EFFECTIVENESS ANALYSIS OF FLEXIBLE MANUFACTURING SYSTEMS

by

LISA ANNE WASHINGTON

B.S., Massachusetts Institute of Technology
(1983)

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS OF THE
DEGREE OF

MASTER OF SCIENCE

IN MECHANICAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
January 1985

© Lisa Anne Washington

The author hereby grants to M.I.T. permission to reproduce and
to distribute copies of this thesis document in whole or in part.

Signature of Author ____________________________________________________

Department of Mechanical Engineering
January 22, 1985

Certified by ___________________________________________________________

Alexander H. Levis
Thesis Supervisor

Accepted by ___________________________________________________________________

Professor Ain A. Sonin, Chairman
Departmental Committee on Graduate Studies
Department of Mechanical Engineering
EFFECTIVENESS ANALYSIS OF FLEXIBLE MANUFACTURING SYSTEMS

BY

LISA ANNE WASHINGTON

Submitted to the Department of Mechanical Engineering

on January 22, 1985

in partial fulfillment of the requirements for the degree of

Master of Science in Mechanical Engineering

ABSTRACT

A methodology for assessing the effectiveness of Flexible Manufacturing Systems (FMSs) is presented. The methodology analyzes system capabilities in terms of the goals which must be achieved within specific manufacturing, corporate and marketing environments. These environments constitute the context in which the system must operate.

Four example systems, which exhibit different types and degrees of flexibility, are analyzed. Measures are defined to show how effectively the system will be used; and how effectively the goals will be met. The system which best fulfills both criteria within a hypothetical context is then identified. Effectiveness analysis is found to be a useful tool in choosing an appropriate FMS for a manufacturing operation.

Thesis Supervisor: Dr. Alexander H. Levis

Title: Senior Research Scientist
ACKNOWLEDGEMENT

I would like to thank Dr. Alexander H. Levis for the enjoyable experience of working with him. His guidance is sincerely appreciated.

Lisa Babine deserves thanks for her help in typing this document and completing the finishing touches.

Thanks, also, to Art Giordani of LIDS for his expert drafting of figures.

Special thanks to Processor Rajan Suri of Harvard University, and Dr. Ramakrishna Akella of LIDS/MIT for sharing some of their expertise.

Professor Don Rosenfield of MIT's Sloan School of Management and Arthur D. Little, Inc., also deserves thanks for providing an overview of manufacturing operations.

Stuart Greenberg, Robert Gallagher, and John Powley of Digital Equipment Corporation (DEC) are gratefully acknowledged for arranging a visit to one of DEC's manufacturing sites.

Special thanks to the International Business Machine Corporation (IBM), and to the National Consortium for Graduate Degrees for Minorities in Engineering, Inc. (GEM) for providing fellowship support.

Finally, I would like to thank some of my friends who indirectly and directly contributed to this thesis—Bernard, Terri, Jerome and Byron.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>2</td>
</tr>
<tr>
<td>Acknowledgement</td>
<td>3</td>
</tr>
<tr>
<td>List of Figures</td>
<td>7</td>
</tr>
<tr>
<td>List of Tables</td>
<td>9</td>
</tr>
<tr>
<td><strong>CHAPTER I. INTRODUCTION</strong></td>
<td>11</td>
</tr>
<tr>
<td>1.1 Introduction</td>
<td>11</td>
</tr>
<tr>
<td>1.2 The Problem of FMS Assessment</td>
<td>13</td>
</tr>
<tr>
<td>1.3 Summary of FMS Effectiveness Analysis</td>
<td>15</td>
</tr>
<tr>
<td><strong>CHAPTER II. METHOD OF ANALYSIS</strong></td>
<td>19</td>
</tr>
<tr>
<td>2.1 Introduction</td>
<td>19</td>
</tr>
<tr>
<td>2.2 System Effectiveness Analysis</td>
<td>20</td>
</tr>
<tr>
<td><strong>CHAPTER III. ASSESSMENT OF FLEXIBLE MANUFACTURING SYSTEMS</strong></td>
<td>25</td>
</tr>
<tr>
<td>3.1 Background</td>
<td>25</td>
</tr>
<tr>
<td>3.2 Context</td>
<td>27</td>
</tr>
<tr>
<td>3.3 Mission</td>
<td>28</td>
</tr>
<tr>
<td>3.4 Definition of Attributes</td>
<td>30</td>
</tr>
<tr>
<td>3.5 Definition of Primitives</td>
<td>32</td>
</tr>
<tr>
<td>3.5.1 Mission</td>
<td>32</td>
</tr>
<tr>
<td>3.5.2 System</td>
<td>32</td>
</tr>
<tr>
<td><strong>CHAPTER IV. DEVELOPMENT OF FMS MISSION AND SYSTEM MODELS</strong></td>
<td>34</td>
</tr>
<tr>
<td>4.1 Context and Mission</td>
<td>34</td>
</tr>
</tbody>
</table>
4.2 Presentation of Systems ........................................ 36
  4.2.1 System 1: Automated Line ............................. 38
  4.2.2 System 2: Computerized Automated Line ............. 38
  4.2.3 System 3: Automated Line/Potential Routing Flexibility ........................................ 40
  4.2.4 System 4: Automated Line/Actual Routing Flexibility ........................................ 43

4.3 System Attribute: In-Process Lead Time .................. 43
  4.3.1 Elements of Queueing Theory ......................... 45
  4.3.2 In-Process Lead Time Primitives ..................... 47
  4.3.3 System In-Process Lead Time Ranges .................. 50

4.4 System Attribute: Market Response Time .................. 54
  4.4.1 Market Response Time Primitives ..................... 54
  4.4.2 System Market Response Time Ranges .................. 56

4.5 System Attribute: Product Quality ........................ 58
  4.5.1 System Ranges of Product Quality .................... 58

4.6 System Attribute: Net Present Value ........................ 60
  4.6.1 Net Present Value Primitives .......................... 61
  4.6.2 Materials Costs ........................................ 62
  4.6.3 Labor Costs ............................................. 65
  4.6.4 Inventory Costs ......................................... 70
  4.6.5 System NPV Ranges ....................................... 72

4.7 Summary of System Attribute Calculations ................ 74

CHAPTER V. COMPARISON OF ALTERNATIVES ..................... 75
  5.1 Introduction ................................................ 75
  5.2 Presentation of the Mission Locus ....................... 75
5.3 Presentation of the System Loci ........................... 78
5.4 Measures of Effectiveness ................................... 90
5.5 Summary and Discussion of Effectiveness Measures ....... 104
5.6 Additional Effectiveness Analysis and Final System Selection ........................................... 105
5.7 Modification of System Effectiveness ......................... 107

CHAPTER VI. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH ........................................... 110
6.1 Conclusions .................................................. 110
6.2 Recommendations for Further Research ..................... 111

REFERENCES ..................................................... 112

APPENDIX A M/M/1 AND M/M/C COMPUTER PROGRAM ................. 115

APPENDIX B NPV COMPUTER PROGRAM AND INPUT PARAMETERS ............. 117
<table>
<thead>
<tr>
<th>FIGURE</th>
<th>DESCRIPTION</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>System Effectiveness Methodology</td>
<td>24</td>
</tr>
<tr>
<td>4.1</td>
<td>System 1 - Automated Line</td>
<td>39</td>
</tr>
<tr>
<td>4.2</td>
<td>System 2 - Computerized Automated Line</td>
<td>41</td>
</tr>
<tr>
<td>4.3</td>
<td>System 3 - Automated Line/Potential Back-up Capacity</td>
<td>42</td>
</tr>
<tr>
<td>4.4</td>
<td>System 4 - Automated Line/Actual Back-up Capacity</td>
<td>44</td>
</tr>
<tr>
<td>4.5</td>
<td>M/M/1 Model</td>
<td>46</td>
</tr>
<tr>
<td>4.6</td>
<td>M/M/c Model</td>
<td>46</td>
</tr>
<tr>
<td>4.7</td>
<td>ATE Processing Time</td>
<td>49</td>
</tr>
<tr>
<td>4.8</td>
<td>Actual Product Quality Patterns</td>
<td>59</td>
</tr>
<tr>
<td>4.9</td>
<td>System Yield</td>
<td>63</td>
</tr>
<tr>
<td>4.10</td>
<td>Inventory Characterization</td>
<td>71</td>
</tr>
<tr>
<td>5.1</td>
<td>Projection of the Mission Locus in the Space ( NPV^<em>, T_M^</em>, T_L^* )</td>
<td>79</td>
</tr>
<tr>
<td>5.2</td>
<td>Projection of the Mission Locus in the Space ( NPV^<em>, T_M^</em>, Q^* )</td>
<td>79</td>
</tr>
<tr>
<td>5.3</td>
<td>Projection of the Mission Locus in the Space ( T_L^<em>, T_M^</em>, Q^* )</td>
<td>80</td>
</tr>
<tr>
<td>5.4</td>
<td>Projection of the Mission Locus in the Space ( NPV^<em>, T_L^</em>, Q^* )</td>
<td>80</td>
</tr>
<tr>
<td>5.5</td>
<td>Projection of the System 1 Locus in the Space ( NPV^<em>, T_M^</em>, T_L^* )</td>
<td>82</td>
</tr>
<tr>
<td>5.6</td>
<td>Projection of the System 1 Locus in the Space ( NPV^<em>, T_M^</em>, Q^* )</td>
<td>83</td>
</tr>
<tr>
<td>5.7</td>
<td>Projection of the System 1 Locus in the Space ( T_L^<em>, T_M^</em>, Q^* )</td>
<td>83</td>
</tr>
<tr>
<td>5.8</td>
<td>Projection of the System 1 Locus in the Space ( NPV^<em>, T_L^</em>, Q^* )</td>
<td>84</td>
</tr>
<tr>
<td>5.9</td>
<td>Projection of the System 2 Locus in the Space ( NPV^<em>, T_M^</em>, T_L^* )</td>
<td>85</td>
</tr>
<tr>
<td>5.10</td>
<td>Projection of the System 2 Locus in the Space ( NPV^<em>, T_M^</em>, Q^* )</td>
<td>85</td>
</tr>
<tr>
<td>5.11</td>
<td>Projection of the System 2 Locus in the Space ( T_L^<em>, T_M^</em>, Q^* )</td>
<td>86</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>5.12</td>
<td>Projection of the System 2 Locus in the Space ((NPV^<em>, T_L^</em>, T_M^<em>, T_L^</em>))</td>
<td>86</td>
</tr>
<tr>
<td>5.13</td>
<td>Projection of the System 3 Locus in the Space ((NPV^<em>, T_M^</em>, T_L^*))</td>
<td>88</td>
</tr>
<tr>
<td>5.14</td>
<td>Projection of the System 3 Locus in the Space ((NPV^<em>, T_M^</em>, Q^*))</td>
<td>88</td>
</tr>
<tr>
<td>5.15</td>
<td>Projection of the System 3 Locus in the Space ((T_L^<em>, T_M^</em>, Q^*))</td>
<td>89</td>
</tr>
<tr>
<td>5.16</td>
<td>Projection of the System 3 Locus in the Space ((NPV^<em>, T_L^</em>, Q^*))</td>
<td>89</td>
</tr>
<tr>
<td>5.17</td>
<td>Projection of the System 4 Locus in the Space ((NPV^<em>, T_M^</em>, T_L^*))</td>
<td>91</td>
</tr>
<tr>
<td>5.18</td>
<td>Projection of the System 4 Locus in the Space ((NPV^<em>, T_M^</em>, Q^*))</td>
<td>91</td>
</tr>
<tr>
<td>5.19</td>
<td>Projection of the System 4 Locus in the Space ((T_L^<em>, T_M^</em>, Q^*))</td>
<td>92</td>
</tr>
<tr>
<td>5.20</td>
<td>Projection of the System 4 Locus in the Space ((NPV^<em>, T_L^</em>, Q^*))</td>
<td>92</td>
</tr>
<tr>
<td>5.21</td>
<td>System 1 Effectiveness Analysis in the Space ((NPV^<em>, T_M^</em>, T_L^*))</td>
<td>94</td>
</tr>
<tr>
<td>5.22</td>
<td>System 1 Effectiveness Analysis in the Space ((NPV^<em>, T_M^</em>, T_L^*))</td>
<td>94</td>
</tr>
<tr>
<td>5.23</td>
<td>System 1 Effectiveness Analysis in the Space ((T_L^<em>, T_M^</em>, Q^*))</td>
<td>95</td>
</tr>
<tr>
<td>5.24</td>
<td>System 1 Effectiveness Analysis in the Space ((NPV^<em>, T_L^</em>, Q^*))</td>
<td>95</td>
</tr>
<tr>
<td>5.25</td>
<td>System 2 Effectiveness Analysis in the Space ((NPV^<em>, T_M^</em>, T_L^*))</td>
<td>97</td>
</tr>
<tr>
<td>5.26</td>
<td>System 2 Effectiveness Analysis in the Space ((NPV^<em>, T_M^</em>, T_L^*))</td>
<td>97</td>
</tr>
<tr>
<td>5.27</td>
<td>System 2 Effectiveness Analysis in the Space ((T_L^<em>, T_M^</em>, Q^*))</td>
<td>98</td>
</tr>
<tr>
<td>5.28</td>
<td>System 2 Effectiveness Analysis in the Space ((NPV^<em>, T_L^</em>, Q^*))</td>
<td>98</td>
</tr>
<tr>
<td>5.29</td>
<td>System 3 Effectiveness Analysis in the Space ((NPV^<em>, T_M^</em>, T_L^*))</td>
<td>100</td>
</tr>
<tr>
<td>5.30</td>
<td>System 3 Effectiveness Analysis in the Space ((NPV^<em>, T_M^</em>, T_L^*))</td>
<td>100</td>
</tr>
<tr>
<td>5.31</td>
<td>System 3 Effectiveness Analysis in the Space ((T_L^<em>, T_M^</em>, Q^*))</td>
<td>101</td>
</tr>
<tr>
<td>5.32</td>
<td>System 3 Effectiveness Analysis in the Space ((NPV^<em>, T_L^</em>, Q^*))</td>
<td>101</td>
</tr>
<tr>
<td>5.33</td>
<td>System 4 Effectiveness Analysis in the Space ((NPV^<em>, T_M^</em>, T_L^*))</td>
<td>102</td>
</tr>
<tr>
<td>5.34</td>
<td>System 4 Effectiveness Analysis in the Space ((NPV^<em>, T_M^</em>, Q^*))</td>
<td>102</td>
</tr>
<tr>
<td>5.35</td>
<td>System 4 Effectiveness Analysis in the Space ((T_L^<em>, T_M^</em>, Q^*))</td>
<td>103</td>
</tr>
<tr>
<td>5.36</td>
<td>System 4 Effectiveness Analysis in the Space ((NPV^<em>, T_L^</em>, Q^*))</td>
<td>103</td>
</tr>
<tr>
<td>Table</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>-------</td>
<td>-----------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4.1</td>
<td>Transportation Time Primitives</td>
<td>48</td>
</tr>
<tr>
<td>4.2</td>
<td>Number of Components Inserted per Processor</td>
<td>48</td>
</tr>
<tr>
<td>4.3</td>
<td>Processor Component Insertion Times</td>
<td>48</td>
</tr>
<tr>
<td>4.4</td>
<td>Mean Processing Times</td>
<td>50</td>
</tr>
<tr>
<td>4.5</td>
<td>Minimum Service Rate and Corresponding Part Input Rates</td>
<td>50</td>
</tr>
<tr>
<td>4.6</td>
<td>System 3 Processing Data in Case of DIP Failure</td>
<td>53</td>
</tr>
<tr>
<td>4.7</td>
<td>Manual Changeover Times</td>
<td>55</td>
</tr>
<tr>
<td>4.8</td>
<td>Computerized Changeover Times</td>
<td>55</td>
</tr>
<tr>
<td>4.9</td>
<td>System Yield Primitives</td>
<td>65</td>
</tr>
<tr>
<td>4.10</td>
<td>Processor Uptime</td>
<td>66</td>
</tr>
<tr>
<td>4.11</td>
<td>System Operational States</td>
<td>67</td>
</tr>
<tr>
<td>4.12</td>
<td>NPV Results</td>
<td>73</td>
</tr>
<tr>
<td>4.13</td>
<td>System Attribute Results</td>
<td>84</td>
</tr>
<tr>
<td>5.1</td>
<td>Scaled System Attributes</td>
<td>81</td>
</tr>
<tr>
<td>5.2</td>
<td>System Effectiveness Results</td>
<td>104</td>
</tr>
</tbody>
</table>
TO
MY  FAMILY
CHAPTER I

INTRODUCTION

1.1 INTRODUCTION

Flexible Manufacturing Systems (FMSs) are expected to play a major role in worldwide productivity improvements. In order to harness the potential benefits, industry has been installing "flexible" manufacturing equipment such as robots and Computerized Numerically Controlled (CNC) machining centers in rapidly increasing numbers. Although there is little doubt that flexible manufacturing systems have the potential to impact the overall manufacturing process in a positive manner, it is not apparent that the use of these systems is understood well enough to assure either optimal benefits or successful usage. A gap exists between the status of FMS technology and the ability of industry to assess and use the technology effectively. Development of analytical methods to aid decisions concerning applications of FMS technology is therefore still in the early stages.

