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Assembly system selection in a conceptual manufacturing system design model

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**Assembly system selection in a
conceptual manufacturing system design model**

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by

Hsiu-Chen Wu

A Thesis Submitted to the
Graduate Faculty in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE

Department: Industrial and Manufacturing Systems Engineering
Major: Industrial Engineering

Signatures have been redacted for privacy

Iowa State University
Ames, Iowa
1991

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CHAPTER 1. INTRODUCTION

Modern manufacturing systems are highly complex and consist of tangled relationships among various subsystems. For instance, the initial decision for material handling equipment selection by economic analysis may suggest an automated guided vehicle. While solving the machine layout problem later, constraints, such as space limitations, may change the material handling decision to a robot. Obviously, the key to success in manufacturing is to integrate proper selection and effective use of machines, tools, fixtures, and material handling systems corresponding to a good product design. Additionally, to ensure success, essential elements such as the machine layout, information systems, and economic analysis must be considered.

A good design is very important for the whole manufacturing system. Wierda states that about 75% of the eventual costs are defined in the product design stage [34]. Therefore, the designer is in an excellent position to reduce the production costs. A competent designer can utilize a fundamental knowledge of engineering principles and his experience with successful or even unsuccessful designs, and satisfy all the specifications of the product. Recently, designers have attempted to develop new technologies to cope with the complexities of manufacturing systems. As a result, the designing of manufacturing systems is composed of diverse sets of disjointed design tools that should be well integrated. However, a satisfactorily defined methodology

that describes the integration of the design tools does not exist.

The purpose of this research is to develop a conceptual model for manufacturing system design. Additionally, since the selection of production systems plays an important role in the complete model of manufacturing system design, the technique of selecting production systems applied to assembly systems is stated and a working prototype will be developed on an engineering workstation. This research will provide a starting point for developing a more detailed methodology used to guide the engineer through the design of the manufacturing system.

CHAPTER 2. REVIEW OF RELEVANT LITERATURE

In order to be competitive, industry today faces the problem of reducing manufacturing costs [24]. But at the same time, many factors tend to increase manufacturing costs, such as more product variants, shorter delivery times, and higher quality. In order to reduce cost while still fulfilling the above requirements, new production technologies have been developed to emphasize the integration of the following systems: production layout, management organization, automation, manufacturing processes, and information technology. It is obvious that modern manufacturing systems have become more complex and present close relationships among various subsystems. So, the understanding of systems could be the first step in facing today's manufacturing problems.

The Nature of Systems

In order to learn more about manufacturing system design, it is necessary to illustrate and define the basic concepts of systems.

Definition and components of systems

Blanchard and Fabrycky say that a system is a combination of elements or parts which form a complex or unitary whole, such as a transportation system [9].

Basically, systems are composed of components, attributes, and relationships. These are described as follows.

1. Components are the operating parts of a system including input, processing, and output.
2. Attributes characterize the parameters of a system.
3. Relationships are the links between components and attributes.

Consider the air-conditioning system in a house as an example. The components of the system include the house, the heat pump, the thermostat, and the air within the house. The attributes of each component could be different. For example, the attribute of air in the system is temperature. Now focus on the relationships among thermostat, air, and heat pump. The thermostat action depends on the temperature of the air; the heat pump state depends on the action of the thermostat.

System classifications

Systems may be classified in different ways [31], such as static versus dynamic or open versus closed. A static system is one that has structure without activity. A bridge crossing a river is a static system. A dynamic system, like a manufacturing factory, combines structure components with activity and involves time-varying behavior. A closed system is one that does not interact significantly with its environment. An example is the chemical equilibrium eventually reached in a closed vessel. An open system, such as a business organization, is one that interacts with its environment and allows information and energy to cross its boundaries.

System Life Cycle

The system life cycle of a system or product begins with the recognition of need, then extends through planning, research, design, production, evaluation, system use, and product phaseout [9]. A large system, such as a communication network, may evolve through all activities. The major activities in a system life cycle for the producer are explained as follows:

1. System planning: marketing analysis and feasibility study.
2. System research: investigation of different methods for the specific objectives.
3. System design: conceptual design, preliminary system design and detail design.
4. Production: operations analysis, quality control, and production operations.
5. System evaluation: formal test and evaluation, data collection, analysis, and corrective action.

System Approach

The system approach is a technique that represents a systematic approach to problems that may be interdisciplinary [20]. Its usefulness increases with problem complexity by permitting the engineer to take a broad overall view of the problem under consideration. It emphasizes that the problem should be critically examined and the problem environment should be broadly defined. The system approach discourages the engineer from presenting a specific problem definition or adopting a particular model in the beginning. In this way, the engineer may induce the environ-

mental components or impacts explicitly for the problem. Based on the concept of the system approach, the steps of any problem approach could be as follows:

1. Collecting many alternatives.
2. Developing criteria to measure whether each proposed alternative satisfies the stated requirements.
3. Identifying as many alternatives as possible that may satisfy the stated requirements.
4. Determining if each component of the system is technologically and economically feasible.
5. Building a model of the system.

Design of Engineering Systems

Many of the studies of design in the field of engineering are not new. In Jain and Agogino's research of the theory of design [17], the optimizing design theory and methodology are described through a multispeed gearbox design example. The gearbox design problem is decomposed into three stages: selection of the gear type and clutching sequence, kinematic synthesis, and parametric redesign. In most cases, realistic design problems are too large to be solved entirely in one step. Therefore, it is necessary to decompose the design space into manageable sizes.

Mechanical design

Duffey and Dixon [12] state that a mechanical design process is determined by three different factors: the design problem type, the designer(s), and the environment. The design problems must be classified independently of other factors. Nobel and Tanchoco emphasize the importance of functional and economic justification in developing a product [22]. The traditional design process has not dealt explicitly with the issue of the economics of design. This means that economic considerations are always kept in mind, but the actual evaluation is not done until the design is completed.

Routine design approach

Brown and Chandrasekaran use a routine design approach in mechanical design [3]. This approach occurs when the designer makes selections from previously known sets of well understood design alternatives and makes parametric redesign. Using a bicycle as an example, when a bicycle needs its handlebars redesigned for new customers, only the parameters of the handlebars are changed in order to achieve the new requirements. Because the changes made to the bicycle are easy to identify, the new bicycle appears to be a routine design activity. The routine design task may become very complex by just looking at a design database or prototype library if there are many possible combinations of initial requirements.

Engineering design

Boyle describes engineering systems design as a feedback process that suffers from complexity and uncertainty [7]. He also emphasizes the importance of a full

understanding of the design process. In the broad range of design methodologies, there is a split into three design techniques: analytical, procedural, and experimental. In analytical design, or attribute-centered design, the attributes of the objects are used to decide the proper design actions. The final solution is synthesized from the attributes of the object and the associated design objectives. Procedural design, or operation-centered design, is a trade-off process. The objective, which tends to be modified, is to transform the object into having the desired attributes. In experimental design, or object-centered design, one works through a set of objects to find the object whose attributes best match the design objectives. Experimental design relies on search rather than on formal procedures.

Design-Related Specialities

In the manufacturing field's existing design, much has been accomplished in design-related specialities, such as design for producibility, design for reliability, design for manufacturability.

Design for producibility

Priest states that design for producibility [23], or design for production, is the philosophy of designing a product so that it can be produced with high quality and at low cost. A good production design must not only fulfill all performance requirements but must also minimize production and life cycle cost and maximize quality and reliability. Although producibility analyses may require additional expenses, the benefits obtained from reduced costs of testing or maintenance make them more than worthwhile.

Design for reliability

One of the most significant design specialties is reliability [9]. Only reliable systems can achieve all the design specifications. There are four important elements which determine system and product reliability: probability, satisfactory performance, time, and specified operating conditions. The probability is stated as a quantitative expression representing a fraction specifying the number of times that an event is expected to occur in a total number of trials. Of course, reliability must be an integral part of the overall system engineering process.

Design for manufacturability

In order to bridge the gap between design and manufacturing it is essential for designers to have more manufacturing information during the design of the product. In response to this point, design for manufacturability has become an important issue. Cutkosky and Tenenbaum describe a methodology for concurrent product and process design which is based on the premise that manufacturability is best assured by simultaneous design of the part and the process used to assemble or fabricate it [11]. They also indicate simultaneous engineering, team design, and rapid prototyping, as three of the most promising methodologies.

Computer-Based Design Tools

It is also known that modern designers need more support in the conceptual development process of design and evaluation among design alternatives because design complexities have increased. Computer-based models of design processes should be very helpful in performing design tasks. Recently, a number of papers have been

published in the area of expert systems, which use a problem-solving approach following the same procedures humans use to show that computers can do design work. In expert systems, solutions are most frequently obtained by utilizing heuristic algorithms.

Expert systems in manufacturing design

Heragu and Kusiak state that expert systems have been applied in the area of manufacturing design and operational planning [15]. In manufacturing system design, the first step is to design the set of parts. Once this is done, the production process required to produce the set of parts is designed. This is process planning. Process planning specifies the number and types of equipment to be used and influences the layout of the equipment on the factory floor. Therefore, four activities involved in manufacturing design are: part design, process planning, equipment selection, and facility layout. There are existing expert systems applied in these four activities. Heragu and Kusiak also state the three issues in an expert system: knowledge representation, knowledge acquisition, and inference strategy.

Simulation in manufacturing systems

In addition to expert systems, a lot of work related to simulation has been done in recent years. A simulation program called "Flexible Manufacturing Simulation" [27] is used for designing, simulating, and optimizing manufacturing plants. In this simulation program, machine and product design, floor layout, simulation run, statistical output, and user interface are included. The power of this system design lies in the ease with which it is used and the immediate feedback of simulation runs. It

is also said that the user does not need to be familiar with computers, programming or simulation languages.

Bringing Manufacturing Systems into Being

Definition of manufacturing systems

Before designing a specific manufacturing system, the meaning of manufacturing systems should be clearly defined. Manufacturing systems, which are composed of workstations, operations, and a series of manufacturing processes, are used to make a desired product(s) and component(s) [8]. Because of inconsistencies in popular usage, the terms such as production systems, manufacturing systems, and manufacturing processes tend to overlap. Black states that production system means the whole company, including people, machines, material, and information. That is, the production system includes the manufacturing system and the servicing of them. Additionally, it is emphasized that the designing of a product is different from the designing of a manufacturing system. It could be routine to build a working prototype of a product, but it is much more difficult to develop a working model of a manufacturing system.

Hierarchical system structure for manufacturing system

The hierarchical system structure is used to identify the components contained in the system and depicts the relation of the system's components [20]. Furthermore, this structure permits the analysis of a system in terms of both higher and lower level systems. Based on this concept, the hierarchical system structure in this research is shown in Figure 2.1.

