	3.10	99.60%
36	Front Seat **Feeders System**	15	8000	90	533.3	6.0	0.0	3.10	98.89%
37	Install Front Seat	15	12000	90	800.0	6.0	0.5	3.20	99.26%
38	Inspect Front Seat	15	50000	200	3333.3	13.3	0.1	3.20	99.60%
39	Car Shell **Feeder System**	15	4000	120	266.7	8.0	0.0	3.20	97.09%
40	Install Car Shell	15	8000	70	533.3	4.7	0.5	3.40	99.13%
	Generic Discharge/Buffer Load Operatio	10	50000	90	5000.0	9.0	0.0	0.00	99.82%
	Buffer => capacity of 25								
	Generic Buffer Unload Operation	10	25000	40	2500.0	4.0	0.0	0.00	99.84%
41	Attachment Screw #1 **Feeder System**	15	20000	30	1333.3	2.0	0.0	3.40	99.85%
42	Transfer and Tighten Screw	15	10000	60	666.7	4.0	0.0	3.42	99.40%
43	Attachment Screw #2 **Feeder System**	15	20000	30	1333.3	2.0	0.0	3.42	99.85%
44	Transfer and Tighten Screw	15	10000	60	666.7	4.0	0.0	3.44	99.40%
45	Inspect Car Shell Installation	15	75000	175	5000.0	11.7	1.0	3.44	99.77%
46	Clean	15	50000	300	3333.3	20.0	0.0	3.44	99.40%
47	Apply Decal #1	15	20000	150	1333.3	10.0	0.0	3.45	99.26%
48	Apply Decal #2	15	20000	150	1333.3	10.0	0.0	3.46	99.26%
49	Apply Decal #3	15	20000	150	1333.3	10.0	0.0	3.47	99.26%
50	Apply Decal #4	15	20000	150	1333.3	10.0	0.0	3.48	99.26%
51	Final Inspection	15	30000	200	2000.0	13.3	0.0	3.48	99.34%
52	Discharge Good Cars (not generic)	15	50000	150	3333.3	10.0	0.0	3.48	99.70%
53	Discharge Defective Cars	15	50000	150	3333.3	10.0	0.0	3.48	99.70%
54	Inspect Empty Pallet	15	50000	150	3333.3	10.0	0.0	3.48	99.70%
	Total labor for car assembly less subassemblies = $1.00								

Appendix 23

Loop Process #		1										
Number of Machine Groups				6								
Equipment Cost, MM				6.8								
Install. Cost, MM				0.4								
Startup Costs, MM				4.0								
First Workstation in Each Machine Group				1, 12, 24, 29, 33, 41								
Data format: Buffer size, Actual cycle time												
	Iterations											
Group #	1		2		3		4		5		6	
1	0	13	25	13	25	13	25	13	25	13	25	13
2	25	13	0	13	25	13	25	13	25	13	25	13
3	10	13.95	10	13.95	10	13.95	1	13.95	10	13.95	10	13.95
4	10	10	10	10	10	10	10	10	1	10	10	10
5	25	15	25	15	0	15	25	15	25	15	25	15
6		15		15		15		15		15		15
T-put/shift	1523.551		1480.66		1462.539		1493.245		1447.551		1537.134	
Payback	1.029		1.061		1.075		1.051		1.087		1.019	
IRR	1.216657		1.166663		1.145503		1.181345		1.127983		1.232463	
NPV	26.25454		24.96522		24.4205		25.34353		23.96997		26.66283	