A precise definition of a flexible manufacturing system (FMS) is difficult to compile. Literature tends to identify such systems in terms of their components (i.e. robots, Computerized Numerically Controlled (CNC) machines, automated parts transfer lines, ...). For the purpose of this research, it is appropriate to define FMSs in terms of the flexible capabilities a system may exhibit. For instance, FMSs may exhibit characteristics such as ability to process more than one part or families of parts, production capacity which may be expanded or contracted as needed, ability to process parts in random order, system components which work in different configurations, ability to handle operational problems, and back-up capacity.

Brown, et al. (1984) define eight different types of flexibility which may be exhibited by an FMS. They are the following:
1. Machine Flexibility - ease of making changes to produce a given set of part types.

2. Process Flexibility - ability to produce a given set of part types in several ways.

3. Product Flexibility - ability to change to a new set of products economically and quickly.

4. Routing Flexibility - ability to handle breakdowns and continue producing parts.

5. Volume Flexibility - ability to operate an FMS profitably at different production volumes.

6. Expansion Flexibility - ability to easily expand a system as needed.

7. Operation Flexibility - ability to interchange the ordering of several operations for each part type.

8. Production Flexibility - the universe of part types that the FMS can produce.

An example of a reasonably flexible system might be computer controlled CNC machining centers with multiple head changing capabilities, automated parts handling, and automated machining and assembly. A less flexible system might be a robot performing parts transfer between a drilling machine and a lathe. The given definition may be used to determine not only whether a system is flexible, but also to determine the relative flexibility of systems when differentiating between them.

Current methods for assessing manufacturing systems generally culminate in a financial statement. It is not, however, appropriate to assess an FMS solely in financial terms. Flexible manufacturing systems are difficult to
assess due to longer life periods, impact on the strategic position of the company, downstream benefits such as incorporation of engineering changes, and other benefits which typically are not expressed in financial terms. This research addresses the problem of assessing flexible manufacturing systems in such a way that the probability of successful implementation will be greatly enhanced. The approach will concentrate on analyzing the system in terms of the tasks it must accomplish given particular manufacturing, marketing and corporate environments.

1.2 THE PROBLEM OF FMS ASSESSMENT

Usage of FMS technology in the U.S. has increased rapidly during the past decade. Forecasts predict that increase will continue. However, the U.S. lags countries such as Japan, which has taken a leading role in using FMS technology to attain major gains in productivity (Lerner, 1981). There are also major problems with implementation of "flexible" manufacturing technology in the U.S. For example, the use of robots has increased at a phenomenal rate during the past decade. Ayres and Miller (1982) point out that around 200 robots were being used in the U.S. in 1970; by 1982, that number had increased to 4500. Although robots may be considered to be FMS technology, they still represent only components of a system. It seems that too often companies are attempting to stay abreast of the state-of-the-art in technology (as far as having it in the company) but not the state-of-the-art in implementation. The rising usage of robots has brought out a major problem in using "flexible" technology; that problem is the need to take a "systems" approach to manufacturing processes. Industry has found that robots can create more problems than they eliminate when put into a process without considering and possibly redesigning the entire system. Learning experiences from robotics, however, should ease the introduction of more advanced and integrated FMS concepts.

There are two basic obstacles hindering the use of FMSs in the U.S. The first obstacle is justifying the capital expenditures required for an FMS. This equipment is typically much more expensive than dedicated manufacturing
equipment. Also, management often focuses more on short-term profits, rather than the long-term position of the firm. Justification methods used by industry reflect this concern with short-term gains. FMS usage however, must be justified in terms of both short and long-range benefits. A second obstacle is the problem of implementing FMSs. Droy (1983) reports a study which showed that over half of the existing FMSs installed in the U.S. were failures. Essentially all of these failures were attributed to poor planning. However, successes of FMSs are causing recognition of the importance manufacturing processes may have on a company's competitive position. Because of this, it will be necessary to include manufacturing decisions at higher levels of management and to give these decisions higher status among a company's priorities. There is a need for assessment methodologies which will help the decision making process in determining where to install an FMS or how to best use existing systems. This necessity becomes more apparent when considering the scope of effects FMS usage may have.

Anticipated immediate benefits of an FMS are those which are directly related to the manufacturing process. For instance, improved product quality, machine uptime, and inventory control are typical expected benefits. On a larger scale however, FMSs can have dramatic impact on company operations. For instance, a company may change product lines more easily and therefore may be more inclined to move into new markets if it is using FMS technology. Also, the ability to tie production levels more closely to market demand with increased customization may help increase market share. There are also indications that FMS usage may impact heavily on an international level. Lerner (1981) points out that in the batch metal manufacturing industry, Japan is attempting to use FMS technology to manufacture capital equipment itself (such as machine tooling). An ability to manufacture capital equipment at substantially lower cost would not only cause a productivity jump in Japan, but would also enable it to gain a large share of the worldwide capital equipment market. Already, in the robotics market, Japan imports only 4% of its robots while remaining the world's leading robotics exporter (Lerner, 1981). This is an indication of the
worldwide competitive position which may be achieved through effective use of manufacturing technology.

Packer (1983) introduces very relevant definitions of efficiency and effectiveness in productivity analysis. Efficiency is defined as how well an enterprise converts its input resources into immediate outputs. Effectiveness is defined as how well the enterprise uses its input resources to meet its ultimate goals and purpose. Presently, U.S. companies tend to look for productivity gains in areas which are related only to efficiency. However, it will be necessary for U.S. industry to make use of FMS technology quickly, efficiently and effectively in order to remain competitive. This will require more emphasis on the long-range effects of manufacturing decisions. Assessment methods designed for FMS technology are required to determine what benefits are offered by an FMS, when an FMS should be used, and what the implications are for the future. This research will present a method for making decisions of this type based on analysis of system effectiveness.

1.3 SUMMARY OF FMS EFFECTIVENESS ANALYSIS

Flexible Manufacturing Systems (FMSs) are generally assessed solely in financial terms. Conventional financial performance measures do not, however, reflect the full range of benefits an FMS can provide. A methodology is presented which not only emphasizes financial performance, but also emphasizes other major benefits which are generally expected from FMS usage. These other benefits include: reduction in in-process lead times, ability to incorporate minor product changes, ability to change product lines more easily, and increased product quality. The methodology identifies five attributes which provide a comprehensive measurement of system performance in terms of expected benefits. The attributes are: in-process lead time, market response time, strategic response time, product quality, and net present value. A context in which an FMS might operate is described. This context includes a description of the specific manufacturing task, the company strategy, management practice and the marketplace. Definition of the
context enables formulation of the system mission, which defines the desired operating ranges of the attributes. The mission may be represented by a locus of points mapped in an N-dimensional attribute space (N = the number of attributes). The mission locus covers desirable attribute values. Possible systems for the manufacturing task are then presented.

The example systems exhibit different types and degrees of flexibility. The various levels of technology which are represented are also reflected in system costs. Methods for calculating the admissible attribute operating ranges for each system are then presented. Each system then yields a set of system attributes which form a locus of points in the N-dimensional attribute space. It is then possible to compare the desired system operating points (the mission locus), with the reachable system operating points (the system locus).

Two partial measures of effectiveness are formed to compare the two loci. The first measure indicates how effectively the system capabilities will be used. This measure penalizes systems which exhibit lower technological capabilities than are required; and, contrary to conventional thought, penalizes systems which exhibit greater technological capabilities than are required. This measure confronts the problem of buying complex technology simply because it is available, rather than because the capabilities are needed. The measure shows how much of the system's operating range will be used to accomplish the mission. The second measure indicates how well the system covers the desired operating range. Since the mission for an FMS may include an entire range of requirements which actually evolve during some planning horizon, this measure indicates when the FMS will be used effectively during the planning horizon. For example, if the system capabilities are included in the mission, the first measure of effectiveness will be very high. However, if the system capabilities cover only a small range of the mission, the second measure will be low. The second measure may indicate that although the system may meet the current mission effectively, at some future time during the planning horizon, when the actual mission includes only part of the current mission (probably the part which places
higher demands on the system), the system may become ineffective. The two measures of effectiveness are then combined to form a global measure of effectiveness. The appropriate system for the given mission is then chosen.

Four systems are analyzed. For the given context and mission, the methodology shows that an essentially inflexible system, and a system which demonstrates high routing flexibility may be eliminated from consideration. The inflexible system exhibits lower technological capabilities than are necessary. The system with routing flexibility exhibits technological capabilities which are not necessary and which are obtained at prohibitive cost. A third system, which exhibits the capability of simultaneously processing different part types (part mix flexibility), is penalized because its flexibility is greater than required. The final system, which is selected, exhibits low routing flexibility, and exhibits flexibility in terms of batch production of parts rather than individual part production. Some of the input parameters for this system are then varied to show the resulting changes in effectiveness.

The general methodology may be summarized in the following steps:

Step 1: Define the system, mission and context.

Step 2: Determine which attributes of the system are of interest to satisfy the mission. Calculate the possible ranges of system and mission attributes, independently, by varying the independent variables (primitives) in their formulation.

Step 3: Scale the system and mission attributes so that they may be represented in a common attribute space.

Step 4: Map the system and mission attribute ranges into the attribute space. This step results in two loci which describe the desirable and possible system operating points.
Step 5: Define measures of effectiveness to describe how well the system fulfills its mission.

This method of assessing FMSs identifies the system which will satisfy the mission in the most effective manner. In doing so, it indicates what types of flexibilities are appropriate, and how flexible the FMS needs to be.

The general system effectiveness methodology is described in more detail in Chapter II. Chapter III defines the terms of the methodology for an FMS. The mission requirements, and methods for calculating the system attributes are presented in Chapter IV. The system and mission loci are mapped in Chapter V. Chapter V also presents measures of effectiveness, comparison of alternative systems, and final system selection. Chapter VI presents conclusions and possible directions for further research.
CHAPTER II

METHOD OF ANALYSIS

2.1 INTRODUCTION

The general methodology which will be developed here for FMS assessment was originally presented by Dersin and Levis (1981,1982) for effectiveness analysis of power systems. It was also developed by Bouthonnier and Levis (1984) for effectiveness analysis of military Command, Control and Communication (C³) systems. In a mechanical system application, Levis, Houpt and Andreadakis (1984) applied the methodology to the assessment of an internal combustion engine powered automotive system. The key concept of the methodology is that system effectiveness is determined by how well the performance of a system meets the requirements of its mission given a context in which it must operate.

Assessment is carried out by defining the system and mission independently in terms of common attributes. These attributes may also be referred to as a set of assessment criteria. They are formed by aggregating basic characteristics, or primitives, of the system or mission. Primitives are often dependent on the context. Once the system and mission attributes have been identified and determined in a quantitative manner, the system capabilities and mission requirements may be mapped into a common attribute space for comparison. The resulting loci describe where the system and mission intersect. Measures of effectiveness are then defined to describe how well the system fulfills its mission. In cases where assessment has been carried out for subsystems, the resulting effectiveness measures must then be aggregated to form a global measure of effectiveness.

This method is particularly appropriate for FMS assessment because there are so many factors which must be considered in choosing an FMS. It is also appropriate for showing how various attributes may influence each other; there may be trade-offs between system or mission characteristics which,
while not readily apparent, will be reflected in changes in the mission or system loci. Perhaps most importantly, when it is unclear which FMS best suits an operation within a company, this assessment methodology will provide an objective framework for comparing systems.

2.2 SYSTEM EFFECTIVENESS ANALYSIS

In order to present the general methodology, it is necessary to describe the terms system, mission, context, attributes, primitives and measures of effectiveness.

System: The system is the set of equipment and standard operating procedures under consideration. A system may be a large-scale power system, a military Command, Control and Communication (C3) system, an automotive system, or a Flexible Manufacturing System.

Mission: The mission describes the benefits sought by utilization of the system. For instance, it may be desirable to achieve high reliability at low cost with a C3 system.

Context: The context describes the environment in which the system must operate and in which the mission must be achieved. The context may include the geographical location, the immediate physical environment, and some description of the people who will interact with the system.

Attributes: Attributes describe the major benefits which may be derived from the system and which are required by the mission. System attributes will be denoted by the set \( \{A_s\} \), and mission attributes by the set \( \{A_m\} \).

Primitives: Primitives are the basic parameters of the system or mission. They are often largely influenced by the context. They may be thought of as the independent variables in the analytical formulation. System primitives will be denoted by the set \( \{x_i\} \), and mission primitives by the set \( \{y_j\} \).
Measures of Effectiveness: These are measures which define, analytically, how well a system meets the requirements of its mission.

The first step of the methodology is to define the system, mission and context. The importance of identifying the overall goals a system is expected to support can not be overemphasized. The mission should be determined without any consideration of the proposed systems. Selection of system and mission attributes must then be made. Each attribute will be a function of one or more primitives, i.e.,

\[ A_s = f(x_1, x_2, \ldots) \quad ; \quad s = 1, 2, \ldots \]  \hspace{1cm} (2.1)

\[ A_m = f(y_1, y_2, \ldots) \quad ; \quad m = 1, 2, \ldots \]  \hspace{1cm} (2.2)

Therefore, selection of the attributes determines which primitives will be of interest. Attributes which have primitives in common will be dependent attributes; otherwise they will be independent.

Any set of specific values for the primitives will result in specific values for the attributes. If primitives are allowed to vary over their admissible ranges, corresponding ranges for each attribute will be obtained. Because individual attributes may be expressed in terms of vastly different quantities, it is necessary to scale the attributes so they may be mapped into a common, commensurate N-dimensional attribute space (N = number of attributes). The possible system operating ranges of attributes may then be represented in the attribute space by a volume or manifold. Similarly, the desirable ranges of attributes may be represented in the attribute space. Characterizations of the system and mission are therefore represented independently in the attribute space. The result is two loci of points which are representations of the system and mission. The system locus will be denoted by \( L_s \) and the mission by \( L_m \).
The placement of the system and mission loci in the attribute space will fall under one of the following categories:

1. The two loci have no points in common.
   \[ L_s \cap L_m = \emptyset \]  \hspace{1cm} (2.3)

This case results in an effectiveness rating of 0 since the system does not meet any of the mission requirements.

2. The two loci have some points in common, but neither locus is contained in the other:
   \[ L_s \cap L_m \neq \emptyset \]  \hspace{1cm} (2.4)

and
   \[ L_s \cap L_m < L_s \quad \text{and} \quad L_s \cap L_m < L_m \]

In this case, only some of the mission requirements are met by the system. There are many measures of effectiveness which could be defined at this point. A possible measure, which maps the effectiveness, \( E \), between 0 and 1 is:

\[ E = \frac{L_s \cap L_m}{L_s} \]  \hspace{1cm} (2.5)

The effectiveness is then defined by the ratio of the volume of the intersection of the two loci to the volume of the system locus. The usefulness of this measure becomes more apparent when one looks at the final two categories:
3. The system locus is entirely contained within the mission locus.

\[ L_s \cap L_m = L_s \]  \hspace{1cm} (2.6)

From the effectiveness measure defined in Eq. (2.5), this yields the maximum effectiveness of 1. In this case, the system will always fulfill the mission.

4. The mission locus is entirely contained within the system locus.

\[ L_s \cap L_m = L_m \]  \hspace{1cm} (2.7)

In this case, the resulting effectiveness will be less than 1. Although the system is capable of fulfilling the mission, it may also operate in ranges which do not satisfy the mission.

The measure of effectiveness given in Eq. (2.5) may represent only one of several measures which are of interest in a common attribute space, or may only represent the effectiveness of a subsystem. Therefore, \( E \) may be one of several partial measures of effectiveness. The partial measures may be combined to form a single global measure of effectiveness, \( E \), using utility theory such that:

\[ E = u(E_1, E_2, \ldots, E_k) \]  \hspace{1cm} (2.8)

where \( E_k \) denotes a partial measure and \( u \) represents the utility function. Bouthonnier (1982) describes the use of utility theory in more detail. Subjective judgements of the people involved in use of the methodology may be incorporated in the determination of the partial measures of effectiveness and in selection of the utility function (Karam, 1985). A schematic of the entire methodology is shown in Fig. 2.1.
Figure 2.1  System Effectiveness Methodology
CHAPTER III

ASSESSMENT OF FLEXIBLE MANUFACTURING SYSTEMS

3.1 BACKGROUND

Commonly used justification methods analyze manufacturing systems solely in terms of financial impact. The payback period, Internal Rate of Return (IRR), and Net Present Value (NPV) are certainly not the only justification methods, but they offer a good overview of the types of methods which are commonly used. Each is briefly described below:

Payback Period: This very common method determines how long it will take a system to pay for itself. The "payback" of the system is almost always in the form of direct labor savings. The time period which is determined is actually an indication of financial liquidity, although it usually is not interpreted as such.