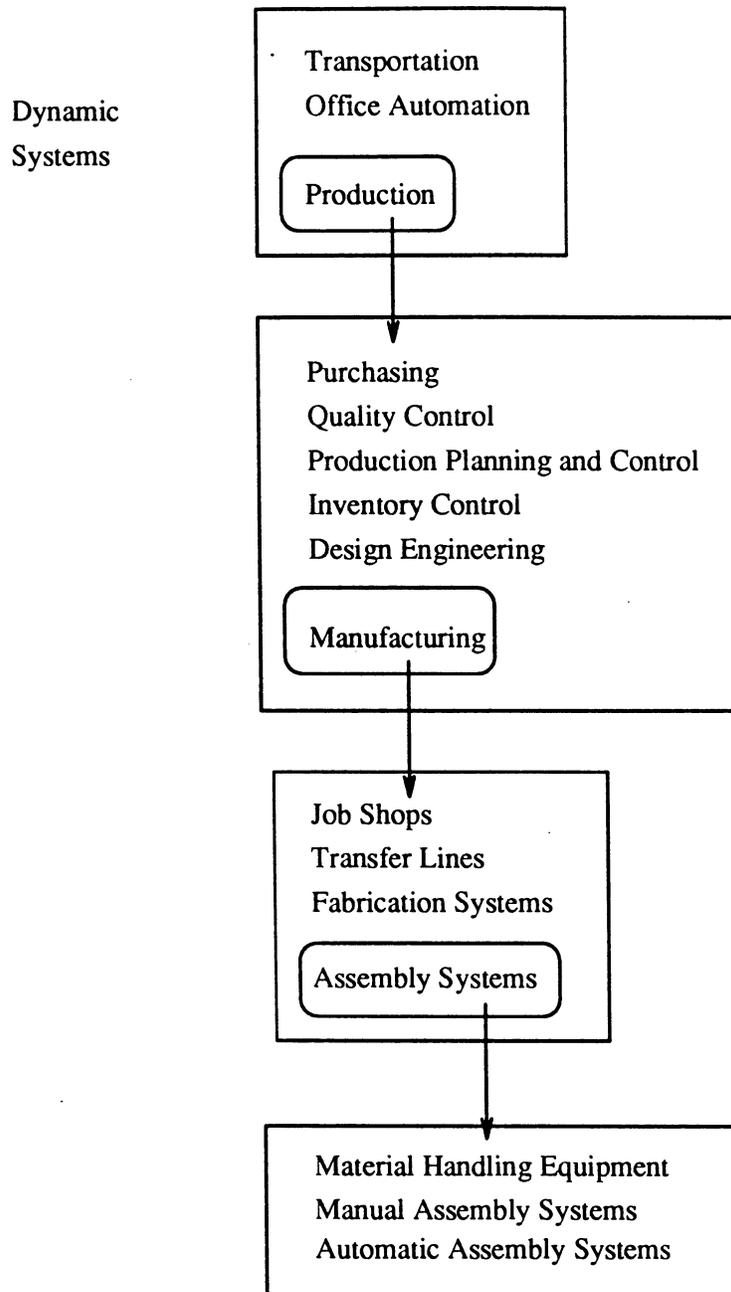


Figure 2.1: The hierarchical system

Basic issues in manufacturing system design

Nevins et al. emphasize the importance of careful specification of the information needed for a good manufacturing system design [21]. The manufacturing system design procedure is comprised of these steps:

1. Analyze the product and operations. Identify alternative fabrication methods or assembly sequences.
2. Select an assembly sequence for the assembly system.
3. Take production capacity and yield rate into account.
4. Estimate the cost and time for each operation.
5. Select a set of equipment or people for the product.
6. Make economic analyses.

They also state the design factors as follows: capacity planning, resource choice, task assignment, workstation design, floor layout, material handling equipment choice, part provision, and economic analysis.

Mathematical models for manufacturing system design

Kusiak states that the manufacturing system design is a complex activity that requires solving problems arranged in a hierarchy. There are two hierarchical approaches, four-level and two-level, used in manufacturing system design [18]. The four-level approach involves equipment selection, machine cell formation, machine layout, and cell layout. If group technology, machines grouped into cells based on

the similarity of process plans, is not used the design of a manufacturing system involves only equipment selection and layout of machines. Each of the models used to solve problems could be an integer programming formulation or transformed into an equivalent linear mixed integer programming model. Necessary matrices, such as operation-machine cost, and operation-machine time, and necessary vectors, such as available time on each machine, and number of operations performed should be generated.

Assembly System Design as the Prototype of Manufacturing System Design

Manufacturing system design is a very complex job. Even if it could be supported by well-developed computer aids, all the factors which influence manufacturing system design are still too many or too intangible to be dealt with easily. For these reasons, the assembly systems design, as part of the whole manufacturing system, has been selected as a prototype, and the selection of assembly systems, the first step of assembly system design, is emphasized in this research.

The significance of assembly process

Corresponding to product design, there are fabrication and assembly systems design which have many similarities. For example, in each of the fabrication and assembly system designs, the stations must be selected and arranged to increase the adaptability to new products. Boothroyd, one of the well known researchers in the field of automatic assembly, states that assembly cost often accounts for more than 50% of the total manufacturing costs [10]. The assembly process is responsible for

most of the added value to a product. Therefore, by the application of automation and modern techniques, the assembly system offers significant opportunities to reduce manufacturing costs.

The influence of proper assembly design

Boothroyd and Dewhurst say that design is the first stage of manufacturing which determines major portion of manufacturing costs [4]. They also illustrate this with an example that computer-related products could be reduced 20 to 40% in manufacturing cost and increased 100 to 200% in assembly productivity through proper consideration of assembly at the design stage. The first step of an assembly system design is to identify the most economic assembly process for a particular product. Then the product can be designed for the selected process. The selection in the early stage is very important. For example, manual assembly is different from automatic assembly in product design because an operation that is easy for a person could be impossible or very difficult for a robot or special-purpose workhead. Therefore, the best way to achieve the lowest assembly cost is to design a product which can be economically assembled by the most appropriate process.

Classification of assembly systems

According to the different types of assembly processes, there are three basic types of assembly systems [29]:

1. Manual assembly: manual assembly on an assembly line using only simple tools.
2. Special-purpose machines: automatic assembly using special purpose machines.

3. Programmable machines: automatic assembly using programmable machines.

Each system has its own advantages and restrictions.

Selection of assembly systems by dimensionless assembly cost

Boothroyd analyzes the economics of different assembly systems to select the proper one [6]. He uses the following variables for the analysis:

1. Part quality: the average ratio of defective to acceptable parts.
2. Number of parts in the assembly.
3. Annual production volume per shift.
4. Product style variations: the ratio of the total number of parts available to the number of parts actually used in the product.
5. Design changes: the number of parts which are changed during the life of the machine.
6. Number of products to be assembled: the number of different but similar products employed.
7. Economic climate: represented by $\frac{S_h Q_e}{W_a}$, where

S_h = the number of shifts per day,

Q_e = the cost of capital equipment that can be used economically to do the work of one operator on one shift (\$),

W_a = the annual cost of employing one assembly operator (\$).

The cost of assembly for a complete assembly (C_a) is given by:

$$C_a = T_b \left(W_t + \frac{C_e W_a}{S_h Q_e} \right)$$

where

T_b = the average time between delivery of complete assemblies (second),

W_t = the total rate for the machine operations (\$),

C_e = the total capital cost for all equipment (\$).

Boothroyd et al. use dimensionless assembly cost per part as the assembly cost index to select the most economical assembly system. The lower the value on the cost index, the more economical the assembly system [29]. The dimensionless assembly cost (C_d) per part is given by:

$$C_d = \frac{C_a}{N_a W_a T_a}$$

where

C_a = the cost of assembly for a complete assembly (second \$/year),

N_a = the number of parts in the assembly such as the number of screws, nuts, and washers in an assembly,

W_a = the annual cost of employing one assembly operator (\$),

T_a = the average manual assembly time per part (second).

Choosing systems based on unit cost

Gustavson indicates that a unit-cost-to-produce analysis can be used in choosing manufacturing systems [13]. Appropriate systems are chosen based on minimum cost at the particular production quantities. His analysis has been applied to the selection of assembly systems. There are two cost factors to be considered, variable and fixed costs. Variable unit cost (C_v) is the sum of labor and operating/maintenance costs and can be expressed as:

$$C_v = \frac{wL_h + O_h}{q_h}$$

where

w = number of workers,

L_h = average loaded labor rate (\$/hour: wages + benefits + overtime premiums),

O_h = total operating/maintenance rate (\$/hour),

q_h = hourly production rate (unit/hour).

The factors such as number of stations, system efficiency, and system cycle time are counted in the variable unit cost.

Fixed unit cost (C_f) is the annualized capital cost divided by annual production volume. It is given by:

$$C_f = \frac{P_a}{Q_y}$$

where

P_a = total annualized and installed system price (\$),

Q_y = yearly production quantity (unit/year).

The ratio of total installed cost to hardware price, minimum attractive rate of return, and investment horizon are included in the fixed cost.

The total unit cost (C_t) is the sum of the fixed unit cost (C_f) and variable unit costs (C_v). It is described as:

$$C_t = C_f + C_v$$

By equating the total unit costs for any two alternative systems, the cross-over point can be established. According to this point, the corresponding production volume is indicated. Choosing either of the systems at this point is the same based on unit cost. If the yearly production volume is above or below the indicated production volume, one of the systems is chosen according to the lower unit cost.

Research Objectives

The basis for this research is to supplement the above methodologies and to build a conceptual model for manufacturing system design and, finally, to develop a working prototype on a workstation. The working prototype is applied primarily to the assembly systems. The methodologies used in the economic analysis for manufacturing system design are described in Chapter 3.

CHAPTER 3. METHODOLOGY

The techniques discussed in Chapter 2 are used to develop the conceptual model for manufacturing system design and the working prototype on a workstation. Three sections are presented in this chapter. The first is the conceptual model for manufacturing system design. The second is the detailed description of the selection of manufacturing systems according to both the research of Boothroyd and Gustavson. Finally, the methodology used in this research is introduced in the third section.

Model of the Conceptual Manufacturing System Design

The conceptual manufacturing system design model is divided into ten submodels which are classified into six stages:

Stage 1 Requirements Analysis.

Stage 2 Manufacturing System Selection.

Stage 3 Product and Process Design.

Stage 4 Equipment Selection, Material Handling Equipment Selection, and Machine Layout.

Stage 5 Information System and Economic Analysis.

Stage 6 Recommendations.

The first stage is the basis. Each stage should refer to the preceding stages; submodels at the same stage are parallel. On the proposed model of conceptual manufacturing system design described in Figure 3.1, the availability and constraints of resources or the probability of demand changes are not included.

The Selection of Manufacturing Systems

The selection of manufacturing systems is an essential subsystem within the whole model of manufacturing systems design. It influences all following design stages. In this research, this is implemented in a workstation primarily as the selection of assembly systems.

Boothroyd's methodology

Besides the description of assembly systems in Chapter 2, Boothroyd's methodology in calculating C_d , the dimensionless assembly cost per part, and the classification of assembly systems are described in following sections in detail. Additionally, a program written in FORTRAN is implemented in a workstation environment to demonstrate the results of different input variables. It is provided in Appendix B.

Classification of assembly systems In Boothroyd's methodology, assembly systems are classified into six types for analytical purposes [4]. The systems are:

1. AI: automatic assembly using special-purpose indexing machines, workheads, and automatic feeders.

2. AF: automatic assembly using special-purpose free-transfer machines, work-heads, and automatic feeders.
3. AP: automatic assembly using manually loaded part magazines and a free-transfer machine with programmable workheads capable of performing several assembly tasks.
4. AR: automatic assembly using manually loaded part magazines and a sophisticated two-arm robot with a special-purpose gripper that can handle all the parts for one assembly.
5. MA: manual assembly on a multistation assembly line.
6. MM: manual assembly with mechanical assistance.