Appendix 24

Loop Process #	**1**											
Number of Machine Groups				6								
Equipment Cost, MM				6.8								
Install. Cost, MM				0.4								
Startup Costs, MM				4.0								
First Workstation in Each Machine Group				1, 12, 24, 29, 33, 41								
Data format: Machine group efficiency, Average buffer level												
	Iterations											
Group #	1		2		3		4		5		6	
1	89.76%	0	89.76%	23.64	89.76%	23.91	89.76%	23.65	89.76%	23.9	89.76%	23.73
2	89.58%	21.78	89.58%	0	89.58%	23.74	89.58%	23.48	89.58%	23.79	89.58%	23.55
3	89.91%	8.95	89.91%	7.75	89.91%	9.12	89.91%	0.89	89.91%	9.19	89.91%	9.01
4	85.75%	9.24	85.75%	9.02	85.75%	9.31	85.75%	8.88	85.75%	0.92	85.75%	9.24
5	91.94%	19.78	91.94%	19.57	91.94%	0	91.94%	19.35	91.94%	17.57	91.94%	19.79
6	93.41%		93.41%		93.41%		93.41%		93.41%		93.41%	
T-put/shift	1523.551		1480.66		1462.539		1493.245		1447.551		1537.134	
Payback	1.029		1.061		1.075		1.051		1.087		1.019	
IRR	1.216657		1.166663		1.145503		1.181345		1.127983		1.232463	
NPV	26.25454		24.96522		24.4205		25.34353		23.96997		26.66283	

Appendix 25

		1995	1996	1997	1998
Income Generated					
	Net Income	19.88	20.88	21.92	23.02
	Depreciation	-0.85	-1.70	-1.70	-1.70
	Burden	-4.40	-4.84	-5.32	-5.86
	Startup Costs	-4.00			
	sum	10.63	14.34	14.90	15.46
	less tax	-4.15	-5.59	-5.81	-6.03
	Income after tax	6.49	8.75	9.09	9.43
Cash outlay for Equip.		-7.20	0.00	0.00	0.00
Payback for Equip					
	NPV calculation	-4.45	-4.45	0.00	0.00
	IRR calculation	-10.48	-10.48	0.00	0.00
Payback					
	Cash pos. end of yr	0.14	10.45	10.79	11.13
	Cumulative cash position	0.14	10.58	21.37	32.50
	Payback Period (Yrs)	1.02			
NPV					
	Cash pos. end of yr	2.89	6.00	10.79	11.13
	Cumulative cash position	2.89	8.88	19.67	30.80
	NPV of cash flows	2.75	5.44	9.32	9.16
	NPV	26.66			
IRR					
	IRR	123.25%			

Appendix 26

Manufacturing Cell Comparasion Original vs. Redesigned			
Evaluation Criteria	Original Configuration	Redesigned Configuration	Improvement
Number of Machine Groups	3	6	
Number of Buffers	4	8	
Equipment & Installation Cost (Million)	6.4	7.2	
Cycle Time of Slowest Machine Group (Sec)	15.99	15.29	4%
Worst Performing Machine Group (PPUT)	0.0456	0.0588	29%
Throughput per Year (Million)	1.21	1.54	27%
Payback Period (Years)	1.24	1.02	18%
NPV (Million)	17.68	26.66	51%

WORKS CITED

Askin, Ronald G., and Standridge Charles R. Modeling and Analysis of Manufacturing Systems. New York: John Wiley & Sons, Inc., 1993.

Burman, Mitchell. Personal interview. August 1994.

Burman, Mitchell. "New Results in Flow line Analysis." Ph. D. Thesis. MIT, 1995.

Dallery, Yves, David, Rene, and Xie, Xiao-Lan. "An Efficient Algorithm for Analysis of Transfer Lines with Unreliable Machines and Finite Buffers." IIE Transactions Vol. 20, Num. 3 (1988): 280-83.

Dallery, Yves, and Gershwin, Stanley B. "Manufacturing Flow Line Systems: A Review of Models and Analysis Results." MIT, Laboratory for Manufacturing and Productivity, Report, LFM-91-002. 1991.

Gershwin, Stanley B. "An Efficient Decomposition Algorithm for the Approximate Evaluation of Tandem Queues with Finite Storage Space and Blocking." Operations Research., Vol. 35 (1987): 291-305.

Gershwin, Stanley B. Manufacturing Systems Engineering. Englewood Cliffs: PTR Prentice Hall, 1994.

Hayes, Robert H., Wheelwright, Steven C., and Clark, Kim B. Dynamic Manufacturing. New York: The Free Press, 1988.

Myers, Stuart C. "Finance Theory Lecture." MIT, Sloan School of Management. 28 Feb. 1994.

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