IRR: This measure selects manufacturing systems which offer a higher rate of return than the opportunity cost of capital. This method can be difficult to apply correctly to complicated or long-lived systems such as FMSs.

NPV: This method discounts future cash flows during the system's life to present-day dollars. The discount rate depends on the riskiness of the forecast cash flows. This method may be somewhat difficult to apply to long-lived assets with uncertain cash flows like FMSs. However, as a financial measure, this method is one of the best because it recognizes the opportunity and time costs of money.

Other justification methods tend to combine ideas embodied in these methods (i.e. discounted payback, rate of return, ...). Performance characteristics of a system such as machine uptime, percentage of defective parts and required maintenance are generally not included in justification.
There are several problems with extending current methods to FMSs. The main problem is that FMS use impacts very heavily on performance characteristics in the short-run; while the financial impact is felt more in the long-run. Also, the effects of FMS use are often indirect, and therefore are easily omitted when assessing a system. FMS impact on inventory costs, lead time, flexibility of production volumes, accommodation of engineering changes, and machine uptime must be included in any assessment method which fairly analyzes the system capabilities. Current assessment methods simply do not account for the wide range of potential benefits an FMS has.

FMS literature discusses many of the issues which complicate justification. Hughes and Hegland (1983) mention the need to include subjective judgements of customer satisfaction, market share and response to changing demand in FMS justification. Ayres and Miller (1982) mention the need to quantify indirect benefits. Van Blois (1983) separates needed justification measures into tactical (short-term) and strategic (long-term) measures. Kumatilaka (1984) discusses the costs which should be incorporated in a financial justification of an FMS, and addresses the problem of determining the riskiness of such an asset. Suresh and Meredith (1984) evaluate the impact of an FMS on various costs and suggest some quantitative measures. Finally, Goldhar and Jelinek (1983) suggest that decisions should be made based on the return on investment for the company as a whole if it does not incorporate FMS usage into its manufacturing operations. There is little work done in the literature in actually developing analytical methods.

Hutchinson (1982) simulates the dynamic behavior of a transfer line and an FMS in the event of demand changes for parts and new parts introduction. His premise is that an FMS can reduce short-term capital requirements by closely matching production levels to demand. Long-term capital requirements should also be reduced due to conversion possibilities of an FMS. Results are stated solely in financial terms (cost per part, incremental cost per part, ...), however his work does indicate some areas in which flexible manufacturing is more cost effective than dedicated equipment. For instance, he has found that FMS effectiveness is highly dependent on the frequency of
new parts introduction and frequency of shifts in demand.

Arbel and Seidmann (1984) describe a performance evaluation methodology for selecting and FMS. Basically, they form a benefit model and a cost model, and then evaluate possible systems based on how well the benefits are maximized, and how well the costs are minimized. The full paper was not available for study; however, the general approach is probably closest to the methodology presented here. There are some key differences in the overall evaluation however. Arbel and Seidmann's approach seems to be much more deterministic, with a sensitivity analysis done after formulation of the models. The methodology presented here incorporates the possible scenarios and interdependency of attributes into the formulation of the models. A second difference lies in the treatment of a system which may be technologically too advanced or too flexible for the assigned mission. Although the possible benefits of such a system could be very high, the methodology presented here would assign a low effectiveness rating due to the mismatch of the system and mission. The following sections will transfer the terms of the general methodology presented in Chapter II to FMS assessment.

3.2 CONTEXT

As mentioned previously, the system and mission models must operate within the same context. Tanner (1979) mentions a case where an FMS was a complete success, 100%, in one location of a company, and had an 85% success rate in another location. The difference in success was attributed to different degrees of management familiarization. This is an example of the effect of a context change on system effectiveness.

For an FMS, the context may be divided into two basic categories. The first category describes the physical manufacturing environment and includes the following considerations:

- atmosphere (dust, metal particles, ...)
- high temperatures or sharp temperature shifts
-floor space
-floor layout
-possible wall/ceiling mounts
-corrosive environments
-vibration

The second category is heavily dependent on the company and market and includes these considerations:

-previous FMS experience
-market volatility
-company strategy
-company forecasting reliability

Current and future parts or families of parts may also be considered as a part of the context. Current and proposed parts fall under both categories since they are a part of the physical manufacturing environment and are largely determined by the market. Since the context represents known components of the environment, only those parts which definitely will be made may be considered in the context. Adaptability to possible future parts may be included in the mission.

The context may be used to eliminate obviously unsuitable systems. For instance, the system must be able to manufacture the products a company definitely wants to produce, and the system must be able to fit in the available floor space. Once a system has passed the restrictions placed on it by the context, analysis is more difficult. This necessitates effectiveness analysis in terms of the system and mission attributes.

3.3 MISSION

When defining the mission, it is necessary to realize that the system should be able not only to meet the requirements of the manufacturing task at hand, but also should support the overall goals of the company. It is

-28-
important to note that the methodology does not indicate the merit of the mission, but shows how well a system can fulfill a given mission. Although the mission must eventually be expressed in terms of the mission attributes, the initial formulation should be done in terms of broader goals.

Market requirements are a major driving force for any company. If the market has constantly changing needs which may be reflected in design changes, quality requirements, or even changes in product line, the mission should require the necessary support for those changes. If market needs are highly unpredictable, the mission should include a wide range of possible scenarios. In a competitive environment, the company may not only need to meet the requirements of its market but may also need to meet those needs better and faster than its competitors.

The mission is also highly dependent on the competitive nature of the company. It may not be possible for a company to beat its competitors in meeting market needs in all areas. Therefore, it is often necessary to pick one or two areas in which to excel. For instance, a company may differentiate itself from competitors by providing more customized products. The mission should then place stringent requirements on attributes which influence that capability.

Subjective judgements or desires of management will also determine the mission. For instance, management may have decided that it wants to compete for a specific market segment; if that segment demands high quality, the mission will reflect that requirement. Even if there are no indications that a total switch in product type is ever likely to be necessary, management may still wish to have that capability; therefore the mission would place requirements on attributes which indicate the possibility of the system creating strategic options.

Limitations may also be placed on the mission if some aspect of the company's current position requires it. For instance, if short-term cash flow problems are being experienced, the mission should reject systems which
are profitable only in the long-run. Definition of the mission is clarified by considering the selection of system and mission attributes.

3.4 DEFINITION OF ATTRIBUTES

The selection of system and mission attributes has been based on aggregation of characteristics or requirements which appear to be important in the FMS literature. A possible set of attributes is listed below.

Possible Attributes:

- cost per part
- machine uptime/reliability
- in-process inventory
- payback period
- production capacity
- system response to volume shifts in demand
- system response to design changes
- system response to shifts in product line
- in-process lead time
- net present value
- product quality
- potential strategic options

A closer look at the lists indicates that many of the proposed attributes are closely linked, and in fact can be combined.

The following attributes seem to implicitly contain essentially all of the initial attributes: In-Process Lead Time, Market Response Time, Strategic Response Time, Product Quality and a financial analysis; in this case, Net Present Value (NPV) is appropriate. Although at first glance this list may seem to represent only a small fraction of what an FMS is capable of achieving, further consideration of the implications of these attributes shows that these provide a fairly comprehensive basis for measuring
effectiveness. A description of each attribute follows:

**In-Process Lead Time:** FMS allow more customization of parts while still being able to bring the product to the market quickly. Lead time measures how quickly a part can be received after a customer has ordered it. FMS increase the possibility of using just-in-time production which substantially reduces finished goods inventory costs and can possibly increase distribution channels (more direct sales). However, lack of inventory and possibilities for greater customization increase the need to be able to manufacture and deliver products quickly. The system-dependent part of the lead time is the in-process lead time. In-process lead time is the interval from the time when a product enters an FMS to the time the finished product leaves an FMS. A reduced in-process lead time also decreases work-in-process inventory costs.

**Market Response Time:** One of the major benefits of an FMS is the ability to incorporate design changes rapidly; therefore increasing the desirability of the product from the market’s standpoint. Being able to consistently outperform competitors in addressing market needs may lead to increased market share.

**Strategic Response Time:** This attribute is similar to Market Response except that the concern here is with response to shifts in product line. A benefit of using a FMS can be that the system does not have to be dedicated to one product. Therefore, if response to a product is not as great as expected, it may be possible to shift to a different product line without having to scrap the system.

**Product Quality:** Improved quality is expected to be a benefit of using FMS technology. This attribute is concerned with measurement of expected gains in product quality; primarily in terms of whatever product performance parameters are important for the particular industry. This attribute could be concerned with accuracy, repeatability or defective parts.
NPV: This attribute discounts the present and future cash flows caused by a particular system to present day dollars. A general rule is that the NPV must be greater than zero; although some managers may also want it to be above some positive cutoff value.

3.5 DEFINITION OF PRIMITIVES

The necessary system and mission primitives are dictated by the selection of attributes. The mission primitives will be described in general terms; system primitives will be listed with their respective attributes.

3.5.1 Mission

Mission primitives must be extracted from data on competitors and the market. They may include: historical forecasting error of the company, variability of market demand, market demand elasticities with respect to market response time or product quality, competitor's lead times and required times to move into new product areas, and current working capital. These primitives and formulation of the requirements would be determined by a company's financial position and marketing data.

3.5.2 System

In-Process Lead Time: This attribute is determined by the transportation times between workstations, the rate parts are entered into the system, and the processing times at workstations.

Market Response Time: Primitives forming this attribute include reprogramming times, tooling configuration times, and any necessary system warm-up time.

Strategic Response Time: The system response is be influenced by system reconfiguration times, tooling changes, reprogramming time, scheduling, and other preparatory steps for implementation.
Product Quality: This attribute is be affected by the reliability of the various components of the FMS. Possible primitives include the repeatability of system components and the reliability of syste inspection stations.

Net Present Value: The NPV is determined by the cash flows which are generated by obtaining and running the system. These cash flows include: initial equipment costs, inventory costs, materials costs and labor costs.
CHAPTER IV

DEVELOPMENT OF FMS MISSION AND SYSTEM MODELS

4.1 CONTEXT AND MISSION

As an example of the methodology, consider the hypothetical case of a printed circuit (P/C) board manufacturing company which has decided to automate its assembly operation. The company is particularly interested in installing flexible automation in order to deal better with the uncertainties of its business. Because the company supplies circuit boards to manufacturers of personal computers, a business in which a shakeout is already in progress, there is great uncertainty in predicting not only the expected sales volumes for the next few years, but also in predicting demand for various types of boards. Regardless of what happens in the personal computer market, the company plans to continue to function as a supplier of P/C boards since that is the only product for which management has experience.

In order to maintain a strong hold in the market during the shakeout, it is believed that service to the customer must be improved in several ways. The first requirement is that the quality of boards which are manufactured must be improved. Customers are not expected to be willing to accept the same percentage of defective boards they were willing to accept in the past. A second requirement involves incorporation of design changes into the manufacturing process. These changes stem from two sources - the engineers within the company often propose design improvements, and the customers also often propose either design improvements, or may want an order customized in some manner. It is felt that the company would achieve some distinction from its competitors if it were able to incorporate these changes with ease. A third area in which the company would like to improve its reputation is in its ability to manufacture boards relatively quickly. The combination of being able to incorporate design changes while still being able to deliver boards quickly would provide a substantial edge over its competitors.
There are also financial considerations. The company has been experiencing some cash flow difficulties which are expected to worsen unless steps are taken to alleviate the problem. A large amount of capital has traditionally been tied up in inventory because of the variety of boards the company offers, and the unpredictability of demand for each board type. It is expected that reduction of changeover times will improve finished goods inventory levels. The finance department is also attempting to alleviate cash flow difficulties by specifying that any new projects should be shown to be profitable within three years in order to be acceptable.

Although there are many P/C board types which are offered by the company, there are two types - Part 1 and Part 2, that represent the extremes of simplicity and complexity in the manufacturing operation. It is possible that demand in subsequent years may be as high as 100% for either part type. It is therefore necessary to analyze the limiting cases of manufacturing systems producing either of these part types. Marketing has split on predictions for sales volumes during the next few years. The optimistic projection is that sales will fall between 40,000 and 60,000 units annually. The pessimistic projection is that sales will fall between 28,000 and 42,000 units.

The mission for the manufacturing systems under consideration may then be summarized by the following requirements:

1) In-Process Lead Time

\[ T_{L_{\text{max}}} > T_L > T_{L_{\text{min}}} \]  \hspace{1cm} (4.1)

This range is determined by customer needs and competitor capabilities.

2) Market Response Time

\[ T_{M_{\text{max}}} > T_M > T_{M_{\text{min}}} \]  \hspace{1cm} (4.2)
This range is determined by customer needs, competitor capabilities, and desired reduction of inventory.

3) Product Quality

\[ Q > Q_{\text{min}} \quad (4.3) \]

with required quality levels set by management and the target market.

4) Net Present Value

\[ \text{NPV} > 0 \quad \text{within 3 years} \quad (4.4) \]

This requirement is set by the company's financial position.

The attribute, Strategic Response Time, is not applicable within this context since the basic business must remain unchanged.

4.2 PRESENTATION OF SYSTEMS

The following sections present the systems which are under consideration for the assembly operation. Each of the systems has been chosen to exhibit only one type of flexibility in order to stress the methodology rather than analytical formulation of the attributes. In a more demanding context, several complex FMSs (exhibiting several types of flexibilities) might be under consideration.

The major components of each system are listed and described below:

Transportation Elements - there are two types of transportation elements, rotary elements and linear elements. Rotary elements rotate parts in 90-degree increments with each increment requiring a fixed time for rotation, \( t_R \). Linear elements transfer parts between two points. The time for
transfer on each linear element is given by:

\[ t_L = \frac{s}{v} \]  

(4.5)

- \( s \) - length of the element
- \( v \) - velocity of the element

There is also a fixed time, \( t_g \), required to transfer a part between any two elements.

**Variable Center Distance Inserter (VCD)** - Components which have only two leads, such as resistors, are inserted by this device. The components are pre-loaded on a tape in the correct sequence; this tape is then fed to the VCD. The act of insertion is similar to a stapling action.

**Dual In-line Package Inserter (DIP)** - This device inserts integrated circuits (ICs) into the P/C board. It is generally able to accommodate about 70 different ICs at a given time. This is accomplished by loading the DIP with 70 tubes, each of which carries one type of IC. The insertion mechanism then loads itself from a tube and inserts the IC in a pre-programmed pattern.

**Robot** - This device is used primarily for insertion of non-standard components. The more flexible insertion characteristics of a robot are required when component types are used infrequently or are somewhat problematic to insert. For P/C board assembly, the flexibility of a robot is determined largely by the number of part types its gripper can accommodate, the level of repeatability it exhibits, and the types of sensory interfaces which are available.

**Wave Solder (WS)** - Upon entrance of a board, this process generates a wave of solder to pass underneath the board and solder all of its components. For the purposes of illustrating the methodology, it will be assumed that this step of the process is run in a continuous manner.
Automatic Test Equipment (ATE) - At this stage of the process, the connections of components to the board are checked. In addition, there are some logic checks performed to ensure that the board is functioning properly.

Buffers - buffers are included between processing steps to hold boards whenever the next stage of processing is occupied.

An individual VCD, DIP, Robot, WS or ATE will be referred to as a processor. Each major step of the process flow for a system will be referred to as a stage. Loading and unloading the VCD, DIP and Robot with components will not be modeled as part of the system. These processors will always be assumed to be loaded as necessary.

4.2.1 Automated Line

System 1 is an automated line composed of the components which are described in Section 4.2. A schematic of the system is shown in Figure 4.1. Each operation is manned by one attendant; in cases of processing error, the attendant is responsible for removing the affected part from the process flow. Defective boards are detected when a processor jams, or by visually noticing the defect. The process flow is as follows:

1) \[ \text{VCD} \rightarrow \text{DIP} \rightarrow \text{Robot} \rightarrow \text{WS} \rightarrow \text{ATE} \]

Component insertion or testing proceeds according to a pre-programmed routine. In the event of a part change, an attendant goes to each machine and changes the program; this is in accordance with past company practice of sequential changeover.

4.2.2 Computerized Automated Line

The process flow of System 2 is identical to that of System 1 except for the addition of real-time computer control for all stages. The computer allows storage of a library of programs for different part types. When a P/C
board travels to a processing area, sensors are used to detect the P/C board pattern and to match it with patterns in storage. Once the board type is established, the machine at that stage will select the correct program to follow for component insertion or inspection. The robot's gripper in this system must be of a more universal design in order to handle the various non-standard parts without a gripper change. This system exhibits part-mix flexibility in that it can simultaneously process several different part types. This system allows quick changeover between batches. A schematic is shown in Figure 4.2.