Description of C_d As described in Chapter 2, the dimensionless assembly cost per part (C_d) is given by:

$$C_d = \frac{C_a}{N_a W_a T_a}$$

and the total cost of assembly (C_a) is:

$$C_a = T_b \left(W_t + \frac{C_e W_a}{S_h Q_e} \right)$$

Therefore, all these variable parameters are needed to calculate C_d . In this equation, T_b is the greater value of T_p and T_q , that is:

$$T_b = \max(T_p, T_q)$$

where T_p is the production time obtainable for a particular assembly system and T_q is the required production time for one assembly system. Table 3.1 shows the

equations employed in the six assembly systems and in Appendix A the definitions of constant factors and variable parameters are given.

However, if there are several product styles or the effects of other factors, (i.e., a part design change which needs new feeders or workheads) are considered, these equations must be modified. The equations applying these factors are given in Table 3.2.

It should be noted that in Boothroyd's methodology, if the required production volume is greater than that obtainable from the system, then it is assumed that backup will be provided in the form of manual assembly stations. Then a second system will be employed when the required volume approaches twice that obtainable from the system and so on. Therefore, the assembly cost is independent of the number of assembly systems.

Output analysis After Boothroyd's methodology in assembly system selection has been described, a program interpreted from equations in Table 3.2 is used to calculate results for C_d , dimensionless assembly cost per part. The following provides an example calculation. Suppose, the annual volume per shift (V_s) is 200,000 and the number of parts in the assembly (N_a) is 4. This is a single product; N_p is 1. The total number of parts required to manufacture different styles (N_t) is 5. Assume one major design change is expected during the product life; N_d is 1. The investment factor (R_i) is 4 which is defined as:

$$R_i = \frac{S_h Q_e}{W_a}$$

In this formula, the number of shifts (S_h) is 2; annual cost of employing one assembly operator (W_a) is 36,000; the cost of capital equipment that can economically be

Table 3.1: Summary of equations employed in the comparison of assembly syst

| System | Equations |
|--------|---|
| AI | $T_p = T_w + N_a P_q T_d$ $W_t = N_i W_a + W_s \quad (N_a > 6)$ $\text{or } N_r W_a + W_s \quad (N_a \leq 6)$ $C_e = N_a (C_c + C_{fd} + C_{tr} + C_w)$ |
| AF | $T_p = T_w + P_q T_d, W_t = N_i W_a + W_s$ $C_e = N_a (C_{fd} + C_w + (1 + T_d/T_w)(C_b + C_c/2))$ |
| AP | $T_p = N_s (T_r + P_q T_d), W_t = N_i W_a + W_s$ $C_e = (N_a/N_s)(C_r + (1 + T_d/T_r)(C_b + C_c/2)) + (N_a(C_g + C_m))$ |
| AR | $T_p = N_a (T_r/2 + P_q T_d), W_t = W_s$ $C_e = 2C_r + C_c + N_a (C_g + C_m)$ |
| MA | $T_p = N_s T_a (1 + P_q), W_t = (N_a/N_s) W_a$ $C_e = (N_a/N_s)(2C_b + C_c)$ |
| MM | $T_p = N_s T_m (1 + P_q), W_t = (N_a/N_s) W_a$ $C_e = (N_a/N_s)(2C_b + C_c) + N_a C_{fd}$ |
| | $T_q = 7.2e/V_s$ $\text{for AP } N_s = T_q / (T_r + P_q T_d)$ $\text{for MA } N_s = T_q / (T_a (1 + P_q))$ $\text{for MM } N_s = T_q / (T_m (1 + P_q))$ |
| | $C_d = (T_p/T_a)(W_t/(W_a N_a)) + (C_e/N_a)/(S_h Q_e)$ |

Table 3.2: Summary of modified equations employed in the comparison of assembly systems

| System | Equations |
|--------|--|
| AI | $T_p = T_w + N_a P_q T_d$ $W_t = N_i W_a + W_s \quad (N_a > 6)$ $\text{or } N_r W_a + W_s \quad (N_a \leq 6)$ $C_e = N_a (S_v C_{tr} + N_p (S_v C_c + (S_v + R_d)(C_{fd} + C_w)))$ |
| AF | $T_p = T_w + P_q T_d, W_t = N_i W_a + W_s$ $C_e = N_a (S_v + (1 + T_d/T_w)(C_b + N_p C_c/2)) + N_p (S_v + R_d)(C_{fd} + C_w)$ |
| AP | $T_p = N_s (T_r + P_q T_d), W_t = N_i W_a + W_s$ $C_e = N_a ((C_r + (1 + T_d/T_r)C_b)/N_s$ $+ N_p ((S_v + R_d)C_m + C_g + (1 + T_d/T_r)(C_c/2/N_s))$ |
| AR | $T_p = N_a (T_r/2 + P_q T_d), W_t = W_s$ $C_e = 2C_r + N_p (C_c + N_a C_g + N_a (S_v + R_d)C_m)$ |
| MA | $T_p = N_s T_a (1 + P_q), W_t = (N_a/N_s)W_a$ $C_e = (N_a/N_s)(2C_b + N_p C_c)$ |
| MM | $T_p = N_s T_m (1 + P_q), W_t = (N_a/N_s)W_a$ $C_e = (N_a/N_s)(2C_b + N_p C_c + N_s (N_p (S_v + R_d)C_{fd}))$ |
| | $S_v = N_t/N_a$ $R_d = N_d/N_a$ $T_q = 7.2e/V_s$ $\text{for AP } N_s = T_q/(T_r + P_q T_d)$ $\text{for MA } N_s = T_q/(T_a(1 + P_q))$ $\text{for MM } N_s = T_q/(T_m(1 + P_q))$ |
| | $C_d = (T_p/T_a)(W_t/(W_a N_a) + (C_e/N_a)/(S_h Q_e))$ |

Table 3.3: Results of C_d from Boothroyd's methodology

| Assembly Systems | $V_s = 0.2$ $Q_e = 72$ | $V_s = 1.0$ $Q_e = 72$ | $V_s = 0.2$ $Q_e = 12$ | $V_s = 1.0$ $Q_e = 12$ |
|------------------|---------------------------|---------------------------|---------------------------|---------------------------|
| AI | 3.3163 | 0.8277 | 6.4224 | 1.6081 |
| AF | 4.5303 | 0.9666 | 10.6217 | 2.2663 |
| AP | 3.9373 | 0.9744 | 5.9570 | 2.3132 |
| AR | 3.2085 | 1.4467 | 5.7960 | 2.6133 |
| MA | 1.3369 | 1.0872 | 1.8112 | 1.4729 |
| MM | 1.1205 | 1.0258 | 2.1778 | 1.6097 |

used to do the work of one operator on one shift (Q_e) is 72,000. Annual cost of employing one machine supervisor (W_s) is 156,000. Plant efficiency (e) is 69%. The other time and cost variables are given in Appendix A. After the comparison of C_d among the six assembly systems, manual assembly with mechanical assistance (MM) is chosen as the most economical system (lowest C_d). If the production volume is higher, such as 1 million per shift, the automatic assembly using special-purpose indexing machines (AI) could be used. If the company's investment policy becomes less generous, reduction of Q_e to 12,000, the manual assembly (MA) would be the most appropriate system. Table 3.3 shows the results which can be compared with Boothroyd's assembly method choice chart [4]. The units for Q_e and V_s are thousand dollars and million. Since input variables W_s and e are not indicated in the chart, the results from the chart and from the program are not always consistent. For example, when V_s is 1 million and Q_e is 12,000, Boothroyd's assembly method choice chart indicates AI is the most economical system, but the program results MA.

Gustavson's methodology of the selection of assembly systems

As described in Chapter 2, Gustavson employs variable and fixed costs in the unit cost analysis to choose the appropriate assembly system.

Nomenclature

D number of working days per year

e system efficiency (%/100%)

f the annual cost factor

h investment horizon (years)

L_h average loaded labor rate (\$/hour: wages + benefits + overtime premiums)

m_s maximum number of stations that a worker can handle

n number of tasks to be performed

$\frac{n}{\sigma}$ number of tasks per station

O_h total system operating cost (\$/hour)

P_a total annualized system price (\$)

P_r average hardware price for each station (\$)

P_t average tool/material handling hardware price (\$)

q_h hourly production volume

\dot{Q}_y yearly production volume

r minimum attractive rate of return (%/100%)

s number of shifts actually used

t average task cycle time

T average cycle time

v portion of the system cost at end of year h .

V_h average operating/maintenance rate per station (\$/hour)

w number of workers

σ number of stations in the system

ρ the ratio of the actual installation cost to hardware cost

3600 seconds per hour

8 working hours per day

Variable cost The variable unit cost is given as:

$$C_v = \frac{wL_h + O_h}{q_h}$$

For any proposed system, the number of workers (w), the total system operating cost (O_h), and the hourly production (q_h) should be well-defined. For initial design, w can be estimated by:

$$\text{truncate} \left[\frac{\sigma - 1}{m_s} + 1 \right]$$

When performing new system design, it is helpful to define O_h in terms of each usable station. This relationship is:

$$O_h = \sigma V_h$$

The hourly production rate (q_h) (unit/hour) is a function of the efficiency (e) and theoretical system cycle time (T). That is:

$$q_h = \frac{3600}{\frac{T}{e}}$$

System cycle time ($\frac{T}{e}$) can be measured by timing studies from an existing system. When performing initial system design, the theoretical cycle time (T) (sec/unit) can be given by:

$$T = \frac{n}{\sigma} t$$

Although this equation can only be applied to a balanced system, it does provide a good first approximation.

Fixed cost For cost accounting purposes, manufacturing capital investment is annualized. The fixed unit cost (C_f), as in Chapter 2, is expressed as:

$$C_f = \frac{P_a}{Q_y}$$

Yearly production volume (Q_y) (unit/year) is given as:

$$Q_y = s(8D) q_h$$

Substituting the equation of q_h into the above equation:

$$Q_y = s(8D) \left[\frac{3600}{\left(\frac{n}{\sigma}\right)t} \right]$$

In practical applications, s is likely to be 1, 2, or 3.

For most manufacturing systems, the annualized cost (P_a) (\$/year) can be approximated by:

$$P_a = \rho(\sigma P_r + n P_t) f$$

For known technology the factor ρ is approximately 1.5. If the technology is new, the factor will become higher. The annual cost factor (f), or capital recovery factor, is calculated with an estimate of the minimum attractive rate-of-return, the specification of the investment horizon, the economic life and the depreciation method. It is expressed as:

$$f = \left[1 - \frac{v}{(1+r)^h} \right] \left[\frac{r(1+r)^h}{(1+r)^h - 1} \right]$$

The annual cost factor establishes the proportion of a capital investment which can be charged to a product on a yearly basis. Then it can be used in the comparison of alternative systems.

Total unit cost Total unit cost is given as:

$$C_t = C_f + C_v$$

Substituting equations for C_f and C_v into the above equation results in the following:

$$C_t = \left[\frac{\left(\frac{n}{\sigma}\right) \frac{t}{e}}{3600} \right] \left[\frac{\rho(\sigma P_r + n P_t) f}{s(8D)} + w L_h + \sigma V_h \right]$$

Cross-over point The relationships between fixed and variable costs within a system as well as among various systems are very important when creating least-cost systems. For example, two systems will be compared, a base (B) system and an

alternative (*A*) system. The cross-over point is found by dividing the difference in system fixed costs by the difference in system variable unit costs:

$$Q_y = \frac{P_{aA} - P_{aB}}{C_{vB} - C_{vA}}$$

Therefore, the quantity at this point can be found. If the required quantity is not in the equilibrium point, the more economical system should be chosen by lower unit cost. It should be noted that, in practice, the maximum number of shifts is 3, that is, that maximum Q_y is achieved from the system with its maximum number of shifts. Therefore, when using crossing-over point calculation, a system can not be selected if the required production volume is over its maximum capacity.

The Proposed Methodology

Based on the methodologies discussed in this chapter, a hybrid methodology is proposed. Boothroyd's investment factor (R_i) for equipment could be replaced by an annualized cost which is influenced by the annual cost factor (f), and the ratio of the actual installation cost to hardware cost (ρ). The details will be described in the following chapters.

CHAPTER 4. CONCEPTUAL MODEL FOR MANUFACTURING SYSTEM DESIGN

As was shown in Figure 3.1, there are ten submodels in the conceptual manufacturing system design model. Each is separate but has a close relationship to other submodels. As described in Chapter 3, these submodels are classified into six stages according to their priority; submodels in the same stage are parallel.

Structure of the Design Model

The first stage contains requirements analysis, which serves as the basis of the complete system design model. Once the requirements have been determined, the suitable manufacturing system should be selected. It is very important to decide which type of manufacturing system, such as manual or automatic, is to be used at an early design stage. For example, a product design for automatic assembly machines is different from a design for manual assembly.

The third stage consists of product and process design. Although the manufacturing system design model focuses on system design, product and process design should be included from the “simultaneous” design point of view. That is, any design change of product and process might influence the initial system design. Alternatively, product and process might need to be changed due to a limitation of the

machinery; for example, the machinery may not provide the required preciseness.

The fourth stage is made up of equipment selection, material handling equipment selection, and machine layout. A stage containing the information system and economic analysis is located between stages 3 and 4. Database, local network and simulation techniques in an information system are used to store data, communicate data and evaluate existing system designs, respectively. Economic analysis is used to compare alternative systems.

Finally, the last stage is recommendations. If the existing system design is physically feasible within a reasonable unit cost, the manufacturing system configuration has been determined. Alternatively, if the existing system design needs redesign, then all design stages beginning with stage 2 need to be reformulated. This process might resemble a loop once any redesign is needed.

In the following sections, the ten individual models for conceptual manufacturing system design are described in detail.

Analysis of Requirements

In order to make rational comparisons of various technologies, the first issue for manufacturing system design is to analyze requirements which involve local and global issues for the proposed system. Based on the research of Gustavson et al., the requirements could be stated as follows [14].

1. Global:

- Cost and productivity
- Labor needs

- Space needs
- How it interfaces with other systems

2. Local:

- Machine layout
- Equipment requirements
- Part feeding
- Material handling equipment requirements

Manufacturing System Selection by Unit Cost Performance

The selection of manufacturing systems is mainly an economical decision. The design of a manufacturing system should be based on the same consideration [16]. Once the requirements have been determined, the available manufacturing systems can be analyzed with these requirements in mind. The system with the lowest unit cost should be considered in the following detailed manufacturing system design, such as process design, equipment selection, and machine layout.

The input data and methodology used for the selection of assembly systems will be demonstrated on a workstation as described in the following chapters. Some production data, such as product cycle time and number of parts for a system, or factory economic data, such as labor rate and working days per year, are necessary for the proposed methodology.

Product Design

The input data for each of the product and process models are the basis for the following detailed manufacturing system design. According to product design, there are assembly and fabrication systems which are described as follows.

Assembly systems

The input data for an assembly product could be classified into four levels [2]. The product level is made up of product data. The subassembly level stores information regarding identified subassemblies. A subassembly for a final product could be identified as a product for a subassembly supplier; consequently, the “subassembly information” is stored at a specified level according to each company’s practice. The next level, parts level is represented by the list of parts for each subassembly. The last one stores the attributes of the parts. By means of this data representation structure, it is possible to represent a product with variants. The contents for each level are as follows.

1. Product level:

- Product identification code
- Required production volume
- Number of product variants

2. Subassembly level:

- Product identification code
- Subassembly identification code

- Subassembly quantity
- Number of subassembly variants

3. Part level:

- Product identification code
- Subassembly identification code
- Part identification code
- Part quantity
- Number of alternative parts

4. Attributes of parts:

- Feeding or orienting operations
- Inserting or securing operations

The attributes of assembly parts for feeding or orienting are rotational, non-rotational, and prismatic. Other attributes of parts could be dimensions, lengths, weights, basic sizes, tolerances, and materials.

Fabrication systems

The input data for a product of a fabrication system are directly related to the characteristics of parts.

1. Types, hardness, and strength of working materials.
2. Geometric size, shape, and weight.

3. Tolerance between parts.
4. Surface finish.
5. Initial surface condition of parts.

Process Design

Corresponding to process design, there are also assembly and fabrication systems as in the previous section.

Assembly systems

The input data for an assembly system can be divided into three levels: part, subassembly, and final assembly for a modular product [2]. The parts level of the process is related to the parts level for the product database. At the subassembly level, devices are evaluated, such as a feeder with a single part or a robot with various parts. The database is simplified; for example, if only one robot is inside the station, the data for various parts are stored in only one datum.

1. Parts level:

- Device typology for feeding, orienting, inserting, and securing
- Number of devices according to variants of parts
- Number of alternative stations to assemble alternative parts

2. Subassembly level:

- Candidate of subassembly sequence

- Total operation time for subassembly
- Number of effective stations
- Total operation time

3. Final assembly level:

- Candidate of assembly sequence
- Total number of stations in the system
- Total equipment cost
- Number of direct operators
- Number of supervisors
- System volume capacity

In the subassembly level, the number of effective stations can be evaluated by alternative subassembly systems associated with the parts' variants. The purpose of classifying the process structure into three levels is to make product evaluation and analysis more simplified within many alternatives.

Fabrication systems

The data related to the machining process are as follows [19].

1. Type of machining operation:

- Turning: used in the production of various cylindrical components
- Drilling: used to produce interior circular and cylindrical holes

- Milling: used to produce different special shapes with various types of cutters
- Grinding: used in finishing cylindrical or flat surface
- Planing or shaping: used to produce horizontal, vertical, or inclined flat surfaces

2. Machine tool parameters:

- Size and rigidity
- Horsepower
- Spindle speed
- Feed rate levels
- Conventional or N/C
- Operation time data

3. Cutting tool parameters:

- Tool material type
- Type of tools
- Geometry: angles and number of teeth
- Tool cost data

4. Operating parameters other than feed and speed:

- Depth of cut
- Cutting fluid

- Workpiece rigidity
- Fixtures and jigs used

Equipment Selection

Based upon the product and process design in stage 3, the following stage for manufacturing system design is equipment selection, material handling equipment selection and machine layout. Equipment selection could be classified into assembly and fabrication equipment.

Assembly systems

According to number of parts, number of variants, number of different products, required production volume, and allowable investment from company's financial policy, assembly machines could be manual or automatic. If an automatic machine is selected, workheads could be programmable or special-purpose according to requirements.

Other equipment includes:

1. Special-purpose devices: feeding, orienting, inserting, and securing.
2. Loaded magazines: manual or automatic.
3. Workpiece orientation: vibratory bowl feeder and hoppers.

Fabrication systems

The equipment selected includes machine, tool, and fixture [11]. The tools are chosen by specified machines and their necessary operations. The classification of

equipment could be as follows:

1. Machines: casting, metal-forming, joining, and metal-cutting machines.
2. Fixtures: clamp, vise, and block.
3. Tools: lathe, boring, countersink, counterbore, drill, endmill, and tap tools.

The input data used for equipment selection are operation descriptions which are based on the data in the product and process models. Some of the important factors are tolerance, geometric shape, size, and weight of parts.

Machinability data According to the operation descriptions, the normal combinations of operations, materials, tools, and machines can be obtained with machinability data. The data include the elemental operation description, the relationship of cutting speed and feeding, tool life, set up time, material cost, machining time, surface finish, power, and the consumption and capabilities of the machines [19]. For example, drilling can be done on drill presses, milling machines, lathes, and some boring machines. The principle for the selection among alternative combinations is to minimize the cost and cycle time. That is, minimize the number of fixtures, tools, and parts; maximize the commonality of tools; minimize tool replacement.

Material Handling Equipment

In practice, the material handling equipment selection is not an optimizing process. Input data for the selection include:

1. The function, cost, and limitation of the equipment.

2. The size of carriers or pallets.
3. The width of aisles.
4. The weight, shape, and volume of the product.
5. Fixed or flexible production routes.

According to Tompkins and White's research, the material handling equipment is classified to the following categories: conveyors; monorails, hoists and cranes; industrial trucks; containers and supports; and auxiliary or other equipment such as AGVs and robots [32].

The factors affecting material handling costs are as follows [1]:

1. Direct costs: operator wages, equipment installation cost, equipment depreciation, maintenance cost, and power and fuel costs.
2. Indirect costs: management effectiveness and downtime space occupied.
3. Indeterminate cost factors: space lost or gained, inventory control, and percent of time equipment used.
4. Intangible factors: quality of equipment, durability, standardization, flexibility, and financial policy.

Machine Layout

Tompkins and White have identified four basic types of facility layouts: fixed material location, production line, product family, and process departments [32].

Basically, the layout procedures are:

1. Define the objectives of the facility.
2. Determine the interrelationships among all activities.
3. Determine the space requirements for all activities.
4. Generate alternative facility layouts.
5. Evaluate alternative facility layouts.
6. Select a facility layout.

If the layout is focused on the machine, the basic types could be [18] linear, single-row; linear, double-row; circular, and multirow. And the input data for solving the machine layout problem are:

1. Number of machines.
2. Frequency of trips among each machine.
3. Handling cost per unit distance.
4. Size of each machine.
5. Minimum distance between machines.
6. Material flow according to material handling equipment.
7. Type of material handling equipment.
8. Total available space.

Information Systems

Database

A database is a collection of information, or data, which is stored in a computer and recalled for processing, optimization, or alteration [33]. For a manufacturing system, a database could be the data of the characteristics of a workpiece, or tools, such as speed and cost. Databases could be time critical or non-time-critical. Time-critical databases are typically used for on-line real time consulting such as getting the information of recent work in progress. Other databases usually provide a historical record of the company, such as the operators' salaries.

Local network

The task of a data-communication network could be a set of functionally-separate models used in manufacturing system design and analysis. The networks are usually organized as a series of layers. The number, name, and function, of each layer depends on the particular network. For open systems interconnection, there are seven layers in sequence from 1 to 7 [26]. The layers are physical, data link, network, transport, session, presentation, and application.

Within a local area network, layers 1 and 2 must be performed for the minimum critical communication function. The physical layer includes the mechanical, electrical, functional and procedural attributes of the physical connections. The data link layer makes the physical link reliable and specifies how each node can access the network. Basically, the objectives of these networking concepts are ease of use, network capacity, high reliability, and optimal use of resources [19].