4.2.3 Automated Line/Potential Routing Flexibility

System 3 (shown in Figure 4.3) includes what Brown, et al. (1984) call potential routing flexibility. Using System 1 as the basis for comparison, the difference here is in the utilization of the robot. There are two possible process flows. The first is the same as in System 1. The second occurs in the case of a DIP breakdown. When such a breakdown occurs, parts are routed through the DIP processing area and proceed to the robot where both standard and non-standard components are inserted. This system requires computer control to monitor the DIP and robot. The possible process flows are:

1)  VCD → DIP → Robot → WS → ATE

2)  VCD → Robot → WS → ATE

It will be assumed that the DIP attendant joins the robot attendant in checking for defective parts so that overall quality levels remain unchanged. Like System 2, the robot gripper must be of a more universal design because of the variety of part types which must be accommodated.
Figure 4.3 System 3 - Automated Line/Potential Back-up Capacity
4.2.4 Automated Line/Actual Back-up Capacity

System 4, as shown in Figure 4.4, is an example of actual routing flexibility. Redundancy of the VCD and robot provides several possible paths through the system in the case of a processor failure. In this system, the robot performs only non-standard part insertion. The possible process flows for this system are as follows:

1) \[ \text{VCD1} \rightarrow \text{DIP} \rightarrow \text{Robot1} \rightarrow \text{WS} \rightarrow \text{ATE} \]
2) \[ \text{VCD2} \rightarrow \text{DIP} \rightarrow \text{Robot2} \rightarrow \text{WS} \rightarrow \text{ATE} \]
3) \[ \text{VCD1} \rightarrow \text{DIP} \rightarrow \text{Robot2} \rightarrow \text{WS} \rightarrow \text{ATE} \]
4) \[ \text{VCD2} \rightarrow \text{DIP} \rightarrow \text{Robot1} \rightarrow \text{WS} \rightarrow \text{ATE} \]

In addition, process flows 1 and 2 may occur simultaneously. Since there are two more processors in this system, it will be assumed that two additional attendants and one additional supervisor are required.

4.3 SYSTEM ATTRIBUTE: IN-PROCESS LEAD TIME

This section will describe computation of the in-process lead time for each of the systems. The in-process lead time is defined as the time increment which begins when a part enters a system, and ends when the same part leaves the system. There are three components of the in-process lead time, \( T_L \): total transportation time, \( \Delta t_t \), total waiting time in buffers, \( \Delta t_b \), and total processing time, \( \Delta t_p \).

\[
T_L = \Delta t_t + \Delta t_b + \Delta t_p
\]
or

\[
T_L = \Delta t_t + \Delta t_s \quad (4.6)
\]
Figure 4.4: System 4 - Automated Line/Actual Back-up Capacity
where

\[ \Delta t_s = \Delta t_b + \Delta t_p = \text{total time in processing area} \]

The total transportation time, \( \Delta t_t \), is fixed by the path the part must follow through the system, and the number of transportation elements it utilizes in that path. The total time spent in the processing area may be determined using queueing theory.

4.3.1 Elements of Queueing Theory

Queueing theory models processes in which customers enter a system, wait their turn for service, and then leave. Two models used in queueing theory are of interest here. The first one is known as the M/M/1 model (Figure 4.5). In this model, the customer interarrival rate is assumed to be exponential, with mean arrival rate \( \lambda \). The service rate (single server) is also assumed to be exponential with mean service time \( \mu \). The buffer space is assumed to be infinite, and the queue discipline is first-come, first-served. The process is fully characterized by the interarrival rate, \( \lambda \), and the service rate, \( \mu \). Although there are several parameters which might be calculated, as listed in the M/M/1 section of the computer program in Appendix A, the concern, when determining the in-process lead time, is with the time spent in the processor area due to processing and waiting in the queue. In all future references, \( i \) represents the processor number, and \( j \) represents the part number. The total time in the processing area, \( \Delta t_{sij} \), then is given by:

\[ \Delta t_{sij} = \frac{1}{\mu_{ij} - \lambda_j} \]  \hspace{1cm} (4.7)

The second model which is of interest is the M/M/c model (Figure 4.6). This model is similar to the M/M/1 model except for the fact that multiple,
Figure 4.5 M/M/1 Model

Figure 4.6 M/M/C Model
parallel servers are now allowed; c represents the number of servers. This model is of interest in the case of System 4 where a stage may contain duplicate processors. The same assumptions hold for this model as for the M/M/1 model. Characterization of the process is complete with the parameters, λ, μ, and c. Because determination of the equations governing the process service time is much more complex than for the M/M/1 model, reference may be made again to Appendix A for the M/M/c section of the computer program.

4.3.2 In-Process Lead Time Primitives

In order to determine the transportation time component of the in-process lead time, it is necessary to know the velocity and length of the linear transportation elements, the time for transfer between elements, the time required for rotation, and the number of linear and rotational elements traversed by a part as it moves through the system. This information is summarized for the systems under consideration in Table 4.1. The service time component of the in-process lead time is determined by the input rate, λ, and the processing times at each stage. Let \( t_i \) represent the time required for machine i to insert one component. Then, the processing time, \( \tau_{ij} \), of part i at machine j is given by:

\[
\tau_{ij} = N_{ij} \cdot t_i \quad i=1 \text{ to } 3 \quad ; \quad j=1 \text{ to } 2
\]

(4.8)

Table 4.2 lists the number of components inserted into Parts 1 and 2 at each processor. Table 4.3 lists the time required at each machine for insertion of one component. Time spent in the ATE may be expected to increase in a parabolic manner with the number of components on the board. The ATE processing time may be characterized by the curve shown in Figure 4.7. The equation for the ATE processing time is:

\[
\tau_{sj} = 0.0032 \cdot N_j^3 + 4.5 \text{ s.}
\]

(4.9)

\( N_j \) - number of components in part type j
### Table 4.1 Transportation Time Primitives

<table>
<thead>
<tr>
<th>Linear Elements</th>
<th>Rotational Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length ( s )</td>
<td>Time for rotation ( t_R ) 3 s.</td>
</tr>
<tr>
<td>Velocity ( v )</td>
<td>Number ( n_R ) 16</td>
</tr>
<tr>
<td>Number ( n_L )</td>
<td>18</td>
</tr>
</tbody>
</table>

Transfer time between elements \( t_E = 1 \) sec.

### Table 4.2 Number of Components Inserted per Processor

<table>
<thead>
<tr>
<th>Processor #</th>
<th>Processor Type</th>
<th>Number of Components</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Part Type 1</td>
</tr>
<tr>
<td>1</td>
<td>VCD</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>DIP</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Robot</td>
<td>3</td>
</tr>
</tbody>
</table>

### Table 4.3 Processor Component Insertion Times

<table>
<thead>
<tr>
<th>Processor #</th>
<th>Processor Type</th>
<th>( t ) (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VCD</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>DIP</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Robot</td>
<td>6</td>
</tr>
</tbody>
</table>

\( t \) - time to insert one component
Figure 4.7 ATE Processing Time

The information in Tables 4.1, 4.2 and 4.3, and Equations 4.6 and 4.9 yields, when combined, the mean processing times for each part type at each processor. The mean processing times and corresponding service rates are listed in Table 4.4. The minimum mean service rate for any part type limits the input rate of that part. The input rate must be lower than the minimum service rate or the number of parts in the buffers will increase towards infinity. Table 4.5 lists the minimum mean service rate for each part type and the input rate which will be used for each part type in the case of a single server. The selected part input rates are lower than the minimum service rates, and are set by the past input rates from the upstream process of board preparation.
Table 4.4 Mean Processing Times

<table>
<thead>
<tr>
<th>Processor #</th>
<th>Processor Type</th>
<th>Part Type</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>VCD</td>
<td>20</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>DIP</td>
<td>30</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Robot</td>
<td>18</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>ATE</td>
<td>8</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Part Type</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.0</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>3.33</td>
<td>0.625</td>
</tr>
<tr>
<td>5</td>
<td>7.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 4.5 Minimum Service Rate and Corresponding Part Input Rates (single server)

<table>
<thead>
<tr>
<th>Part Type</th>
<th>Minimum Service Rate (parts/min.)</th>
<th>Input Rate (parts/min.) (parts/hr.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1.7</td>
</tr>
<tr>
<td>2</td>
<td>0.6</td>
<td>0.5</td>
</tr>
</tbody>
</table>

4.3.3 System in-Process Lead Time Ranges

SYSTEMS 1 AND 2

Systems 1 and 2 will have the same range of in-process lead times because the process flows are identical. The in-process lead time for Parts 1 and 2 may be determined as follows.
Transportation Time

Transportation time for all of the systems will be equal. The transportation time is given by:

\[ \Delta t_m = \sum_{k=1}^{n_L} \frac{s_k}{v_k} + (n_L + n_R) \cdot t_T + n_R \cdot t_R \]  \hspace{1cm} (4.10)

The variables are as defined in Table 4.1

Use of data in Table 4.1 yields a time spent in transport of 142 seconds or 2.367 minutes.

Since the wave solder is run as boards pass through it continuously, the processing time of the wave solder will be modeled as an additional time of 15 seconds spent in transport. Therefore, the total time in transport (including wave solder processing) is 157 seconds or 2.617 minutes.

Service Time

Use of data in Tables 4.4 and 4.5 in Equation 4.7 yields the service time at each stage for the two part types. For Systems 1 and 2, the service time is calculated using the M/M/1 model. The total service time, \( \Delta t_{sj} \), where \( j \) represents the part type, is given by:

\[ \Delta t_{sj} = \sum_{i=1}^{3} \Delta t_{sij} \hspace{1cm} j = 1 \text{ to } 2 \]  \hspace{1cm} (4.11)

Using Equation 4.11 and the results of Equation 4.10 yields a minimum service time, \( \Delta t_{s1} \), of 4.88 minutes when Part 1 is produced; and a maximum service time, \( \Delta t_{s2} \), of 22 minutes when Part 2 is produced.
In-Process Lead Time

The total in-process lead time is found using Equation 4.6. Using the minimum and maximum service times found using Equation 4.11 yields the following bounds on the mean in-process lead time.

\[ 24.617 \text{ mins.} > T_L > 7.497 \text{ mins.} \quad (4.12) \]

The minimum in-process lead time occurs when Part 1 is produced; and the maximum in-process lead time occurs when Part 2 is produced.

SYSTEM 3

When System 3 is fully operational, the range of possible in-process lead times is as given in Equation 4.12. When mapping the system attribute, the fully operational in-process lead times will be used. However, this system may also operate when the DIP has failed. The partially operational in-process lead time will be calculated for future reference. Table 4.6 gives the processing times and input rates in the case of DIP failure. Using this information, and Equations 4.7, 4.8 and 4.11, the bounds on the partially operational in-process lead time, \( T_{Lp} \), are obtained.

\[ 42.517 \text{ mins.} > T_{Lp} > 12.364 \text{ mins.} \quad (4.13) \]

SYSTEM 4

In the case of System 4, the range of in-process lead times shown in Inequality 4.12 corresponds to the case when a Robot and/or VCD has failed. For System 4:

\[ 24.617 \text{ mins.} > T_{Lp} > 7.497 \text{ mins.} \quad (4.14) \]

The service times in the fully operational state must be calculated using the \( M/M/c \) model. Doubling the VCD and Robot allows an increased input rate for
Table 4.6  System 3 Processing Data in Case of DIP Failure

<table>
<thead>
<tr>
<th>Processor #</th>
<th>Processor Type</th>
<th>Processing Times (sec.)</th>
<th>Minimum Service Rate (parts/min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VCD</td>
<td>Part Type 1 100 78 8</td>
<td>Part Type 1 0.77 0.278</td>
</tr>
<tr>
<td>3</td>
<td>Robot</td>
<td>Part Type 2 216</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>ATE</td>
<td>Part Type 1 60</td>
<td></td>
</tr>
</tbody>
</table>

Part Type 1 input rate = 0.66 parts/min = 40/hr.
Part Type 2 input rate = 0.25 parts/min = 15/hr.

Part 2 since the mean service rate at each of those stages is effectively double. Therefore, with System 4, the Part 2 input rate may be increased to 0.8 parts/minute. The input rate is now limited by the service rates of the DIP and ATE. This input rate, and the M/M/c section of the program in Appendix A yield the following minimum and maximum service times.

\[ \Delta t_{s1} = 4.251 \text{ mins.} \]  \hspace{1cm} (4.15)

\[ \Delta t_{s2} = 16.35 \text{ mins.} \]  \hspace{1cm} (4.16)

The bounds on the in-process lead time in the fully operational state are then given by adding the transportation time to the service times yielding:

\[ 18.967 \text{ mins.} > T_L > 6.868 \text{ mins.} \]  \hspace{1cm} (4.17)

Again, the minimum in-process lead time corresponds to Part 1, and the maximum in-process lead time corresponds to Part 2.
4.4 SYSTEM ATTRIBUTE: MARKET RESPONSE TIME

Market response time is defined as the time increment which begins when a system ceases producing a given part type, in order to change to a new type, and ends when the system begins producing the new part type. This time is also known as changeover time. The lower bound of the market response time will be taken to be the average changeover time when all input primitives fall in expected ranges. A company may, however, take an infinite amount of time for changeover. Therefore, since the methodology requires computation of the system volumes, a maximum allowable market response time of 90 minutes will be used.

If scheduling of production runs is done in advance (as is usually the case), then the minimum market response time, $T_{M\text{min}}$, consists of essentially three components:

$$
T_{M\text{min}} = \sum_{i=1}^{5} (\Delta t_{ri} + \Delta t_{fxi}) + \Delta t_{wu}
$$

(4.18)

$\Delta t_{rp}$ - reprogramming time
$\Delta t_{fx}$ - time to mount and test fixtures
$\Delta t_{wu}$ - warm-up time

Equation 4.18 calculates sequential changeover time.

4.4.1 Market Response Time Primitives

Data which could have been compiled from vendor specifications or from the company's past experience with similar machines are given in Tables 4.7 and 4.8. Table 4.7 gives the components of the market response time for each processor when changeover must be done manually, and the robot gripper is capable of handling only a small range of parts. Manual changeover assumes that an operator must go to each machine and manually punch in the new
program. To change the robot, a new gripper will have to be installed, and some program testing will have to be done on line. Table 4.8 gives the same data in the case when computer changeover and increased gripper capabilities are available. The warm-up time, \( \Delta t_{wu} \), for Systems 1 and 4 will be assumed to be 5 minutes. Systems 2 and 3 require negligible warm-up time since changeover is rapid.

Table 4.7 Manual Changeover Times

<table>
<thead>
<tr>
<th>Processor #</th>
<th>Processor Type</th>
<th>( \Delta t_{rp} ) (min.)</th>
<th>( \Delta t_{fx} ) (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VCD</td>
<td>2 ± 1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>DIP</td>
<td>4 ± 1</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Robot</td>
<td>30 ± 10</td>
<td>20 ± 5</td>
</tr>
<tr>
<td>4</td>
<td>WS</td>
<td>4 ± 1</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>ATE</td>
<td>4 ± 1</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.8 Computerized Changeover Times

<table>
<thead>
<tr>
<th>Processor #</th>
<th>Processor Type</th>
<th>( \Delta t_{rp} ) (sec.)</th>
<th>( \Delta t_{fx} ) (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VCD</td>
<td>6.25 ± 1.25</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>DIP</td>
<td>6.25 ± 1.25</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Robot</td>
<td>6.25 ± 1.25</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>WS</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>ATE</td>
<td>6.25 ± 1.25</td>
<td>0</td>
</tr>
</tbody>
</table>
4.4.2 System Market Response Time Ranges

In this section, the average of the range of minimum market response times for each system will be calculated.

SYSTEMS 1 AND 4

The market response times for Systems 1 and 4 are determined using Table 4.7 since all changeover must be done manually. For System 1, the maximum market response time occurs when all machines take the maximum changeover time.

\[
\text{Max } T_{\text{Mmin}} = \sum_{i=1}^{5} (\text{Max } (\Delta t_{rpi}) + \text{Max } (\Delta t_{fxi})) + \Delta t_{wu} \quad i = 1 \text{ to } 5
\]

(4.19)

Similarly, the minimum market response time occurs when all machines require the minimum changeover time.

\[
\text{Max } T_{\text{Mmin}} = \sum_{i=1}^{5} (\text{Min } (\Delta t_{rpi}) + \text{Min } (\Delta t_{fxi})) + \Delta t_{wu} \quad i = 1 \text{ to } 5
\]

(4.20)

Using Table 4.7 and Equations 4.19 and 4.20, the bounds on the market response time are given by:

\[
83 \text{ mins. } > T_{\text{Mmin}} > 47 \text{ mins.}
\]

(4.21)

The average expected response time is therefore:

\[
T_{\text{Mmin}} = 65 \text{ mins.}
\]

(4.22)

Although System 4 includes an additional VCD and an additional robot, it
will be assumed that additional labor is used to reset the two VCDs and robots in parallel. Therefore, the market response time is given in Equations 4.21 and 4.22 as for System 1.