Simulation

With the simulation on a computer, a mathematical model allows emulation of manufacturing operations. Discrete simulation is usually used to analyze the system. A simulation model for a manufacturing system can be classified into a four-level hierarchy [25].

Level 1 Basic components of a manufacturing system.

Level 2 Machine control.

Level 3 Scheduling.

Level 4 Order processing and planning.

Level 1 The lowest level contains the basic components, such as conveyors, robots, machine tools, fixtures, and buffers. For example, the size of the buffer in front of the testing station may be used to control the machine idle time. At this level the instructions of the higher control level are executed. The elements of this level are standard modules.

Level 2 On the machine control level, the objectives are defined at the scheduling level. For instance, a unit part should be sent to the first available machine or to the machine that has been waiting the longest. This level is used for specific types of actions which may be standardized.

Level 3 The scheduling level is responsible for planning future actions and for making supervisory decisions. An example is how to distribute work orders among

machines, tools and conveyors by the yield rate and operation time. This level causes most of the difficulties. The existing techniques used to handle layout of conveyors and machine tools still can not provide solutions easily.

Level 4 At the highest level, the model handles all order processing and planning activities. For example, it measures the feasibility of mixed products for the existing manufacturing system.

In the proposed manufacturing process, it is impossible to acquire all necessary information from the different levels. Using a well-designed simulation is a good substitution. The simulation languages could be event, process, translation, or activity oriented, according to different concepts.

For a simulation model, the standard data accumulated for obtaining statistical information could be as follows:

1. Order-specific processing times.
2. Loading of the system such as machine tools, robots, and conveyors.
3. Maximum and average contents of a buffer.

Economic Analysis

The purpose of this model is to identify alternative systems, then compare each with the initial system in terms of unit cost and other strategic benefits. Basically, manufacturing system costs are divided into four categories [21]:

1. Fixed cost: annualized initial investment.

2. Variable cost: labor rate, operation or maintenance rate, number of workers.
3. Material cost: the cost of raw materials at the beginning of production.
4. Institutional cost: cost factors such as sales, service, and administrative.

Normally, the last cost factor is eliminated from system comparison because it is assumed to be a constant. Methods of comparing alternatives could be [30]:

1. Annual equivalent and present equivalent: using compound interest formula factors to convert cash flow into a uniform annual or present equivalent sum.
2. Rate of return: based on zero present worth, the investment is assumed to be paid back at the rate of return.
3. Break-even point analysis: applying the break-even concept to examine the variability and sensitivity of the selected parameter.

Additionally, the payback period is also a method used in industry. At this cross-over point, the cumulative undiscounted cash flow goes from negative to positive.

Recommendations

The decision of accepting or discarding the existing system design is made in the last design stage. If the existing design is accepted, the complete manufacturing system configuration is the output. If redesign is needed, then all design stages will need to be formulated again.

CHAPTER 5. SELECTION OF ASSEMBLY SYSTEMS

In a complete model of manufacturing system design, the selection of production systems plays an important role because it directly influences other submodels, such as product, process, equipment selection, and machine layout. In this chapter, the technique of selecting production systems is applied to assembly systems. The most economical assembly system is based on lowest total unit cost.

The Importance of the Selection at an Early Design Stage

In the “Product Design for Assembly” technique, Boothroyd and Dewhurst emphasize that it is very important to decide which type of assembly method is to be adopted based on the lowest costs at an early design stage [5]. Other researchers, Scott and Husband, keep the selection of assembly system at the first design stage after they compare the “orthodox” with an alternative design hierarchy for assembly systems [28]. The “orthodox” design hierarchy is described as follows:

1. Design:

- Product design: selection of assembly system, such as special-purpose machines
- Assembly design: decision of the assembly sequence

- Assembly system design: taking product-design flexibility and quality into systems design.
2. Analysis: cycle-time and cost analysis.
 3. Evaluation: decision.

An alternative hierarchy to follow when designing an assembly system is:

1. Product design: selection of assembly system; eventual comparison between possible products made by each assembly system.
2. Prediction: cycle-time estimation.
3. Analysis: cost analysis.
4. Evaluation: decision.
5. Directed detailed design: design of assembly sequence and detailed design of assembly systems.

Scott and Husband's research is based on an investigation of industrial case studies, design proposals, and general assembly research. The "orthodox" hierarchy tends to synthesize the various stages of a particular assembly system. The alternative hierarchy is employed to replace the "orthodox" and to solve some problems. For example, the detailed design involved in the first stage may choose the wrong system.

Each design hierarchy is consistent with Boothroyd and Dewhurst's methodology in the point of the selection of assembly systems. Undoubtedly, the selection of assembly systems is very important in assembly system design and should be done at the early design stage.

Formulation of Assembly System Selection

The methodology of assembly system selection in this research is formalized in details based on Boothroyd's, Gustavson's, and other general research of assembly systems.

Parameters in assembly system selection

The parameters influencing the selection of assembly systems are classified into three types: variable, derived, and other parameters.

Variable parameters There are nine items described as follows:

1. Required annual production volume per shift (V_s): It has been found that when V_s is small, only manual assembly is worthwhile; when it is large, special-purpose automation is always considered. If V_s is between these extremes, programmable assembly might be selected.
2. Number of shifts (S_h): When expensive automation equipment is installed in a company, the number of shifts tends to be more than one for increasing the utilization of the equipment. In practice, S_h is likely to be 1, 2, or 3, for any system.
3. Number of different products (N_p): The factor N_p is employed as the number of different but similar products. For special-purpose assembly equipment, the transfer device can be re-used, but the workheads, feeders, grippers may be replaced.

4. Number of parts in the assembly (N_a): N_a is a major factor in the selection of an assembly system. Special-purpose automatic machines using indexing transfer mechanisms may be chosen when N_a is less than 10.
5. Total number of parts for different product styles (N_t): When an assembly system is designed to assemble more than one style of the same product, N_t is the total number of parts available.
6. Number of part design changes (N_d): The factor N_d is the number of parts changed during the life of the machine. New feeders and workheads are needed for such changes.
7. Minimum attractive rate of return (r): This factor is used for the derived parameter, annualized factor (f_a).
8. Investment horizon (h): The factor h is the number of years savings are assumed to accumulate for economic analysis.
9. The ratio of actual installation cost to hardware cost (ρ): The ratio ρ can be from 1.2 to 5 depending upon the complexity of systems. For known technology, ρ is approximately 1.5, and for sophisticated programmable assembly systems it is about 1.8 [13]. Basically, when a new system design is to be used this factor is higher.

Derived parameters There are five derived parameters in this research.

1. Annual production volume per shift obtainable from an assembly facility (V_t): If a facility is fully utilized, V_t is the maximum capacity obtainable. The volume is different for each assembly system.

Table 5.1: Depreciated rate under MACRS

| Year | Depreciated Percent(%) | Book Value(%)(v) | Year | Depreciated Percent(%) | Book Value(%)(v) |
|------|---------------------------|-------------------------|------|---------------------------|-------------------------|
| 1 | 14.29 | 85.71 | 5 | 8.92 | 22.32 |
| 2 | 24.49 | 61.22 | 6 | 8.92 | 13.40 |
| 3 | 17.49 | 43.73 | 7 | 8.92 | 4.48 |
| 4 | 12.49 | 31.24 | 8 | 4.46 | 0.02 |

2. The factor used to measure style variations (S_v) is expressed as:

$$S_v = \frac{N_t}{N_a}$$

If no style variations exist, N_t is equal to N_a ; S_v is 1.

3. The factor measuring the design stability (R_d) is described as:

$$R_d = \frac{N_d}{N_a}$$

If there is no design change for the product, R_d is equal to 0.

4. Retained value of equipment (v) (in percent): For a specified depreciation method, v is a portion of the equipment cost at the end of the year h . In this research, equipment is depreciated according to the 7-year modified accelerated capital recovery system (MACRS). Under the 1986 U.S. tax law, manufacturing equipment must be depreciated according to this method. The depreciated rate each year is in Table 5.1. If the investment horizon is less than 8 years, the equipment is assumed to have a salvage value equal to the unused depreciation [21]. Alternatively, if h is more than 8 years, v is equal to 0.

5. Annualized cost factor (f_a) [21] is described as:

$$f_a = \left[1 - \frac{v}{\rho(1+r)^h} \right] \left[\frac{r(1+r)^h}{(1+r)^h - 1} \right]$$

In this equation, f_a is derived from yearly cost (A) and initial investment (C_e).

$$A = C_e \left[1 - \frac{v}{\rho(1+r)^h} \right] \left[\frac{r(1+r)^h}{(1+r)^h - 1} \right]$$

Yearly cost (A) is equal to:

$$C_e \left[\frac{r(1+r)^h}{(1+r)^h - 1} - \frac{vr}{\rho[(1+r)^h - 1]} \right]$$

that is:

$$A = C_e \left[(A/P)_h^r - v \left(\frac{1}{\rho} \right) (A/F)_h^r \right]$$

By dividing both sides of the equation by C_e :

$$f_a = \frac{A}{C_e} = (A/P)_h^r - v \left(\frac{1}{\rho} \right) (A/F)_h^r$$

where $(A/P)_h^r$ is the uniform series worth of present sum and $(A/F)_h^r$ is uniform series worth of a future sum.

Other parameters These three parameters are given the initial values as used in Boothroyd's assembly cost equations. However, they may be given different values as appropriate.

1. Plant efficiency (e): It is the average time worked divided by the time available. Its initial value is 0.69 (69%).
2. Ratio of faulty parts to acceptable parts (P_q): Its initial value is 0.01 (1%) in this research.
3. Available working days per year (D): It is assumed 250 days per year.

Selection of assembly systems by unit cost

Unit cost is chosen as the measurement in the proposed methodology for its simplicity and usefulness. It combines two important factors, cost and quantity. Total unit cost includes fixed and variable unit costs. Materials cost is eliminated based on the assumption that parts cost for any assembly system will be roughly the same.

Variable unit cost It is expressed as:

$$C_v = \frac{w_t}{q_h}$$

The total labor cost per hour (w_t) includes wages, benefits, overtime premiums and overhead. It varies according to the number of laborers actually working in the system. Referred to time and cost factors in Boothroyd's assembly cost methodology, the operating cost is eliminated in this equation. The hourly production rate (q_h) is derived by:

$$q_h = \frac{V_m}{8D}$$

where

$$V_m = \min(V_s, V_t)$$

The factor D is the number of the available working days per year. Each working day has 8 working hours. The factor V_m is determined by the smaller value between V_s and V_t . Based on the same w_t , a partially utilized assembly system should have a higher unit cost than a fully utilized one.

Fixed unit cost It is described as:

$$C_f = \frac{\rho(C_e) f_a}{Q_y}$$

that is:

$$C_f = \frac{\rho(C_e) f_a}{S_h (8D) q_h}$$

The equipment investment cost (C_e) varies according to each type of assembly system. According to the definition of f_a in the last section, annual total equipment cost (A_e) can be expressed as:

$$A_e = \rho C_e f_a = \rho C_e \left[(A/P)_h^r - v \left(\frac{1}{\rho} \right) (A/F)_h^r \right]$$

that is:

$$A_e = \rho C_e (A/P)_h^r - v C_e (A/F)_h^r$$

In this equation, the initial equipment cost (C_e) is multiplied by ρ and the present worth $(A/P)_h^r$. Alternatively, the annualized retained value $v C_e (A/F)_h^r$ eliminates ρ because only hardware investment is depreciable.