SYSTEM 2

The market response time for System 2 is determined using Table 4.8 since computer changeover is available, and the robot gripper accommodates a wide range of parts. In this case, only program changeover occurs. Using Equations 4.19 and 4.20 and the data in Table 4.8 yields:

\[ 0.5 \text{ mins.} > T_{\text{Mmin}} > 0.33 \text{ mins} \]  \hspace{1cm} (4.23)

The average expected response time is then:

\[ T_{\text{Mmin}} = 0.4167 \text{ mins.} \]  \hspace{1cm} (4.24)

SYSTEM 3

System 3 requires use of both Tables 4.7 and 4.8. Robot and VCD changeover are done under computer control since the computer is already being used to monitor their interaction, and the way the robot is being used requires accommodation of a wide range of parts by the gripper. However, the other machines must be changed manually. Using Equations 4.19 and 4.20 with the data from Table 4.7 for the DIP and ATE, and the data from Table 4.8 for the robot and VCD yields:

\[ 8.2 \text{ mins.} > T_{\text{Mmin}} > 5.166 \text{ mins.} \]  \hspace{1cm} (4.25)

Average response time is then:

\[ T_M = 6.683 \text{ mins.} \]  \hspace{1cm} (4.26)
Since $T_{\text{max}}$ for all systems is 90 minutes, the range of possible market response times for each system will range from $T_{\text{min}}$ to $T_{\text{max}}$.

4.5 SYSTEM ATTRIBUTE: PRODUCT QUALITY

Definition of product quality is entirely dependent on the type of part which is being manufactured by the FMS. In the case of a printed circuit board manufacturer, quality, $Q$, may be defined as the percentage of output boards which are not defective.

At any inspection, a part may pass inspection or not pass inspection, and may be defective (bad), or not defective (good). A part which is received by a customer (has passed all inspections) could actually have followed any of the patterns shown in Figure 4.8. It will be assumed that each attendant checks the components inserted at the current processing stage, and also may notice defects which have passed through previous inspections. The probability that a good part will pass through the system's inspection system and on to the customer is then given by

$$Q = \frac{p_{1G}p_{2G}p_{3G}p_{4G}}{p_{1G}p_{1G}p_{3G}p_{5G} + p_{1G}p_{2G}p_{3G}p_{2B} + p_{1G}p_{2G}p_{3B}p_{3B} + p_{1G}p_{2B}p_{3B}p_{4B} + p_{1B}p_{2B}p_{3B}p_{4B}}$$

with $p_{1B} = 1 - p_{1G}$  \hspace{1cm} (4.27)

where $p_{1B}$ is the conditional probability that a part is defective although it has passed inspection at processor $i$.

4.5.1 System Ranges of Product Quality

For simplicity, each of the systems is assumed to have the same inspection process. At each VCD, DIP and robot, the attendant is responsible for visually inspecting parts as they pass by. At the robot, the wavesolder attendant also helps to inspect, reducing the output of defective boards at that stage by half. Since this is not a very reliable means of inspection,
G_1 \rightarrow G_2 \rightarrow G_3 \rightarrow G_5 \rightarrow G_6 \rightarrow G_7 \rightarrow G_8 \rightarrow G_9 \rightarrow G_{10} \rightarrow G_{11} \\

G_1 \rightarrow G_2 \rightarrow G_3 \rightarrow B_5 \\
G_1 \rightarrow G_2 \rightarrow B_3 \rightarrow B_5 \\
G_1 \rightarrow B_2 \rightarrow B_3 \rightarrow B_5 \\
B_1 \rightarrow B_2 \rightarrow B_3 \rightarrow B_5 \\

OUTPUT

G_i - part actually is not defective after passing inspection at processor i.
B_i - part actually is defective although it has passed inspection at processor i.

Figure 4.8 Actual Product Quality Patterns

70% to 85% of the parts which are allowed to continue to the next stage are actually non-defective parts.

0.85 > P_{1G}, P_{2G} > 0.70 \hspace{1cm} (4.28)

Since two attendants inspect parts after the robot,

0.925 > P_{3G} > 0.85 \hspace{1cm} (4.29)

The ATE, which can be an extremely reliable means of checking parts, then allows between 0.4% and 5% of the incoming bad parts to pass through to the customer.

0.996 > P_{5G} > 0.95 \hspace{1cm} (4.30)
Using Equations 4.27, 4.28 and 4.29, and the highest percentage of passed defective parts yields a lower limit on the quality. The lowest possible percentages of passed defective parts yields an upper limit on quality. The resulting quality range for each system is given in Equation 4.31.

\[ 0.996 > Q > 0.936 \]  \hspace{1cm} (4.31)

Therefore the minimum quality level will be 64 defective boards out of every 1000 boards. The maximum quality level will be 4 defective boards out of every 1000 boards. Since each system has the same inspection process, the quality range is the same.

4.6 SYSTEM ATTRIBUTE: NET PRESENT VALUE

The general formula for calculating NPV is as follows:

\[ \text{NPV} = C_0 + \sum_{i=1}^{n} \frac{C_i}{(1+r_i)^i} \]  \hspace{1cm} (4.32)

- \( C_0 \) - initial cash flow
- \( C_i \) - cash flows each year
- \( r_i \) - discount rate (opportunity cost of capital) each year
  (formula is often simplified by assuming constant \( r \))
- \( n \) - system lifespan unless other limit is desired

Cash outflows (such as capital equipment costs or installation and maintenance costs) are negative. Cash inflows (such as sales revenues or salvage value) are positive. The cash flows are discounted to reflect inflation, risk and the time value of money. The formula given in Equation 4.32 is a simplified version of NPV which assumes that all cash flows occurs at the end of the year, however this version is detailed enough for comparing alternative systems.
4.6.1 Net Present Value Primitives

The major cash flows which are of interest when proposing installation of an FMS are listed below; with \( t \) representing the year of operation:

**Cash Outflows**

\( t=0 \)
- Capital Cost
- Labor Retraining Costs
- Interfacing Costs
- Redesign of Product Costs
- Plant Floor Space Costs

\( t=t_1, t_2, \ldots t_n \)
- Labor Costs
- Materials Costs
- Utilities Costs
- Inventory Costs
- Overhead Costs
- Tax Liabilities

**Cash Inflows**

\( t=t_1 \)
- Investment Tax Credit

\( t=t_1, t_2, \ldots t_n \)
- Sales Revenues

When analyzing the given systems, the cash flows may be condensed somewhat into the following list. In this list, \( t \) ends at \( t_3 \) since this is the desired profitability period.

**Cash Outflows**

\( t=0 \)
- Capital Cost
- Plant Floor Space
- Other Costs (OC\((t=0))\)

**Cash Inflows**

\( t=t_1 \)
- Investment Tax Credit
$t = t_1, t_2, t_3$

Labor Costs
Materials Costs
Inventory Costs
Tax Liability
Other Costs (OC(t))

The definition of each of these cash flows is as follows:

Capital Cost : purchasing cost of equipment.
Plant Floor
Space Cost : value of floor space the system occupies.
Labor Costs : salaries of labor required to operate and maintain
the system.
Materials Costs: cost of materials used to produce the sales volume.
Inventory Costs: mainly the cost of capital tied up in inventory.
Tax Liability : amount of profits owed in taxes.
Investment Tax
Credit : reduction of tax liability due to investment
in new equipment.
Sales Revenues : annual cash inflows due to sales of product.

All of these costs are required in the formulation of the NPV, and are
calculated in the following sections.

4.6.2 Materials Costs

In order to calculate the costs of materials, it is necessary to know
the sales volume and the system yield. The possible ranges of sales volumes
were predicted in Section 4.6.1. The system yield, which is the ratio of the
number of output boards to the number of input boards may be calculated as
follows.
At any inspection, a board may be passed to the next stage or may be rejected. A portion of those boards which are rejected may be corrected and returned to the process flow. This is indicated schematically in Figure 4.9.

![Diagram of system flow](image)

**Figure 4.9 System Yield**

If there are five machines in the process flow, the system yield, $Y$, is the ratio of the output of the fifth machine, $y_5$, to the input of the first machine, $x_1$.

$$Y = \frac{y_5}{x_1}$$  \hspace{1cm} (4.33)

At any stage, the ratio of the output to the input is given by:

$$\frac{y_i}{x_i} = (r_i + c_i(1-r_i)) \hspace{1cm} i = 1 \text{ to } 5$$  \hspace{1cm} (4.34)
And, the input of stage i is the output of stage i-1.

\[ x_i = y_{i-1} \]  \hspace{1cm} (4.35)

Combining Equations 4.33, 4.34, and 4.35 yields:

\[ Y = (r_2 + c_2 (1-r_2)) (r_4 + c_4 (1-r_4)) (r_3 + c_3 (1-r_3)) (r_1 + c_1 (1-r_1)) \]  \hspace{1cm} (4.36)

For each of the systems under consideration, it will be assumed that no parts are returned to the process flow, i.e.

\[ c_i = 0 \quad i = 1 \text{ to } 5 \]  \hspace{1cm} (4.37)

Table 4.9 gives the parameters \( r_i \) for each of the stages. The VCD, DIP and robot pass a high percentage of parts, because the inspection is not stringent. The ATE passes a lower percentage of parts because it is picking up the errors of the previous machines. Since no parts are corrected and returned, and the wave solder passes all parts, the yield is calculated as follows:

\[ Y = r_s * r_s * r_s * r_s = 0.73 \]  \hspace{1cm} (4.38)

Once the yield is known, the materials costs may be calculated using Equation 4.39.

\[ CM = \frac{V \cdot CB}{Y} \]  \hspace{1cm} (4.39)

CM - Cost of Materials
V - Volume Produced
CB - Cost per Board
### Table 4.9 System Yield Primitives

<table>
<thead>
<tr>
<th>Stage #</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.95</td>
</tr>
<tr>
<td>2</td>
<td>0.95</td>
</tr>
<tr>
<td>3</td>
<td>0.95</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>0.85</td>
</tr>
</tbody>
</table>

r – probability that a part is passed to next stage

#### 4.6.3 Labor Costs

In order to calculate labor costs, it is first necessary to know the system capacity. This necessitates several preliminary calculations including the probability that the system is operating, the annual available machine hours, and the average annual input rate.

**Probability that the System is Up**

The probabilities of the various systems operating in the possible states (fully operational, partially operational) are calculated using the probabilities that the individual machines are operating along the possible part routes. The probabilities of individual machines operating are given in Table 4.10. For Systems 1 and 2, where there is no back-up capacity, the probability that the system is up is given by:
\[ PS_{11} = p_1 \cdot p_3 \cdot p_4 \cdot p_5 = .81 \] (4.40)

PS_{11} - Probability of either System 1 or System 2 being operable

\( p_1 \) - Probability of machine i being operable

<table>
<thead>
<tr>
<th>Processor #</th>
<th>Processor Type</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VCD</td>
<td>0.95</td>
</tr>
<tr>
<td>2</td>
<td>DIP</td>
<td>0.95</td>
</tr>
<tr>
<td>3</td>
<td>Robot</td>
<td>0.95</td>
</tr>
<tr>
<td>4</td>
<td>WS</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>ATE</td>
<td>0.95</td>
</tr>
</tbody>
</table>

\( p \) - probability that a processor is operating

Equation 4.40 calculates the probability of each of the processors being operable along the operational states listed in Section 4.2.1. The probability that System 3 is up is determined by summing the operational probabilities of the two possible process flows which are stated in Section 4.2.3.

\[ PS_3 = PS_{12} + p_1 \cdot (1-p_3) \cdot p_4 \cdot p_5 = 0.86 \] (4.41)

In the case of System 4, there are five possible ways for the system to be operable; the possible paths are stated in Section 4.2.4. In this case, the probability that the system is up using the data in Table 4.11, is given by:
\[ PS_4 = p^4 + 4 \cdot (1-p) p^3 + 4(1-p)^2 p = 0.90 \quad (4.42) \]

To summarize, Table 4.11 lists the systems, the probabilities that each possible process flow will be followed, and the total probability of the system being operational. The corresponding input rates for Parts 1 and 2 are also listed.

<table>
<thead>
<tr>
<th>System Flows</th>
<th>Process Flow</th>
<th>Probability of Process Flow</th>
<th>Total Probability of an Operational System</th>
<th>Input Rates per Process Flow (parts/hr.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Part 1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0.81</td>
<td>0.81</td>
<td>102</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0.81</td>
<td>0.81</td>
<td>102</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0.81</td>
<td></td>
<td>102</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.045</td>
<td>0.855</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>0.04</td>
<td>0.895</td>
<td>102</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>0.04</td>
<td></td>
<td>102</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>0.735</td>
<td></td>
<td>102</td>
</tr>
</tbody>
</table>

(Refer to Section 4.2 for system process flows).
Annual Machine Set-up Time

The annual time required for machine set-up is given by:

\[ MS = N \times TM \] \hspace{1cm} (4.43)

- \( MS \) - annual machine set-up time
- \( N \) - anticipated number of machine set-ups
- \( TM \) - market response time

The maximum machine set-up time is found when the maximum possible market response time occurs for each set-up, and the minimum machine set-up time is found when the minimum possible market response time occurs for each set-up.

Total Available Machine Hours

Since there are approximately 2000 working hours per shift in a year, the total number of available machine hours, \( AMH \), is given by:

\[ AMH = PS \times 2000 \times \gamma - MS \] \hspace{1cm} (4.44)

\( \gamma \) - represents the efficiency of the scheduling algorithm which is used.

The range of possible available machine hours is determined by the maximum and minimum annual machine set-up time.

Average Annual Input Rate

It will also be necessary to know the average annual input rate of both part types for each system. Given a system and part, the average annual input rate is found by weighting the possible input rates, given in Table 4.10, by the probability that each possible input rate is used (e.g. probability that the corresponding process flow occurs). Therefore, the average input rate (under operating conditions) is given by:
\[ \text{Av IR}_j = \frac{P_f \cdot IR_f}{PS} + \sum_{k=1}^{m} \frac{P_p \cdot IR_p}{PS} \] (4.45)

IR\textsubscript{f} - input rate during full system operation
IR\textsubscript{p} - input rate during partial system operation
m - number of possible partial operating states

The results of applying Equation 4.45 to the data in Table 4.11 are listed in Appendix B with other NPV program input parameters for each of the systems.

**System Capacity and Labor Costs**

The capacity per shift is given by:

\[ C = AMH \cdot IR \] (4.46)

As seen in Equations 4.43 and 4.44, the available machine hours parameter, AMH, has a maximum and minimum corresponding to the maximum and minimum market response times. The input rate has maximum and minimum values which correspond to the part type, and therefore indirectly correspond to the in-process lead time. The capacity per shift, C, is therefore dependent on the in-process lead time and the market response time. Since each of these attributes varies independently, there are four limiting values of C which correspond to the possible limiting combinations of in-process lead times and market response times. The possible combinations are as follows:

1) Part type 1 (Min. T\textsubscript{L}, Min. T\textsubscript{M})
2) Part type 1 (Min. T\textsubscript{L}, Max. T\textsubscript{M})
3) Part type 2 (Max. T\textsubscript{L}, Min. T\textsubscript{M})
4) Part type 2 (Max. T\textsubscript{L}, Max. T\textsubscript{M})
The capacity per shift will be used to determine how many shifts would be necessary under each of the above scenarios. The number of necessary shifts will be assumed to increase in increments of a half shift as capacity is exceeded. There is a minimum requirement of one shift. In a more detailed analysis, the trade-off between overtime and hiring an entire second shift would have to be analyzed. Assuming the possibility of partial shifts yields the following expression for the required number of shifts:

\[ NS = \frac{V}{C} \]  \hspace{1cm} (4.47)

At this point, the analysis will yield eight possible values of the number of shifts, since \( C \) may vary between four scenarios, and the anticipated sales volume also varies between a maximum and minimum.

The possible labor costs, \( CL \), per shift for each of the eight scenarios is then given by:

\[ CL = NS \cdot SL \]  \hspace{1cm} (4.48)

\( SL \) - total compensation per shift

4.6.4 Inventory Costs

The amount of inventory held is assumed to vary linearly with the annual machine set-up time as shown in Figure 4.10. There is assumed to be some amount of inventory which is held regardless of how short the market response time is (even if the company could follow demand almost exactly, there would still be some inventory to cover random fluctuations). This is essentially safety stock. The linear part of the inventory cost curve represents the additional inventory which must be held to cover demand while changeover is occurring. This is a simplified model of an inventory pattern. The cost of inventory will be assumed to consist entirely of the cost of capital tied up
in inventory. The following function may then be chosen to model the inventory costs:

\[ C_I = CB \cdot r (SS + N \cdot T_M) \]  \hspace{1cm} (4.49)

CB - cost per board

SS - minimum average annual inventory (safety stock)

The parameter, SS, is calculated in the NPV program in Appendix B.

Equation 4.49, as listed in the NPV program, exhibits the following characteristics: the required safety stock decreases as the number of machine set-ups increase (e.g. more set-ups implies need to hold less inventory of different part types), the required safety stock decreases as sales volume, and additional inventory increases as the time spent in machine set-up increases. In the context of the proposed systems, all variables such as the number of machine set-ups are fixed, therefore possible inventory costs are determined for four possible scenarios by varying the sales volume and market response time.

Figure 4.10 Inventory Characterization
Other Cash Flows

The investment tax credit, ITC, is assumed to be 15% of the capital cost.

\[ ITC = 0.15 \cdot C0 \]  \hspace{1cm} (4.50)

\( C0 \) - capital equipment cost

If the company is in a 40% tax bracket; the projected life of the system is ten years with no salvage value; the company uses straight line depreciation; and additional costs in further years may be written off; the tax liability per year is given by:

\[ TX = 0.4 \cdot (S-CM-CL-OCT-(0.1\cdot(C0 + OCO)) \]  \hspace{1cm} (4.51)

\( S \) - annual sales revenue
\( OCO \) - additional costs in year 0
\( OCT \) - additional costs in future years

This tax liability may take on eight values corresponding to the eight possible combinations of sales volumes, market response times, and part types.

4.6.5 System NPV Ranges

Because the NPV varies with both \( T_L \), \( T_M \) and the projected sales volume range, there are eight possible values which represent the maximum and minimum NPV for the four limiting combinations of \( T_L \) and \( T_M \). The program listed in Appendix B was used to calculate the net present value ranges for each of the systems. The program inputs are also listed in Appendix B. A discount rate of 30% was used in the program. This relatively high discount rate was chosen to reflect the cost of capital and the riskiness of the asset (risky largely because the technology is new). Details on determining the discount rate may be found in Myers (1983) and Kulatilaka (1984). The output of the program is summarized in Table 4.12.
<table>
<thead>
<tr>
<th>System</th>
<th>Input Case</th>
<th>Max. Sales = 60,000</th>
<th>Min. Sales = 28,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>2.328</td>
<td>0.1976</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>1.861</td>
<td>-0.1290</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>2.177</td>
<td>0.1976</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>1.731</td>
<td>-0.1290</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>3.370</td>
<td>0.8787</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>1.699</td>
<td>-0.2713</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>3.240</td>
<td>0.8787</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>1.568</td>
<td>-0.2913</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>3.375</td>
<td>0.9187</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>1.821</td>
<td>-0.1695</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>3.245</td>
<td>0.9187</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>1.690</td>
<td>-0.1695</td>
</tr>
<tr>
<td>4</td>
<td>A</td>
<td>1.737</td>
<td>-0.393</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>1.270</td>
<td>-0.720</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>1.639</td>
<td>-0.393</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>1.172</td>
<td>-0.720</td>
</tr>
</tbody>
</table>

Case A - Part Type 1, Minimum $T_L$, Minimum $T_M$
Case B - Part Type 1, Minimum $T_L$, Minimum $T_M$
Case C - Part Type 2, Minimum $T_L$, Minimum $T_M$
Case D - Part Type 2, Minimum $T_L$, Minimum $T_M
### 4.7 SUMMARY OF SYSTEM ATTRIBUTE CALCULATIONS

The attribute calculations for each system are summarized in Table 4.13.

<table>
<thead>
<tr>
<th>System</th>
<th>Q</th>
<th>$T_L$ (min.)</th>
<th>$T_M$ (min.)</th>
<th>NPV (millions of dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sales = 60,000</td>
</tr>
<tr>
<td>1</td>
<td>0.996</td>
<td>7.497</td>
<td>90</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>0.936</td>
<td>24.617</td>
<td>90</td>
<td>65</td>
</tr>
<tr>
<td>2</td>
<td>0.996</td>
<td>7.497</td>
<td>90</td>
<td>0.415</td>
</tr>
<tr>
<td></td>
<td>0.936</td>
<td>24.617</td>
<td>90</td>
<td>0.415</td>
</tr>
<tr>
<td>3</td>
<td>0.996</td>
<td>7.497</td>
<td>90</td>
<td>6.683</td>
</tr>
<tr>
<td></td>
<td>0.936</td>
<td>24.617</td>
<td>90</td>
<td>6.683</td>
</tr>
<tr>
<td>4</td>
<td>0.996</td>
<td>6.868</td>
<td>90</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>0.936</td>
<td>18.967</td>
<td>90</td>
<td>65</td>
</tr>
</tbody>
</table>
CHAPTER V

COMPARISON OF ALTERNATIVE SYSTEMS

5.1 INTRODUCTION

This chapter will begin with the presentation of a specific mission locus in a commensurate attribute space. The system attributes which were calculated in Chapter IV will be scaled and mapped into the commensurate attribute space. Each of the resulting system loci will then be compared to the mission locus and measures of effectiveness will be calculated. The chapter will conclude with selection of a system.

5.2 PRESENTATION OF THE MISSION LOCUS

The mission for a hypothetical P/C board manufacturing company was expressed earlier in Equations 4.1 through 4.4. Equation 4.4, in which the requirement for the NPV is stated, specifies a numerical bound. Necessary numerical bounds for the other attributes will be expressed in this section. After scaling the attributes, they will be mapped into the commensurate attribute space.

In-Process Lead Time: The company desires that the maximum in-process lead time, for the most complex board type, be less than or equal to twenty-two minutes per board. The total range of in-process lead times should be between eight and twenty-two minutes. Times less than eight minutes are undesirable from the perspectives of the processor attendants since inspection of parts would have to proceed at an uncomfortable rate. Therefore, the in-process lead time requirement may be restated as:

\[ 22 \text{ mins.} \geq T_L \geq 8 \text{ mins.} \] (5.1)
The scaled attribute, $T_L^*$, which will be mapped in the commensurate attribute space, is given by:

$$T_L^* = 1 - \frac{T_L}{30}$$  \hspace{1cm} (5.2)

The in-process lead time is subtracted so that the system capabilities, as represented by the system volume, will increase as the in-process lead time decreases. The multiplicative factor, $1/30$, is used so that the system capabilities and mission requirements, when scaled, will fall approximately in the range of 0 to 1. The mission requirement in the commensurate attribute space is therefore:

$$0.733 \geq T_L^* \geq 0.267$$  \hspace{1cm} (5.3)

**Market Response Time:** Based on current company capabilities, the company would like the sequential changeover time for new designs to be 90 minutes or less. In projecting future needs, however, it is expected that a market response time as low as 6 minutes will be desired. Therefore, the market response time requirement will be restated as:

$$90 \text{ mins.} \geq T_M \geq 6 \text{ mins.}$$  \hspace{1cm} (5.4)

The scaled market response time may be calculated as follows:

$$T_M^* = 1 - \frac{T_M}{90}$$  \hspace{1cm} (5.5)

$T_M$ is subtracted in order to show increasing system capabilities with decreasing market response times. The multiplicative factor, $1/90$, is used to bring the maximum mission requirement and system capabilities to an order which may be mapped in the commensurate attribute space. The resulting mission requirement in the commensurate attribute space is:
\[ 0.933 \geq \frac{T^*}{M} \geq 0 \quad (5.6) \]

**Product Quality:** The major quality goal is to satisfy the quality constraints of the company's customers. It is necessary for no more than sixty out of every thousand boards to be defective; this requirement corresponds to a quality rating of 0.94 non-defective boards. Therefore, the quality requirement is expressed as:

\[ Q \geq 0.94 \quad (5.7) \]

The scaled quality, \( Q^* \), is given by:

\[ Q^* = (10 \cdot Q) - 9.0 \quad (5.8) \]

Equation 5.8 is appropriate for mapping the quality of systems which have a rating of at least 0.9 (as in the case of the example systems). Since the maximum quality rating possible is 1.0 (100% non-defective), the mission requirement is given by:

\[ 1.0 \geq Q^* \geq 0.4 \quad (5.9) \]

**Net Present Value:** It is desired that the NPV be greater than zero for all possible sales scenarios. Since the NPV may become arbitrarily large, it is necessary to pick a large NPV for scaling purposes. Let:

\[ \frac{NPV^*}{NPV} = \frac{3.5 \cdot 10^6}{NPV} \quad (5.10) \]

Then the mission requirement in the commensurate attribute space may be expressed as:
NPV* \geq 0 \quad (5.11)

where 1.0 represents an NPV of 3.5 million dollars.

The resulting mission locus is shown in four three-dimensional projections in Figures 5.1 through 5.4. All of the mission attributes are independent.

5.3 PRESENTATION OF THE SYSTEM LOCI

The first step in developing the system loci is to calculate the scaled system attributes. Using the data in Table 4.13, and scaling according to Equations 5.2, 5.5, 5.8 and 5.10, Table 5.1, which contains the values for the commensurate attributes of each system, is obtained. The in-process lead time, market response time, and product quality attributes vary independently. The net present value attribute is dependent on the market response time and the in-process lead time (the part input rate is a shared primitive). Because all of the components of the net present value vary linearly, all of the system volumes have planar boundaries. The NPV calculation does, however, have to be checked for discontinuities since labor costs will jump for every half shift. Therefore, for all possible combinations of the part input rate and market response time, the resulting labor requirements must be checked. For the given data, at low sales volumes, there are no discontinuities. At high sales volumes, however, there exist discontinuities in the NPV as a function of the in-process lead time (part type). The resulting "step" function may be closely approximated as a continuous function of T_H and T_L.

The scaled attributes in Table 5.1 are used for mapping. The resulting locus for System 1 is shown in Figures 5.5 through 5.8. The linear approximation of the NPV is shown in Figure 5.5. This function is defined by the equations of the top and bottom planes shown in Figure 5.5.
Figure 5.1 Projection of the Mission Locus in the Space \((\text{NPV}^*, T^*_M, T^*_L)\)

Figure 5.2 Projection of the Mission Locus in the Space \((\text{NPV}^*, T^*_M, Q^*)\)
Figure 5.3 Projection of the Mission Locus in the Space \((T_L^*, T_M^*, Q^*)\)

Figure 5.4 Projection of the Mission Locus in the Space \((NPV^*, T_L^*, Q^*)\)
Table 5.1 Scaled System Attributes

<table>
<thead>
<tr>
<th>System #</th>
<th>Q*</th>
<th>TL*</th>
<th>TM*</th>
<th>Max. Sales</th>
<th>Min. Sales</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.28</td>
<td>0.685</td>
<td>0.058</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.96</td>
<td>0.75</td>
<td>0</td>
<td>0.547</td>
<td>-0.038</td>
</tr>
<tr>
<td></td>
<td>0.28</td>
<td>0.640</td>
<td>0.058</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.36</td>
<td>0.18</td>
<td>0</td>
<td>0.509</td>
<td>-0.038</td>
</tr>
<tr>
<td>2</td>
<td>0.986</td>
<td>0.99</td>
<td>0.250</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.96</td>
<td>0.75</td>
<td>0</td>
<td>0.499</td>
<td>-0.0857</td>
</tr>
<tr>
<td></td>
<td>0.986</td>
<td>0.953</td>
<td>0.250</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.36</td>
<td>0.18</td>
<td>0</td>
<td>0.461</td>
<td>-0.0857</td>
</tr>
<tr>
<td>3</td>
<td>0.926</td>
<td>0.993</td>
<td>0.270</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.96</td>
<td>0.75</td>
<td>0</td>
<td>0.536</td>
<td>-0.0498</td>
</tr>
<tr>
<td></td>
<td>0.926</td>
<td>0.954</td>
<td>0.270</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.36</td>
<td>0.18</td>
<td>0</td>
<td>0.497</td>
<td>-0.0498</td>
</tr>
<tr>
<td>4</td>
<td>0.28</td>
<td>0.511</td>
<td>-0.116</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.96</td>
<td>0.77</td>
<td>0</td>
<td>0.373</td>
<td>-0.212</td>
</tr>
<tr>
<td></td>
<td>0.28</td>
<td>0.482</td>
<td>-0.116</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.36</td>
<td>0.368</td>
<td>0</td>
<td>0.345</td>
<td>-0.212</td>
</tr>
</tbody>
</table>

For System 1, the locus of points is then defined by:

\[ 0.96 \geq Q^* \geq 0.36 \]  

(5.12)
\[ 0.75 \geq T_L^* \geq 0.18 \] (5.13)

\[ 0.28 \geq T_M^* \geq 0 \] (5.14)

\[ a_1 \geq NPV^* \geq b_1 \]

\[ a_1 = 0.493 \ T_M^* + 0.079 \ T_L^* + 0.488 \; ; \; b_1 = 0.343 \ T_M^* - 0.038 \] (5.15)

Equation 5.15 indicates that the lower bound on NPV does not vary with the part input rate. This is the case for all four systems, and it is explained by the fact that at low sales volumes, the minimum possible labor amount of one shift is sufficient for the given range of part types.

Figure 5.5 Projection of the System 1 Locus in the Space \((NPV^*, T_M^*, T_L^*)\)
Figure 5.6 Projection of the System 1 Locus in the Space \((NPV^*, T_M^*, Q^*)\)

Figure 5.7 Projection of the System 1 Locus in the Space \((T_L^*, T_M^*, Q^*)\)
System 2 is defined by the following equations:

\[ 0.96 \leq Q^* \leq 0.36 \quad (5.16) \]

\[ 0.75 \leq T_L^* \leq 0.18 \quad (5.17) \]

\[ 0.986 \leq T_M^* \leq 0 \quad (5.18) \]

\[ a_1 \geq NPV^* \geq b_1 \]

\[ a_1 = 0.499 T_M^* + 0.065 T_L^* + 0.45 \quad ; \quad b_1 = 0.35 T_M^* - 0.086 \quad (5.19) \]

The resulting system locus is shown in Figures 5.9 through 5.12. This system has high capabilities in its market response time and NPV. It should be
noted that NPV is actually a measurement of volume flexibility since it indicates what volume range the system can produce profitably.

Figure 5.9 Projection of the System 2 Locus in the Space (NPV*, T*M, T*L)

Figure 5.10 Projection of the System 2 Locus in the Space (NPV*, T*M, Q*)
Figure 5.11 Projection of the System 2 Locus in the Space \((T^*_L, T^*_M, Q^*)\)

Figure 5.12 Projection of the System 2 Locus in the Space \((NPV^*, T^*_L, Q^*)\)
Figures 5.13 through 5.16 are three-dimensional projections of the locus of points defined by System 3. The system equations are as follows:

\[ 0.96 \geq Q^* \geq 0.36 \]  \hspace{1cm} (5.20)

\[ 0.75 \geq T_L^* \geq 0.18 \]  \hspace{1cm} (5.21)

\[ 0.926 \geq T_M^* \geq 0 \]  \hspace{1cm} (5.22)

\[ a_3 \geq NPV^* \geq b_3 \]

\[ a_3 = 0.49 T_M^* + 0.068 T_L^* + 0.485 \hspace{1cm} b_3 = 0.3445 T_M^* - 0.05 \]  \hspace{1cm} (5.23)

This system is not capable of the extremely quick market response times of System 2, but covers a wider range of response times, and is strong in volume flexibility.

The final system, System 4, is defined by:

\[ 0.96 \geq Q^* \geq 0.36 \]  \hspace{1cm} (5.24)

\[ 0.77 \geq T_L^* \geq 0.368 \]  \hspace{1cm} (5.25)

\[ 0.28 \geq T_M^* \geq 0 \]  \hspace{1cm} (5.26)

\[ a_4 \geq NPV^* \geq b_4 \]

\[ a_4 = 0.5 T_M^* + 0.0746 T_L^* + 0.3165 \hspace{1cm} b_4 = 0.343 T_M^* - 0.212 \]  \hspace{1cm} (5.27)
Figure 5.13 Projection of the System 3 Locus in the Space (NPV*, T*M, T*L*)

Figure 5.14 Projection of the System 3 Locus in the Space (NPV*, T*M, Q*)
Figure 5.15  Projection of the System 3 Locus in the Space $(T_L^*, T_M^*, Q^*)$

Figure 5.16  Projection of the System 3 Locus in the Space $(NPV^*, T_L^*, Q^*)$
The system locus is shown in Figures 5.17 through 5.20. This system is slightly stronger than the others in its in-process lead time capabilities; however, it exhibits poor volume flexibility.

Now that the system volumes and mission volume have been defined analytically, it is necessary to compare each system's capabilities with the mission requirements.