In analyses of the equipment cost, Boothroyd et al. [4] use the economic climate (R_i) to convert the capital cost of the equipment to an equivalent operator rate.

$$R_i = S_h \frac{Q_e}{W_a}$$

The factor Q_e is defined as the amount that can be spent on capital equipment to replace one operator on one shift. It could be expressed as:

$$Q_e = \frac{C_e}{n S_h} = \frac{y W_a}{f}$$

This is based on the assumption that the equipment is equivalent to n operators working S_h shifts for y years at an annual wage rate W_a . The relationship is:

$$C_e f = n S_h y W_a$$

where f (uniform series worth of present sum) is the factor depending upon the accounting procedures and the interest rate in a company. Therefore, the annual cost per shift for the equipment is:

$$\frac{C_e f}{S_h y} = \frac{C_e f W_a}{S_h y W_a} = \frac{C_e W_a}{S_h Q_e}$$

where

$$Q_e = \frac{y W_a}{f}$$

Therefore, the equipment cost is evaluated by the equipment operator rate multiplied by the number of operators. Boothroyd also states the ratio is a constant for a particular company and does not vary with wage rates. Since the factor Q_e is derived from the cost of capital equipment (C_e) and the factor f , it is eliminated in this research.

Total unit cost It is obtained by:

$$C_t = \frac{w_t}{q_h} + \frac{\rho(C_e) f a}{S_h (8D) q_h}$$

and this can be substituted for:

$$C_t = C_v + C_f$$

Total unit cost is the basis for comparison when determining which type of assembly system is most economical under specified requirements. From an economical point of view, if all the systems have the same income, the system with the lowest total unit cost is the most economical one.

Modified Formulation of Assembly System Selection

In the initial formulation, the analysis of total unit cost is under the assumption that no capacity expansion will be required. That is, if V_s is greater than V_t , the hourly rate is still the same. The modification formulation of assembly system selection covers the situation if annual production volume required is over the maximum capacity of existing facilities.

Capacity concern

In practice, planning for the expansion of production capacity is very important. Since the late 1950s many quantification studies of capacity expansion problems have been developed. Most of these models require operations research techniques, such as linear programming, dynamic programming problem, and network analysis [33].

Basic Formulation For a single-facility finite-horizon problem, the objective is to find an expansion policy that minimizes the total cost incurred over the finite horizon t , including the expansion cost plus the holding cost of excess capacity [33]. It could be described as:

$$\text{Minimize } X_t \sum_{t=1}^T [f_t(X_t) + h_t(I_t)]$$

Subject to

$$\begin{cases} I_t = I_{t-1} + X_t - r_t & t = 1, 2, \dots, T \\ I_t \geq 0 & t = 1, 2, \dots, T - 1 \\ I_0 = I_T = 0 \end{cases}$$

where

- $f_t(X_t)$ = the expansion cost function in period t
- $h_t(I_t)$ = the holding cost function in period t
- T = the time horizon; the discrete time periods $t = 1, 2, \dots, T$
- X_t = the expansion size in period t
- I_t = the excess capacity at the end of the period t
- r_t = the demand incurred for additional capacity in period t

In this model, capacity shortages are not allowed. That is, the existing capacity is assumed to exceed the demand at all times. However, in practice, capacity expansion can be deferred by temporary capacity shortages at certain shortage costs or by accumulating inventory during periods in which capacity exceeds demand. Theoretically, in a particular demand, minimum cost could be obtained by calculating the break-even point of the savings due to deferring expansion, the cost of shortage, and the cost of holding inventory.

Modified unit cost

In order to simplify the methodology of the selection of assembly systems in this research, capacity shortages are not allowed at any time. If the demand, annual production volume required, is over the maximum capacity of the existing facility, capacity is automatically expanded by adding another assembly system of the same type. In the proposed methodology, it is assumed that a system can not be modified such as adding a machine in order to increase its basic maximum capacity. An integer variable, E_f , is introduced as the integer part of $\frac{V_s}{V_t}$.

If V_s is less than V_t , that is, the ratio of $\frac{V_s}{V_t}$ is less than 1, the integer part of E_f is 0. Therefore, the number of facilities required is 1; in other words, no facility expansion is required. Alternatively, if V_s is greater than V_t , E_f number of facilities should be added to meet demand. If the annual production volume required is an integer multiple of the maximum capacity of a facility, then this integer number of facilities are needed to meet the demand.

Variable unit cost It is stated as:

$$C_v = \frac{(E_f + 1) w_t}{q_h}$$

for manual and robot assembly systems or

$$C_v = \frac{w_t + (E_f) w_a}{q_h}$$

for automatic and programmable assembly systems. The definition of q_h is changed to:

$$q_h = \frac{V_s}{8D}$$

Fixed unit cost It is expressed as:

$$C_f = \frac{\rho (E_f + 1) (C_e) f_a}{Q_y}$$

The factor Q_y is the annual production rate derived from q_h .

Total unit cost Substituting $C_t = C_v + C_f$ results in:

$$C_t = (E_f + 1) \left[\frac{w_t}{q_h} + \frac{\rho (C_e) f_a}{S_h (8D) q_h} \right]$$

or

$$C_t = \frac{w_t + (E_f) w_a}{q_h} + (E_f + 1) \left[\frac{\rho(C_e) f_a}{S_h (8D) q_h} \right]$$

When a system is expanded, there should be a "jump" in unit cost. For the purpose of analysis, the formulation above, which is interpreted into a FORTRAN program, appears in Chapter 6.

CHAPTER 6. IMPLEMENTATION OF THE METHODOLOGY

This chapter provides an explanation of the implementation of the proposed methodology and indicates the programs' results provided to support that methodology. The definitions of the six assembly systems, AI, AF, AP, AR, MA, and MM, are stated in Chapter 3.

Making a Comparison between each Methodology

As described in Chapter 5, the initial and modified proposed methodologies use total unit cost performance to choose the most economical assembly system. The initial methodology, without the concern for capacity, shows the same results as Boothroyd's methodology, dimensionless assembly cost. The modified methodology, though, has different results. The following sections provide examples to explain these results as calculated by FORTRAN programs.

Boothroyd's and the Initial Proposed Methodologies

The equation of dimensionless assembly cost as described in Chapter 3 is:

$$C_d = \frac{T_b}{T_a W_a N_a} \left(W_t + \frac{C_e W_a}{S_h Q_e} \right)$$

where

$$T_b = \max(T_p, T_q)$$

The factor T_p is the production time obtainable for an assembly. For each type of assembly system it could be different. The other factor T_q is the required average production time for one assembly. It could be expressed as:

$$T_q = \frac{7.2e}{V_s}$$

In this equation, T_q is given in seconds, V_s is in millions, e is a number between 0 and 1, and the factor 7.2 is derived from 250 working days (7.2 million seconds) in one shift per year.

Since the variables T_a , W_a , and N_a are assumed to be the same for each assembly system, within this equation, the factors influencing the priority of each assembly system are:

$$T_b \left(W_t + \frac{C_e W_a}{S_h Q_e} \right)$$

Alternatively, the equation of the initial proposed methodology is obtained by:

$$C_t = \frac{w_t}{q_h} + \frac{\rho(C_e) f_a}{S_h (8D) q_h}$$

and since

$$q_h = \frac{V_m}{8D}$$

where

$$V_m = \min(V_s, V_t)$$

the equation could be expressed as:

$$C_t = \frac{8D}{V_m} \left(w_t + \frac{\rho(C_e) f_a}{S_h (8D)} \right)$$

The factors deciding the priority of each assembly system are:

$$\frac{1}{V_m} \left(W_t + \frac{\rho(C_e) f_a}{S_h} \right)$$

where

$$W_t = w_t(8D)$$

In order to make these factors deciding the priority of assembly system equivalent to Boothroyd's, the factors can be changed to:

$$\frac{7.2e}{V_m} \left(W_t + \frac{\rho(C_e) f_a}{S_h} \right)$$

The multiplied factor $7.2e$ is a constant factor, therefore it will not change the priority of each assembly system.

For the selection of an assembly system, each of the methodologies will select the same assembly system if

$$\rho f_a = \frac{W_a}{Q_e}$$

Factors, W_t , C_e , and S_h , which influence the priority of assembly systems, are the same for each methodology. Other factors, T_b and $\frac{7.2e}{V_m}$, should be the same, theoretically, because

$$T_b = \max(T_p, T_q)$$

and

$$V_m = \min(V_s, V_t)$$

Mathematically, the solution for V_m is equal to:

$$\frac{1}{V_m} = \max \left(\frac{1}{V_t}, \frac{1}{V_s} \right) = \max \left(\frac{T_p}{7.2e}, \frac{1}{V_s} \right)$$

where

$$V_t = \frac{7.2e}{T_p}$$

$$\frac{7.2e}{V_m} = \max\left(T_p, \frac{7.2e}{V_s}\right) = \max(T_p, T_q)$$

where

$$T_q = \frac{7.2e}{V_s}$$

In the following example, ρ is 1.5 and f_a is 0.33 for each assembly system, derived by letting h equal 6 and r equal 0.25, for the initial proposed methodology, or W_a is 36k (\$) and Q_e is 72k (\$) for Boothroyd's methodology, that is:

$$\rho f_a = \frac{W_a}{Q_e} = 0.5$$

Other parameters are:

- Number of shifts (S_h) = 2
- Number of different products (N_p) = 1
- Ratio of faulty parts to acceptable parts (P_q) = 1%
- Plant efficiency (e) = 69%
- Annual cost for a machine supervisor (W_s) = 156k (\$)

In Table 6.1, each methodology shows consistent results as predicted in this section.

Table 6.1: Summary of Boothroyd's and initial results employed in the comparison of assembly systems

| | V_s | Selected System | C_d Assem Cost | Selected System | Initial Unit Cost |
|----------------------------------|-------|-----------------|---------------------|-----------------|-------------------|
| $N_a = 35 \ N_t = 45 \ N_d = 10$ | 0.1 | MA | 1.0872 | MA | 2.7558 |
| | 0.5 | AP | 0.4636 | AP | 1.1702 |
| | 1.0 | AP | 0.3487 | AP | 0.8793 |
| $N_a = 35 \ N_t = 55 \ N_d = 20$ | 0.1 | MA | 1.0872 | MA | 2.7558 |
| | 0.5 | AP | 0.5265 | AP | 1.1728 |
| | 1.0 | AP | 0.3497 | AP | 0.8806 |
| $N_a = 12 \ N_t = 15 \ N_d = 3$ | 0.1 | MA | 1.0872 | MA | 0.9449 |
| | 0.5 | AI | 0.6917 | AI | 0.5999 |
| | 1.0 | AF | 0.4955 | AF | 0.4292 |
| $N_a = 12 \ N_t = 19 \ N_d = 7$ | 0.1 | MA | 1.0872 | MA | 0.9449 |
| | 0.5 | AP | 0.7754 | AP | 0.6723 |
| | 1.0 | AP | 0.5045 | AP | 0.4370 |
| $N_a = 4 \ N_t = 5 \ N_d = 1$ | 0.1 | MA | 1.0872 | MA | 0.3150 |
| | 0.5 | MA | 1.0872 | MA | 0.3150 |
| | 1.0 | AI | 0.8277 | AI | 0.2396 |
| $N_a = 4 \ N_t = 7 \ N_d = 3$ | 0.1 | MA | 1.0872 | MA | 0.3150 |
| | 0.5 | MA | 1.0872 | MA | 0.3150 |
| | 1.0 | AI | 0.9160 | AI | 0.2650 |

The Initial and Modified Proposed Methodology

The following two tables describe the comparison between the initial and modified proposed methodologies. In Table 6.2, the minimum attractive rate of return (r) is 0.25 and plant efficiency (e) is 69%. Table 6.3 is based on the assumption that r is 0.15 and e is 85%. Other parameters are:

- Number of shifts (S_h) = 2
- Number of different products (N_p) = 1
- Ratio of faulty parts to acceptable parts (P_q) = 1%
- Investment horizon (h) = 6
- Hourly cost for one machine operator (w_a) = 18 (\$)
- Hourly cost for one machine supervisor (w_s) = 78 (\$)

In Table 6.2, each occurrence of different results from the methodologies is indicated by the symbol “*.” For example, when N_a is 35, N_t is 45, N_d is 10, and V_s is 1.0, the initial methodology without the concern for capacity selects AP, but the modified methodology which includes the effects of capacity chooses AF. In this situation, the maximum capacity (V_t) for each assembly is under 1.0. For the modified methodology, each assembly system requires capacity expansion by adding another assembly system of the same type allowing no capacity shortage. Alternatively, for the initial methodology, it is assumed that backup will be provided in the form of manual assembly stations. Then, when the required volume (V_s) approaches twice V_t , a second machine will be employed and so on. Because of the “smoothing” provided

Table 6.2: Summary of initial and modified results employed in the comparison of assembly systems ($r=0.25$ $e=69\%$)

| | V_s | Initial Selected System | Unit Cost | Modified Selected System | Unit Cost | |
|----------------------------------|-------|-------------------------------|--------------|--------------------------------|--------------|---|
| $N_a = 35$ $N_t = 45$ $N_d = 10$ | 0.1 | MA | 2.7558 | MA | 3.0984 | |
| | 0.5 | AP | 1.1702 | AP | 1.1009 | |
| | 1.0 | AP | 0.8793 | AF | 1.4974 | * |
| $N_a = 35$ $N_t = 55$ $N_d = 20$ | 0.1 | MA | 2.7558 | MA | 3.0984 | |
| | 0.5 | AP | 1.1728 | AP | 1.1059 | |
| | 1.0 | AP | 0.8806 | AP | 1.5328 | |
| $N_a = 12$ $N_t = 15$ $N_d = 3$ | 0.1 | MA | 0.9449 | MA | 1.1619 | |
| | 0.5 | AI | 0.5999 | AI | 0.5999 | |
| | 1.0 | AF | 0.4292 | AI | 0.4439 | * |
| $N_a = 12$ $N_t = 19$ $N_d = 7$ | 0.1 | MA | 0.9449 | MA | 1.1619 | |
| | 0.5 | AP | 0.6723 | AP | 0.6636 | |
| | 1.0 | AP | 0.4370 | AI | 0.5253 | * |
| $N_a = 4$ $N_t = 5$ $N_d = 1$ | 0.1 | MA | 0.3150 | MA | 0.3873 | |
| | 0.5 | MA | 0.3150 | AI | 0.3840 | * |
| | 1.0 | AI | 0.2396 | AI | 0.2640 | |
| $N_a = 4$ $N_t = 7$ $N_d = 3$ | 0.1 | MA | 0.3150 | MA | 0.3873 | |
| | 0.5 | MA | 0.3150 | MM | 0.4183 | * |
| | 1.0 | AI | 2.2650 | AI | 0.3047 | |

by manual assembly stations, the relation between unit cost and required volume (V_s) is independent, when V_s is over V_t . This assumption is weak when V_s is near an integer multiple of V_t . For example, if V_s is 1.9 and V_t is 1 for an assembly system, it would be difficult to justify that the extra volume, 0.9, would be accomplished by manual assembly stations.

In Table 6.3, the different results as indicated by the symbol “*,” can be explained by the same reasoning as above. The different results indicated by the symbol “**,” can be explained by different equations for equipment investment cost (C_e) for AP, MA, and MM. For example, for MA the initial formulation for C_e is:

$$C_e = \left(\frac{N_a}{N_s} \right) (2C_b + N_p C_c)$$

In this equation, N_s is the number of parts in a station. Therefore $\frac{N_a}{N_s}$ is the number of stations in the system. For the modified methodology is:

$$C_e = (N_m) (2C_b + N_p C_c)$$

where

$$N_m = \text{truncate} \left(\frac{N_a}{N_s} + 1 \right)$$

In the modified equation, N_m is based on the same assumption that the number of stations in a system $\frac{N_a}{N_s}$ should be an integer and no capacity shortage is allowed. For example, when $\frac{N_a}{N_s}$ is 1.7, 2 stations are required in the system.

The equations employed in the comparison of assembly systems for each proposed methodology are summarized in Tables 6.4 and 6.5.

Table 6.3: Summary of initial and modified results employed in the comparison of assembly systems ($r=0.15$ $e=85\%$)

| | V_s | Initial | Unit | Modified | Unit | |
|----------------------------------|-------|-----------------|--------|-----------------|--------|----|
| | | Selected System | Cost | Selected System | Cost | |
| $N_a = 35$ $N_t = 45$ $N_d = 10$ | 0.1 | MA | 2.2223 | MA | 2.2857 | |
| | 0.5 | AP | 0.9313 | AP | 0.9344 | |
| | 1.0 | AP | 0.6774 | AF | 0.6793 | |
| $N_a = 35$ $N_t = 55$ $N_d = 20$ | 0.1 | MA | 2.2223 | MA | 2.2857 | |
| | 0.5 | AP | 0.9351 | AP | 0.9382 | |
| | 1.0 | AP | 0.6793 | AP | 0.6929 | |
| $N_a = 12$ $N_t = 15$ $N_d = 3$ | 0.1 | MA | 0.7619 | MM | 0.9620 | ** |
| | 0.5 | AI | 0.5498 | AI | 0.5498 | |
| | 1.0 | AF | 0.3535 | AF | 0.3535 | |
| $N_a = 12$ $N_t = 19$ $N_d = 7$ | 0.1 | MA | 0.7619 | MM | 1.0509 | |
| | 0.5 | AP | 0.5730 | AP | 0.5986 | |
| | 1.0 | AP | 0.3591 | AP | 0.3727 | |
| $N_a = 4$ $N_t = 5$ $N_d = 1$ | 0.1 | MA | 0.2540 | MA | 0.3810 | |
| | 0.5 | MA | 0.3048 | AR | 0.3577 | ** |
| | 1.0 | AI | 0.1860 | AF | 0.2458 | * |
| $N_a = 4$ $N_t = 7$ $N_d = 3$ | 0.1 | MA | 0.2540 | MA | 0.3810 | |
| | 0.5 | MA | 0.3048 | AR | 0.3585 | ** |
| | 1.0 | AI | 2.2019 | AP | 0.2614 | * |

Table 6.4: Initial equations employed to select assembly systems

| System | Equations |
|--------|--|
| AI | $T_p = T_w + N_a P_q T_d$ $w_t = N_i w_a + w_s \text{ (} N_a > 6 \text{) or } N_r w_a + w_s \text{ (} N_a \leq 6 \text{)}$ $C_e = N_a (S_v C_{tr} + N_p (S_v C_c + (S_v + R_d)(C_{fd} + C_w)))$ |
| AF | $T_p = T_w + P_q T_d$ $w_t = N_i w_a + w_s$ $C_e = N_a (S_v (1 + T_d/T_w)(C_b + N_p C_c/2) + N_p (S_v + R_d)(C_{fd} + C_w))$ |
| AP | $N_s = \text{Int}(T_q/(T_r + P_q T_d) + 0.5)$ $T_p = N_s (T_r + P_q T_d)$ $w_t = N_i w_a + w_s$ $C_e = N_a ((C_r + (1 + T_d/T_r)C_b)/N_s + N_p ((S_v + R_d)C_m + C_g + (1 + T_d/T_r)C_c/2/N_s))$ |
| AR | $T_p = N_a (T_r/2 + P_q T_d)$ $w_t = w_s$ $C_e = 2C_r + N_p (C_c + N_a C_g + N_a (S_v + R_d)C_m)$ |
| MA | $N_s = \text{Int}(T_q/(T_a(1 + P_q)) + 0.5)$ $T_p = N_s T_a (1 + P_q)$ $w_t = (N_a/N_s)w_a$ $C_e = (N_a/N_s)(2C_b + N_p C_c)$ |
| MM | $N_s = \text{Int}(T_q/(T_m(1 + P_q)) + 0.5)$ $T_p = N_s T_m (1 + P_q)$ $w_t = N_a/N_s w_a$ $C_e = (N_a/N_s)(2C_b + N_p C_c + N_s (N_p (S_v + R_d)C_{fd}))$ |
| | $T_q = 7.2e/V_s$ $q_h = 10^6 V_t/D/8 \text{ where } V_t = 7.2e/T_p$ $C_t = (w_t/q_h) + (\rho C_e f_a)10^3/(S_h 8Dq_h)$ |

Table 6.5: Modified equations employed to select assembly syst

| System | Equations |
|--------|--|
| AI | $V_t = 7.2e/T_p$ modified $C_e = C_e(Int(V_s/V_t + 1))$ modified $w_t = w_t + Int(V_s/V_t)w_a$ |
| AF | $V_t = 7.2e/T_p$ modified $C_e = C_e(Int(V_s/V_t + 1))$ modified $w_t = w_t + Int(V_s/V_t)w_a$ |
| AP | $V_t = 7.2e/(T_r + P_q T_d)$ modified $C_e = C_e(Int(V_s/V_t + 1))$ modified $w_t = w_t + Int(V_s/V_t)w_a$ |
| AR | $V_t = 7.2e/T_p$ modified $C_e = C_e(Int(V_s/V_t + 1))$ modified $w_t = w_t(Int(V_s/V_t + 1))$ |
| MA | $V_t = 7.2e/(T_a(1 + P_q))$ modified $C_e = C_e(Int(V_s/V_t + 1))$ modified $w_t = w_t(Int(V_s/V_t + 1))$ |
| MM | $V_t = 7.2e/(T_m(1 + P_q))$ modified $C_e = C_e(Int(V_s/V_t + 1))$ modified $w_t = w_t(Int(V_s/V_t + 1))$ |
| | $q_h = 10^6 V_s / D / 8$ $C_t = (w_t / q_h) + (\rho C_e f a) 10^3 / (S_h 8 D q_h)$ |
| | $T_p, C_e,$ and w_t are referred to in Table 6.4. |

Comparison within Modified Proposed Methodology

In last section, initial and modified results are employed in the comparison of assembly systems. In this section, the comparison within modified proposed methodology is given according to different variables. Table 6.6 shows the results for various combinations of parameters: the minimum attractive rate of return (r) is 0.25 or 0.15, plant efficiency (e) is 69 or 85%, and the ratio of faulty parts to acceptable parts (P_q) is 1 or 2%. Other parameters are:

- Number of parts in the assembly (N_a) = 35
- Total number of parts (N_t) = 45
- Number of part design changes (N_d) = 10
- Number of shifts (S_h) = 2
- Number of different products (N_p) = 1
- Investment horizon (h) = 6
- Hourly cost for one machine operator (w_a) = 18 (\$)
- Hourly cost for one machine supervisor (w_s) = 78 (\$)

The results indicate that there is no significant difference when P_q is 1 or 2%. For the four combinations, under the same P_q , it seems that selected assembly systems with higher plant efficiency (e) lead to lower cost. And the methodology tends to select automatic assembly systems when r is lower, based on the same e . It is consistent with Boothroyd's Q_e concept: when Q_e is higher, the investment in automation is likely to be profitable.