5.4 MEASURES OF EFFECTIVENESS

In order to calculate measures of effectiveness, it is necessary to compute analytically each of the system volumes, and the volume of the intersection of the system and mission. The effectiveness measure, $E_i$, will be defined as:

$$E_{i1} = \frac{V_{si} \cap V_m}{V_{si}} ; \quad i : \text{system number}$$

(5.28)

The volume of each system, $V_{si}$, is calculated by integrating over the admissible ranges of each of the attributes.

$$V_{si} = \int_{Q^*} \int_{T_L^*} \int_{T_M^*} \int_{NPV^*} d(NPV^*) \ dT_M^* \ dT_L^* \ dQ^*$$

(5.29)

For System 1, Equation 5.29 becomes:

$$V_{s1} = \int_{0.36}^{0.96} \int_{0.18}^{0.75} \int_{0}^{0.28} \int_{b_1}^{a_1} d(NPV^*) \ dT_M^* \ dT_L^* \ dQ^* = 0.05587$$

(5.30)
Figure 5.17  Projection of the System 4 Locus in the Space \((\text{NPV}^*, T_M^*, T_L^*)\)

Figure 5.18  Projection of the System 4 Locus in the Space \((\text{NPV}^*, T_M^*, Q^*)\)
Figure 5.19 Projection of the System 4 Locus in the Space $(T_L^*, T_M^*, Q^*)$

Figure 5.20 Projection of the System Locus in the Space $(NPV^*, T_L^*, Q^*)$
The volume of System 2 is given by:

$$V_{S_2} = \int_{0.36}^{0.96} \int_{0.18}^{0.75} \int_{0}^{a_3} d\text{NPV}^* \, dt_M^* \, dt_L^* \, dq^* = 0.21566$$  \hspace{1cm} (5.31)

System 3's volume is given by:

$$V_{S_3} = \int_{0.36}^{0.96} \int_{0.18}^{0.75} \int_{0}^{0.926} \int_{b_3}^{a_3} d\text{NPV}^* \, dt_M^* \, dt_L^* \, dq^* = 0.20103$$  \hspace{1cm} (5.32)

The volume of System 4 is calculated as:

$$V_{S_4} = \int_{0.36}^{0.96} \int_{0.368}^{0.77} \int_{0}^{0.28} \int_{b_4}^{a_4} d\text{NPV}^* \, dt_M^* \, dt_L^* \, dq^* = 0.04004$$  \hspace{1cm} (5.33)

The next step is to calculate the volume of the intersection of each system locus with the mission locus.

System 1

The intersection of $V_{S_4}$ with $V_m$ is shown in Figures 5.21 through 5.24. As seen in Figure 5.21, the intersection of the two loci must be calculated in two parts - one part where the NPV ranges from zero to the (equation of the) top plane, and a second part where the NPV ranges from the bottom plane to the top plane. Systems 1 through 3 will all have both negative and positive NPV values. The value of $T_m^*$ where the NPV crosses from negative to
Figure 5.21 System 1 Effectiveness Analysis in the Space $(\text{NPV}^*, T_M^*, T_L^*)$

Figure 5.22 System 1 Effectiveness Analysis in the Space $(\text{NPV}^*, T_M^*, Q^*)$
Figure 5.23 System 1 Effectiveness Analysis in the Space \( (T_L^*, T_M^*, Q^*) \)

Figure 5.24 System Effectiveness Analysis in the Space \( (NPV^*, T_L^*, Q^*) \)
positive values, for System 1, is calculated to be 0.0054. Therefore, the volume of the intersection for System 1 is given by:

\[ V_{S_1 \cap V_m} = \int_{0.4}^{0.96} \int_{0.267}^{0.733} \int_{0}^{0.111} d(NPV^*) \, dT_M^* \, dT_L^* \, dQ^* \]

\[ + \int_{0.4}^{0.96} \int_{0.267}^{0.733} \int_{0}^{0.28} \int_{b_1}^{a_1} d(NPV^*) \, dT_M^* \, dT_L^* \, dQ^* = 0.04229 \]

(5.34)

The measure of effectiveness for System 1, using Equation 5.28, is therefore:

\[ E_{11} = \frac{0.04229}{0.05587} = 0.76 \]

(5.35)

System 2

Figures 5.25 through 5.28 show the intersection of the mission and System 2 locus. The intersection of the two loci is given by:

\[ V_{S_2 \cap V_m} = \int_{0.4}^{0.96} \int_{0.267}^{0.733} \int_{0}^{0.245} \int_{0}^{a_2} d(NPV^*) \, dT_M^* \, dT_L^* \, dQ^* \]

\[ + \int_{0.4}^{0.96} \int_{0.267}^{0.733} \int_{0}^{0.933} \int_{b_2}^{a_2} d(NPV^*) \, dT_M^* \, dT_L^* \, dQ^* = 0.15258 \]

(5.36)

Using Equations 5.28 and 5.31 yields the following measure of effectiveness for System 2.

\[ E_{12} = \frac{0.15258}{0.21566} = 0.71 \]

(5.37)
Figure 5.25  System 2 Effectiveness Analysis in Space \((NPV^*, T^*_M, T^*_L)\)

Figure 5.26  System 2 Effectiveness Analysis in the Space \((NPV^*, T^*_M, Q^*)\)
Figure 5.27  System 2 Effectiveness Analysis in the Space \((T_L^*, T_M^*, Q^*)\)

Figure 5.28  System 2 Effectiveness Analysis in the Space \((NPV^*, T_L^*, Q^*)\)
System 3

Figures 5.29 through 5.32 show the intersection of the mission and System 3 locus. The intersection of the two loci is:

\[ V_s \cap V_m = \int_{0.4}^{0.96} \int_{0.267}^{0.733} \int_{0}^{0.145} \int_{0}^{a} d(NPV^*) \, dT_M^* \, dT_L^* \, dQ^* \]

\[ + \int_{0.4}^{0.96} \int_{0.267}^{0.733} \int_{0.145}^{a} \int_{b}^{a} d(NPV^*) \, dT_M^* \, dT_L^* \, dQ^* = 0.15284 \]

Equations 5.28 and 5.32 yield the following measure of effectiveness.

\[ E_{13} = \frac{0.15284}{0.20103} = 0.76 \]  

(5.39)

System 4

The intersection of the mission and System 4 locus is shown in Figures 5.33 through 5.36. At the low sales forecast, this system always has a negative NPV. For this system, the volume of the mission and system intersection is given by:

\[ V_s \cap V_m = \int_{0.4}^{0.96} \int_{0.368}^{0.77} \int_{0}^{0.28} \int_{0}^{a} d(NPV^*) \, dT_M^* \, dT_L^* \, dQ^* = 0.1826 \]

(5.40)

The measure of effectiveness yielded by Equations 5.28 and 5.33 is therefore:

\[ E_{14} = \frac{0.01826}{0.40044} = 0.46 \]  

(5.41)
Figure 5.29 System 3 Effectiveness Analysis in the Space \((NPV^*, T_M^*, T_L^*)\)

Figure 5.30 System 3 Effectiveness Analysis in the Space \((NPV^*, T_M^*, Q^*)\)
Figure 5.31 System 3 Effectiveness Analysis in the Space \((T^*_{L}, T^*_{M}, Q^*)\)

Figure 5.32 System 3 Effectiveness Analysis in the Space \((NPV^*, T^*_{L}, Q^*)\)
Figure 5.33  System 4 Effectiveness Analysis in the Space \((NPV^*, T_M^*, T_L^*)\)

Figure 5.34  System 4 Effectiveness Analysis in the Space \((NPV^*, T_M^*, Q^*)\)
Figure 5.35  System 4 Effectiveness Analysis in the Space \((T_L^*, T_M^*, Q^*)\)

Figure 5.36  System 4 Effectiveness Analysis in the Space \((NPV^*, T_L^*, Q^*)\)
5.5 SUMMARY AND DISCUSSION OF EFFECTIVENESS MEASURES

The calculations of the preceding sections are summarized in Table 5.2 which lists each system volume, intersection volume, and measure of effectiveness.

Table 5.2 System Effectiveness Results

<table>
<thead>
<tr>
<th>System #</th>
<th>(V_s)</th>
<th>(V_s \cap V_m)</th>
<th>(E_1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.05587</td>
<td>0.04229</td>
<td>0.76</td>
</tr>
<tr>
<td>2</td>
<td>0.21566</td>
<td>0.15258</td>
<td>0.71</td>
</tr>
<tr>
<td>3</td>
<td>0.20103</td>
<td>0.15284</td>
<td>0.76</td>
</tr>
<tr>
<td>4</td>
<td>0.04004</td>
<td>0.01826</td>
<td>0.46</td>
</tr>
</tbody>
</table>

As a reminder, the descriptive labels of the systems are listed.

System 1 - Automated Line
System 2 - Computerized Automated Line (Part Mix Flexibility)
System 3 - Automated Line/Potential Routing Flexibility
System 4 - Automated Line/Actual Routing Flexibility

It is interesting to compare the measures of the system capabilities \((V_s)\) with the effectiveness, \(E\). System 2 has the highest system volume largely because of its capability of producing several part types simultaneously. However, System 2 does not receive one of the higher measures of effectiveness because this capability will not be utilized in the given mission. Although this system may be technologically superior to the
others, the methodology penalizes its superior market response time capability because it is not required. System 1, which has lower system capabilities (higher $T_M$, and slightly lower volume flexibiility - NPV) than System 2, recieves a high effectiveness rating because the system capabilities are more fully utilized by the mission.

System 4 receives the lowest effectiveness rating due to its poor volume flexibility. Although this system provides high reliability, in the form of routing flexibility, it does so at prohibitive cost. This is a case of excessive investment in capital equipment for the given task. In this case, the system's effectiveness is penalized for unnecessary routing flexibility. The highest effectiveness rating is achieved by System 3. Although this system has a volume close in magnitude to the volume of System 2, the system capabilities match the mission requirements more closely. The potential routing flexibility and partial computer control this system offers are assets in meeting the mission.

5.6 ADDITIONAL EFFECTIVENESS ANALYSIS AND FINAL SYSTEM SELECTION

At this point in the analysis, it is clear that System 4 may be dropped from consideration. The effectiveness of Systems 1, 2 and 3, however, warrants closer examination. Therefore, a second measure of effectiveness, $E_{s1}$, will be defined. Let:

$$E_{s1} = \frac{V_{s1} \cap V_m}{V_m} ; \quad i: \text{system number} \quad (5.42)$$

$E_{s1}$ and $E_{s1}$ are now partial measures of effectiveness since each measure represents some aspect of system suitability. The second measure of effectiveness defines how well the system covers the acceptable ranges of the mission. Therefore, it is possible that a system which received a high $E_s$ may receive a low $E_s$ if the system capabilities, while included in the mission, cover only a small fraction of the mission. This measure is
appropriate for an FMS since the mission often reflects current and anticipated requirements. A system which is capable of covering the entire range, then, will be effectively used throughout the planning horizon. The mission volume, \( V_m \), is calculated as in Equation 5.29 to be:

\[
V_m = 0.26087
\]  

(5.43)

Using the intersection volumes in Table 5.2, the following second partial measures of effectiveness are obtained.

\[
E_{11} = \frac{0.04229}{V_m} = 0.16
\]  

(5.44)

\[
E_{12} = \frac{0.15284}{V_m} = 0.586
\]  

(5.45)

\[
E_{13} = \frac{0.15258}{V_m} = 0.585
\]  

(5.46)

Clearly, System 1 which received a high \( E_1 \), is no longer a desirable system because it covers only a small portion of the mission. The partial measures of effectiveness for Systems 2 and 3 may be combined using the following global measure of effectiveness.

\[
\bar{E}_i = E_i^\alpha E_i^\beta ; \quad i: \text{system number}
\]  

(5.47)

In this case, both partial effectiveness measures will be weighed equally:

\[
\alpha = \beta = 0.5
\]  

(5.48)

For System 2, the result is:
\[ E_2 = 0.64 \]  

For System 3, the resulting global measure is:  
\[ E_3 = 0.67 \]  

(5.49)  
(5.50)  

The relatively close global effectiveness measures of Systems 2 and 3 might be expected since the systems have similar structures. However, it is clear that System 3 is the most effective FMS for the mission. The choice is confirmed by the fact that System 3 has a lower capital equipment cost than System 2 (refer to Appendix B).

5.7 MODIFICATION OF SYSTEM EFFECTIVENESS

It is now of interest to see how the planned operating procedures may be changed to increase the effectiveness of System 3. The first desired improvement might be to bring the System 3 NPV range into the mission for all possible operating scenarios. Currently, the NPV becomes negative for \( T_M^* \) less than 0.145. There are many parameters which could be varied to increase the NPV including the cost and price per board or the opportunity cost of capital, \( r \). However, these parameters are largely market-driven and cannot be controlled by the system designer. Parameters which can be controlled, at least partially, include the efficiency of scheduling, \( \gamma \), and the system yield, \( Y \). A system's NPV is sensitive to the scheduling \( \gamma \) only when capacity limitations just barely necessitate hiring an additional half shift of labor (e.g. actual capacity requirement is 1.1 shifts, therefore 1.5 shifts must be hired). In those cases, an increased \( \gamma \) can eliminate the need for the additional half shift of labor. For System 3, however, this is not the case, and an increased \( \gamma \) has no effect on the NPV. A slight increase in yield, \( Y \), does move the System 3 NPV into the desired range. Increasing the yield from 0.73 to 0.75 results in an NPV which is always positive. This yield increase may be attained by requiring the attendants at processors 1, 2 and 3 to correct and return 10% of the parts which initially were rejected. Some of
these parts might have been erroneously rejected; others will contain errors which may be corrected easily. In this case, Equation 4.36 becomes:

\[ Y = r_1 (r_1 + c_1 (1 - r_1)) (r_2 + c_2 (1 - r_2)) (r_3 + c_3 (1 - r_3)) \]  

with \( c_1 = c_2 = c_3 = 0.1 \)

Recomputation of the system locous, and the intersection with the mission yields new effectiveness measures:

\[ \tilde{E}_{x_1} = 0.77 \]  

\[ \tilde{E}_{x_2} = 0.66 \]  

\[ \tilde{E}_x = 0.71 \]

With the correction rate at 10\%, there is a very small increase in the quality, \( Q \); but, it is so minute that the system quality range is not affected. However, it may be possible to modify the in-process lead time range slightly. Referring to Section 4.2.3, the part input rates were partially determined by the upstream process of board preparation; and therefore, past input rates. It may be possible to decrease the Part 2 input rate slightly. Decreasing the Part 2 input rate from 0.5 parts/min. to 0.487 parts/min. yields a corresponding maximum lead time, \( T_{L_{\text{max}}} \), of 22 minutes. Incorporating this change and the increased yield of 0.75 yields the following effectiveness measures:

\[ E_{x_1} = 0.79 \]  

\[ E_{x_2} = 0.66 \]  

\[ \bar{E}_x = 0.72 \]
Therefore, System 3, which exhibits the highest effectiveness rating of 0.66 under planned operating conditions, can be increased to an effectiveness of 0.72 with only minor adjustments made in operating procedures. Any further substantial effectiveness increases would require improvement of the product quality, Q, through more accurate inspection processes. This would essentially involve system redesign.
CHAPTER VI
CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

6.1 CONCLUSIONS

This thesis presents a new technique for assessing Flexible Manufacturing Systems (FMSs). Unlike conventional methods of assessment, the methodology weighs not only a system's financial performance, but also weighs other system attributes which are key indicators of overall system performance. For an FMS, these attributes are: In-Process Lead Time, Market Response Time, Strategic Response Time, Product Quality, and Net Present Value. Therefore, in defining the mission, attributes which influence subjective measures, such as customer satisfaction, are included. Because assessment is carried out in the N-dimensional attribute space, trade-offs between attributes may be shown.

Some of the flexibility of the methodology is demonstrated in selection of the partial measures of effectiveness. Two appropriate partial measures were applied to the FMSs in this thesis. The first measure shows what portion of the system's capabilities are required by the mission. When using this measure, a technologically advanced system may not achieve a high measure of effectiveness if the system capabilities will not be utilized. This measure penalizes the use of complex technology when a simple solution is more appropriate. The second measure shows what portion of the mission can be reached by the system. This measure is important for an FMS since, due to longer life expectancy, the mission will often cover current requirements and anticipated future requirements over some planning horizon. In a sense, this measure indicates the portion of the planning horizon during which the FMS may be used effectively.

The flexibility of the general methodology is demonstrated by the fact that it may be applied to many types of systems; including C³ systems (Bouthonnier and Levis, 1984), an automotive system (Levis, Houpt and
Andreadakis, 1984), large-scale power systems (Dersin and Levis, 1981), and to manufacturing systems.

6.2 RECOMMENDATIONS FOR FURTHER RESEARCH

Continuation of this research should proceed with a direct industry liaison. Assessment of an actual FMS within a real context would be invaluable in refining the methodology. This would be particularly useful in aggregating actual raw data into attributes. Some computer-aided design (CAD) work should also take place to develop graphical displays of the mission and system loci. Ideally, a system designer should be able to interactively vary input primitives and see the resulting intersections of the loci. With the use of this tool, the methodology could easily be used to incorporate judgements of all organizational levels in determining what a system should do, what a system is capable of doing, and how the differences may be reconciled.
REFERENCES


Hughes, Tom and Donald E. Hegland, "Flexible Manufacturing - the Way to the Winner's Circle," Production Engineering, 30, 9, September, 1983, pp.54-63.


APPENDIX A

M/M/1 AND M/M/C COMPUTER PROGRAM *

10 INPUT "NUMBER OF SERVERS?"; C
20 IF C>1 THEN GOTO 350
30 REM M/M/1 QUEUING SYSTEM
40 REM L AVERAGE NUMBER OF CUSTOMERS IN SYSTEM
50 REM LM LAMBDAN - AVERAGE CUSTOMER ARRIVAL RATE
60 REM LQ AVERAGE NUMBER OF CUSTOMERS IN THE QUEUE
70 REM MU AVERAGE SERVICE RATE
80 REM N CUSTOMER COUNTER
90 REM NS PROBABILITY COUNTER
100 REM P(0) PROBABILITY OF 0 CUSTOMERS IN SYSTEM
110 REM P(N) PROBABILITY OF N CUSTOMERS IN SYSTEM
120 REM RQ TRAFFIC INTENSITY RATIO
130 REM W AVERAGE WAITING-TIME IN SYSTEM
140 REM WQ AVERAGE WAITING-TIME IN QUEUE
150 DIM P(5) 
160 INPUT "ENTER AVERAGE CUSTOMER ARRIVAL RATE(\LAMDA):";LM
170 INPUT "ENTER AVERAGE SERVICE RATE(\MU):";MU
180 P(0)=0
190 RQ=LM/MU
200 L=LM/(MU-LM)
210 LQ=LM^2/(MU*(MU-LM))
220 WQ=LQ/LM
230 W=L/LM
240 PRINT "N  P"
250 PRINT "PROBABILITY OF N CUSTOMERS IN THE SYSTEM"
260 FOR N=1 TO 5
270 P(N)=RQ^N*(1-RQ)
280 PRINT N,P(N)
290 NEXT N
300 PRINT "AVERAGE NUMBER OF CUSTOMERS IN THE SYSTEM=",L
310 PRINT "AVERAGE NUMBER OF CUSTOMERS IN THE QUEUE=",LQ
320 PRINT "AVERAGE WAITING TIME IN THE QUEUE=",WQ
330 PRINT "AVERAGE WAITING TIME IN THE SYSTEM=",W
340 GOTO 170
350 REM M/M/C QUEUING SYSTEM
360 REM C NUMBER OF SERVERS
370 REM L AVERAGE NUMBER OF CUSTOMERS IN SYSTEM
380 REM LM LAMBDAN - AVERAGE CUSTOMER ARRIVAL RATE
390 REM LQ AVERAGE NUMBER OF CUSTOMERS IN QUEUE
400 REM MU MU-AVERAGE SERVICE RATE
410 REM N CUSTOMER COUNTER
420 REM NC N FACTORIAL COUNTER
430 REM NF N!
440 REM NM N FACTORIAL COUNTER
450 REM NS PROBABILITY COUNTER
460 REM P(0) PROBABILITY OF 0 CUSTOMERS IN SYSTEM
470 REM P(N) PROBABILITY OF N CUSTOMERS IN SYSTEM
480 REM PS PROBABILITY ACCUMULATOR
490 REM RQ RQ-TRAFFIC INTENSITY RATIO
500 REM W AVERAGE WAITING-TIME IN SYSTEM
510 REM WQ AVERAGE WAITING-TIME IN QUEUE
520 DIM P(5)
530 INPUT "ENTER AVERAGE CUSTOMER ARRIVAL RATE (LAMBDA)" ; LM
540 INPUT "ENTER AVERAGE SERVICE RATE (MU)" ; MU
550 PN=0!
560 F(0)=0!
570 NM=C
580 GOSUB 930
590 FS=( (LM/MU) ^ C/NF ) * ( 1/ ( 1 - (LM/MU)/C ) )
600 FOR NS=1 TO C-1
610 NM=NS
620 GOSUB 930
630 FOR NS=1 TO S
640 FN=(1!/NF)*((LM/MU)^NS)*PN
650 NEXT NS
660 F(0)=1/(FN+FS)
670 FOR NS=1 TO S
680 IF NS<C THEN GOTO 730
690 NM=NS
700 GOSUB 930
710 P(NS)=1/((NF+C^(NS-C))*(LM/MU)^(NS-P(0)))
720 GOTO 760
730 NM=NS
740 GOSUB 930
750 P(NS)=(1!/NF)*((LM/MU)^NS)*P(0)
760 NEXT NS
770 NM=C
780 GOSUB 930
790 W=( ((LM/MU)^C*P(0)) / ( NF*( (LM/MU) / C ) ) ) / ( C*MU*(1! - (LM/MU)/C) )
800 W=W+1/MU
810 LQ=LM=WQ
820 L=LM=W
830 PRINT "PROBABILITY OF N CUSTOMERS IN THE SYSTEM"
840 PRINT "N P"
850 FOR N=0 TO S
860 PRINT N, P(N)
870 NEXT N
880 PRINT "AVERAGE NUMBER OF CUSTOMERS IN THE SYSTEM =", L
890 PRINT "AVERAGE NUMBER OF CUSTOMERS IN THE QUEUE =", LQ
900 PRINT "AVERAGE WAITING-TIME IN THE SYSTEM =", W
910 PRINT "AVERAGE WAITING-TIME IN THE QUEUE =", WQ
920 GOTO 50
930 REM SUBROUTINE TO GENERATE N!
940 NF=1
950 FOR NC=NM TO 1 STEP -1
960 NF=NF+NC
970 NEXT NC
980 RETURN
990 END

*Program adapted from Gorney, 1982.
APPENDIX B

NFV COMPUTER PROGRAM AND INPUT PARAMETERS

10 REM
20 REM NET PRESENT VALUE PROGRAM
30 REM
40 INPUT "SYSTEM NO.";A
50 INPUT "MAX. MARKET RESPONSE";TX
60 INPUT "MIN. MARKET RESPONSE";TN
70 PRINT "INPUT RATES MUST BE ENTERED IN PARTS/HR."
80 INPUT "PART #1 AV. INPUT RATE";IX
90 INPUT "PART #2 AV. INPUT RATE";IAR
100 INPUT "MAX. POSSIBLE SALES VOLUME";VX
110 INPUT "MIN. POSSIBLE SALES VOLUME";VN
120 INPUT "VOLUME PROGRAM WILL BE RUN FOR";V
130 INPUT "PROBABILITY SYSTEM IS UP";FS
140 INPUT "EQUIPMENT COST";CD
150 INPUT "COST OF FLOOR SPACE";CFS
160 INPUT "SYSTEM YIELD";Y
170 INPUT "SCHEDULING GAMMA";G
180 INPUT "COST PER BOARD";PB
190 INPUT "PRICE PER BOARD";PB
200 INPUT "LABOR COSTS OTHER THAN LABOR, MATERIALS OR INV. IN YR. 0";OCO
210 INPUT "COSTS OTHER THAN LABOR, MAT.'S, OR INV. IN SUBSEQUENT YRS.";CTC
220 INPUT "NO. OF MINOR CHANGES";N
230 INPUT "COST OF CAPITAL";R
240 GO SUB 1500
250 REM
260 REM "---------------------------------------"
270 REM CAPACITY CALCULATIONS
280 REM
290 REM WH - ANNUAL WORKING HOURS, NS - ANNUAL MACHINE SET-UP TIME
300 REM AMH - AVAILABLE MACH. HRS., C - CAPACITY, NS - NO. OF SHIFTS
310 REM V - SALES VOLUME
320 REM 1.5 - PART NUMBER PRODUCED
330 REM N,X - MINIMUM OR MAXIMUM MARKET RESPONSE TIME
340 WH=2000
350 MS=X*TX/60
360 MSN=X*TN/60
370 AMH=FS+WH-G-MSN
380 AMHN=FS+WH-G-MSX
390 CIN=AMH*X
400 CIX=AMHN*X
410 CIN=AMH*X
420 CIX=AMHN*X
430 REM
440 REM SHIFT CALCULATIONS
450 REM
460 NSIN=W/CIN
470 NSIX=W/CIX
480 NSN=W/CIN
490 NSK=W/CIX
500 IF NSIN<1 THEN NSIN=1 ELSE IF NSIN<1.5 THEN NSIN=1.5 ELSE NSIN=2
510 IF NSIX<1 THEN NSIX=1 ELSE IF NSIX<1.5 THEN NSIX=1.5 ELSE NSIX=2
520 IF NSN<1 THEN NSN=1 ELSE IF NSN<1.5 THEN NSN=1.5 ELSE NSN=2
530 IF NSK<1 THEN NSK=1 ELSE IF NSK<1.5 THEN NSK=1.5 ELSE NSK=2
540 REM "---------------------------------------"
550 REM LABOR COSTS
560 REM L - LABOR COST CORRESPONDING TO PART TYPE PRODUCTION AND MARKET RESPONSE TIME
570 LIN=NSIN+SL
580 LIX=NSIX+SL

-117-
600 LCN=NSCN*SL
610 LEX=NSIX*SL
620 REM "-----------------------------"
630 REM MATERIALS COSTS
640 REM "-----------------------------"
650 REM CM - COST OF MATERIALS
660 CM=V*CB/Y
670 REM "-----------------------------"
680 REM INVENTORY COSTS
690 REM "-----------------------------"
700 REM K - AVERAGE ANTICIPATED HOURLY DEMAND RATE (BASED ON FORECAST VOLUME EXTREMES)
710 REM CS = SAFETY STOCK
720 K=(VX*VN)/17520
730 CS=4*(VX*VN)/N
740 CIX=CS*CB*R+TX*K*R=CB
750 CIN=CS*CB*R+TN*K*R=CB
760 LPRINT "MAX. INV. COSTS",CIX,"MIN. INV. COSTS",CIN
770 REM "-----------------------------"
780 REM INVESTMENT TAX CREDIT
790 REM "-----------------------------"
800 ITC=.15=CO
810 REM "-----------------------------"
820 REM SALES REVENUES
830 REM "-----------------------------"
840 S=V*PB
850 REM "-----------------------------"
860 REM TAX LIABILITY
870 REM "-----------------------------"
880 LPRINT
890 REM CT - TAX LIABILITY
900 LPRINT "CASE 1-100% PART #1, MIN. MARKET RESPONSE TIME, SALES =",V
910 LPRINT "CASE 2-100% PART #1, MAX. MARKET RESPONSE TIME, SALES =",V
920 LPRINT "CASE 3-100% PART #2, MIN. MARKET RESPONSE TIME, SALES =",V
930 LPRINT "CASE 4-100% PART #2, MAX. MARKET RESPONSE TIME, SALES =",V
940 LPRINT
950 LPRINT
960 LPRINT "CT1=.4*(S-LIN-CM-CIN-.1*(C0-C0)-OCT)
970 CT2=.4*(S-LIN-CM-CIX-.1*(C0-C0)-OCT)
980 CT3=.4*(S-LIN-CM-CIN-.1*(C0-C0)-OCT)
990 CT4=.4*(S-LIN-CM-CIX-.1*(C0-C0)-OCT)
1000 IF CT1<0 THEN CT1=0
1010 IF CT2<0 THEN CT2=0
1020 IF CT3<0 THEN CT3=0
1030 IF CT4<0 THEN CT4=0
1040 LPRINT "TAX LIABILITY-CASE 1",CT1
1050 LPRINT "TAX LIABILITY-CASE 2",CT2
1060 LPRINT "TAX LIABILITY-CASE 3",CT3
1070 LPRINT "TAX LIABILITY-CASE 4",CT4
1080 REM NFV CALCULATIONS
1090 REM "-----------------------------"
1100 REM NFV CALCULATIONS
1110 REM "-----------------------------"
1120 REM NFV: CASE 1
1130 FI=S-CM-LIN+ITC-CIN-OCT-CT1
1140 GOSUB 1C30
1150 LPRINT
1160 LPRINT
1170 LPRINT "CONFIGURATION",A
1180 LPRINT "NFV-CASE 1",NFV
1190 REM NFV: CASE 2
1200 FI=S-CM-LIN+ITC-OCT-CT2
1210 GOSUB 1C30
1220 LPRINT "NFV-CASE 2",NFV
1230 REM NFV: CASE 3
1240 FI=S-CM-LIN+CT1+ITC-OCT-CT3
1250 GOSUB 1C30
1260 LPRINT "NFV-CASE 3",NFV

-118-
1270 REM NPV: CASE 4
1280 F1=S-CM-L2X-CIX+ITC-OCT-CT4
1290 GOSUB 1380
1300 LPRINT "NPV-CASE 4",NPV
1310 PRINT "CONTINUE WITH PARAMETER CHANGES?"
1320 INPUT "1=YES, 0=NO;END PROGRAM";B
1330 IF B#0 THEN GOTO 1360
1340 GOSUB 1450
1350 GOTO 250
1360 END
1370 REM
1380 F0=-(CO+CFS+OC0)
1390 F2=F1-ITC
1400 F2=F2
1410 NPV=F0+F1/(1+R)+F2/(1+R)^2+F3/(1+R)^3
1420 RETURN
1430 INPUT "MAXIMUM VOLUME";VI
1440 INPUT "MINIMUM VOLUME";VN
1450 INPUT "VOLUME PROGRAM SHOULD BE RUN FOR";V
1460 INPUT "SCHEDULING GAMMA";G
1470 INPUT "SYSTEM YIELD";Y
1480 INPUT "NO. OF MINOR CHANGES";N
1490 RETURN
1500 LPRINT "SYSTEM NUMBER";A
1510 LPRINT "MAKET RESPONSE";TX
1520 LPRINT "MIN. MARKET RESPONSE";TN
1530 LPRINT "MAX. AVERAGE INPUT RATE";IRX
1540 LPRINT "MIN. AVERAGE INPUT RATE";IRN
1550 LPRINT "MAX. POSSIBLE SALES VOL.";VX
1560 LPRINT "MIN. POSSIBLE SALES VOL.";VN
1570 LPRINT "PROBABILITY SYSTEM IS UP";PS
1580 LPRINT "EQUIPMENT COST";CO
1590 LPRINT "LABOR COSTS PER SHIFT";SL
1600 LPRINT "COST OF FLOOR SPACE";CFS
1610 LPRINT "ADDITIONAL COSTS IN YEAR 0";OC0
1620 LPRINT "ADDITIONAL COSTS IN SUBSEQUENT YRS.";OCT
1630 LPRINT "SYSTEM YIELD";Y
1640 LPRINT "COST OF CAPITAL";R
1650 LPRINT "SCHEDULING GAMMA";G
1660 LPRINT "COST PER BOARD";CB
1670 LPRINT "PRICE PER BOARD";PB
1680 LPRINT "NO. OF MINOR CHANGES";N
1690 LPRINT
1700 RETURN
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>90</td>
<td>65</td>
<td>102</td>
<td>30</td>
<td>600000</td>
<td>400000</td>
<td>.81</td>
<td>750000</td>
<td>120000</td>
<td>11900</td>
<td>50000</td>
<td>100000</td>
<td>.73</td>
<td>.3</td>
<td>.7</td>
<td>200</td>
<td>250</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
<td>.415</td>
<td>102</td>
<td>30</td>
<td>600000</td>
<td>400000</td>
<td>.81</td>
<td>950000</td>
<td>120000</td>
<td>11900</td>
<td>50000</td>
<td>100000</td>
<td>.73</td>
<td>.3</td>
<td>.7</td>
<td>200</td>
<td>250</td>
<td>50</td>
</tr>
<tr>
<td>---------------</td>
<td>----------------------</td>
<td>----------------------</td>
<td>-------------------------</td>
<td>-------------------------</td>
<td>-------------------------</td>
<td>-------------------------</td>
<td>--------------------------</td>
<td>-----------------</td>
<td>----------------------</td>
<td>---------------------</td>
<td>----------------------</td>
<td>----------------------</td>
<td>---------------</td>
<td>----------------</td>
<td>----------------</td>
<td>----------------</td>
<td>----------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>3</td>
<td>90</td>
<td>6.683</td>
<td>98</td>
<td>29</td>
<td>60000</td>
<td>40000</td>
<td>.86</td>
<td>800000</td>
<td>120000</td>
<td>11900</td>
<td>50000</td>
<td>100000</td>
<td>.73</td>
<td>.3</td>
<td>.7</td>
<td>200</td>
<td>350</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>90</td>
<td>65</td>
<td>102</td>
<td>45</td>
<td>60000</td>
<td>40000</td>
<td>.9</td>
<td>1.2E+06</td>
<td>180000</td>
<td>168000</td>
<td>100000</td>
<td>200000</td>
<td>.73</td>
<td>.3</td>
<td>.7</td>
<td>200</td>
<td>350</td>
<td>50</td>
</tr>
</tbody>
</table>