Table 6.6: Summary of results for the modified methodology with different parameter combinations

| | V_s | Sys | Unit Cost | | Sys | Unit Cost |
|-----------------------|-------|-----|--------------|-----------------------|-----|--------------|
| $P_q=0.01$ | | | | | | |
| $r = 0.25 \ e = 0.69$ | 0.1 | MA | 3.0984 | $r = 0.25 \ e = 0.85$ | MA | 2.3238 |
| | 0.5 | AP | 1.1009 | | AP | 1.1009 |
| | 1.0 | AF | 1.4974 | | AF | 0.8267 |
| $r = 0.15 \ e = 0.69$ | 0.1 | AP | 2.8318 | $r = 0.15 \ e = 0.85$ | MA | 2.2857 |
| | 0.5 | AP | 0.9344 | | AP | 0.9344 |
| | 1.0 | AF | 1.2025 | | AF | 0.6793 |
| $P_q=0.02$ | | | | | | |
| $r = 0.25 \ e = 0.69$ | 0.1 | MA | 3.0984 | $r = 0.25 \ e = 0.85$ | MA | 2.3238 |
| | 0.5 | AP | 1.1009 | | AP | 1.1009 |
| | 1.0 | AF | 1.4974 | | AF | 0.8267 |
| $r = 0.15 \ e = 0.69$ | 0.1 | AP | 2.8318 | $r = 0.15 \ e = 0.85$ | MA | 2.2857 |
| | 0.5 | AP | 0.9344 | | AP | 0.9344 |
| | 1.0 | AF | 1.2025 | | AF | 0.6793 |

In Table 6.7, there are comparisons between different hourly rates, 36, 54, 78 (\$), of one machine supervisor (w_s). Other parameters are:

- Number of shifts (S_h) = 2
- Number of different products (N_p) = 1
- Ratio of faulty parts to acceptable parts (P_q) = 1%
- Investment horizon (h) = 6
- Minimum attractive rate of return (r) = 0.25
- Plant efficiency (e) = 69%

Table 6.7 shows that costs become higher when w_s increases. Since the labor rate does not include w_s for AI (when N_a less than 7), MA, and MM, the methodology tends to select these three systems when w_s increases.

Change the Factor ρ for Assembly Systems

As defined in Chapter 5, the factor ρ is the ratio of actual installation cost to hardware cost. For different types of assembly systems, ρ could be different. For example, ρ is 1.5 for a special-purpose machine and is higher, such as 1.8, for a programmable assembly system. In this section, ρ is 1.2 for manual assembly systems MA and MM, 1.8 for a programmable assembly system AP, 2.5 for a sophisticated assembly system AR, and 1.5 for automatic assembly systems AI and AF.

In Table 6.8, the minimum attractive rate of return (r) is 0.25 and plant efficiency (e) is 69%. In Table 6.9, r is 0.15 and e is 85%. Other parameters are:

Table 6.7: Summary of modified results when different w_s values are employed in the comparison of assembly systems

| | V_s | Sys | $w_s = 36$ | | $w_s = 54$ | | $w_s = 78$ | |
|----------------------------------|-------|-----|------------|-----|------------|-----|------------|--|
| | | | Cost | Sys | Cost | Sys | Cost | |
| $N_a = 35 \ N_t = 45 \ N_d = 10$ | 0.1 | AP | 2.2676 | AP | 2.6276 | MA | 3.0984 | |
| | 0.5 | AP | 0.9329 | AP | 1.0049 | AP | 1.1009 | |
| | 1.0 | AF | 1.4134 | AF | 1.4494 | AF | 1.4974 | |
| $N_a = 35 \ N_t = 55 \ N_d = 20$ | 0.1 | AP | 2.2924 | AP | 2.6524 | MA | 3.0984 | |
| | 0.5 | AP | 0.9379 | AP | 1.0094 | AP | 1.1059 | |
| | 1.0 | AP | 1.4488 | AP | 1.4848 | AP | 1.5328 | |
| $N_a = 12 \ N_t = 15 \ N_d = 3$ | 0.1 | AR | 1.1220 | MA | 1.1619 | MA | 1.1619 | |
| | 0.5 | AI | 0.4319 | AI | 0.5039 | AI | 0.5999 | |
| | 1.0 | AI | 0.3599 | AI | 0.3959 | AI | 0.4439 | |
| $N_a = 12 \ N_t = 19 \ N_d = 7$ | 0.1 | AR | 1.1320 | MA | 1.1619 | MA | 1.1619 | |
| | 0.5 | AP | 0.4956 | AP | 0.5676 | AP | 0.6639 | |
| | 1.0 | AI | 0.4413 | AI | 0.4773 | AI | 0.5253 | |
| $N_a = 4 \ N_t = 5 \ N_d = 1$ | 0.1 | MA | 0.2540 | MA | 0.3810 | MA | 0.3873 | |
| | 0.5 | AI | 0.2160 | AI | 0.2880 | AI | 0.3840 | |
| | 1.0 | AI | 0.1800 | AI | 0.2160 | AI | 0.2640 | |
| $N_a = 4 \ N_t = 7 \ N_d = 3$ | 0.1 | MA | 0.3873 | MA | 0.3873 | MA | 0.3873 | |
| | 0.5 | AI | 0.2567 | AI | 0.3287 | MM | 0.4183 | |
| | 1.0 | AI | 0.2006 | AI | 0.2567 | AI | 0.3047 | |

- Number of parts in the assembly (N_a) = 35
- Total number of parts (N_t) = 45
- Number of part design changes (N_d) = 10
- Number of shifts (S_h) = 2
- Number of different products (N_p) = 1
- Investment horizon (h) = 6
- Hourly cost for one machine operator (w_a) = 18 (\$)
- Hourly cost for one machine supervisor (w_s) = 78 (\$)

In Tables 6.8 and 6.9 a difference is indicated by the symbol “*.” In Table 6.9, for example, if ρ is 1.5 for each assembly system, when N_a , N_t , N_d , and V_s are 4, 5, 1, and 0.5 respectively, AR has the lowest cost. But the methodology chooses AI after AR’s ρ increases to 2.5.

Change the Number of Shifts

Table 6.10 shows the comparisons when a different number of shifts are used to meet the same required production volume. That is, for one particular product, 1 shift producing 0.6 million assemblies will be equal to 2 shifts producing 0.3 million and 3 shifts producing 0.2 million. The parameters used in this table are:

- The factor ρ is 1.5 for each system
- Number of different products (N_p) = 1

Table 6.8: Summary of results of different ρ values employed in the comparison of assembly systems ($r=0.25$ $e=69\%$)

| | V_s | $\rho = 1.5$ | | ρ various | |
|----------------------------------|-------|-----------------|-----------|-----------------|-----------|
| | | Selected System | Unit Cost | Selected System | Unit Cost |
| $N_a = 35$ $N_t = 45$ $N_d = 10$ | 0.1 | MA | 3.0984 | MA | 3.0537 |
| | 0.5 | AP | 1.1009 | AP | 1.2478 |
| | 1.0 | AF | 1.4974 | AF | 1.4974 |
| $N_a = 35$ $N_t = 55$ $N_d = 20$ | 0.1 | MA | 3.0984 | MA | 3.0537 |
| | 0.5 | AP | 1.1059 | AP | 1.2538 |
| | 1.0 | AP | 1.5328 | AP | 1.6364 |
| $N_a = 12$ $N_t = 15$ $N_d = 3$ | 0.1 | MA | 1.1619 | MA | 1.1451 |
| | 0.5 | AI | 0.5999 | AI | 0.5999 |
| | 1.0 | AI | 0.4439 | AI | 0.4439 |
| $N_a = 12$ $N_t = 19$ $N_d = 7$ | 0.1 | MA | 1.1619 | MA | 1.1451 |
| | 0.5 | AP | 0.6636 | AI | 0.6813 * |
| | 1.0 | AI | 0.5253 | AI | 0.5253 |
| $N_a = 4$ $N_t = 5$ $N_d = 1$ | 0.1 | MA | 0.3873 | MA | 0.3817 |
| | 0.5 | AI | 0.3840 | AI | 0.3840 |
| | 1.0 | AI | 0.2640 | AI | 0.2640 |
| $N_a = 4$ $N_t = 7$ $N_d = 3$ | 0.1 | MA | 0.3873 | MA | 0.3817 |
| | 0.5 | MM | 0.4183 | MM | 0.4064 |
| | 1.0 | AI | 0.3047 | AI | 0.3047 |
| for MA & MM $\rho = 1.2$ | | | | | |
| for AI & AF $\rho = 1.5$ | | | | | |
| for AP $\rho = 1.8$ | | | | | |
| for AR $\rho = 2.5$ | | | | | |

Table 6.9: Summary of results of different ρ values employed in the comparison of assembly systems ($r=0.15$ $e=85\%$)

| | V_s | $\rho = 1.5$ | | ρ various | |
|----------------------------------|-------|-----------------|-----------|-----------------|-----------|
| | | Selected System | Unit Cost | Selected System | Unit Cost |
| $N_a = 35$ $N_t = 45$ $N_d = 10$ | 0.1 | MA | 2.2857 | MA | 2.2596 |
| | 0.5 | AP | 0.9344 | AP | 1.0489 |
| | 1.0 | AF | 0.6793 | AF | 0.6793 |
| $N_a = 35$ $N_t = 55$ $N_d = 20$ | 0.1 | MA | 2.2857 | MA | 2.2596 |
| | 0.5 | AP | 0.9382 | AP | 1.0535 |
| | 1.0 | AP | 0.6929 | AP | 0.7971 |
| $N_a = 12$ $N_t = 15$ $N_d = 3$ | 0.1 | MM | 0.9620 | MM | 0.9116 |
| | 0.5 | AI | 0.5498 | AI | 0.5498 |
| | 1.0 | AF | 0.3535 | AF | 0.3535 |
| $N_a = 12$ $N_t = 19$ $N_d = 7$ | 0.1 | MM | 1.0509 | MM | 0.9820 |
| | 0.5 | AP | 0.5986 | AI | 0.6122 * |
| | 1.0 | AP | 0.3727 | AF | 0.4057 * |
| $N_a = 4$ $N_t = 5$ $N_d = 1$ | 0.1 | MA | 0.3810 | MA | 0.3766 |
| | 0.5 | AR | 0.3577 | AI | 0.3637 * |
| | 1.0 | AF | 0.2458 | AF | 0.2458 |
| $N_a = 4$ $N_t = 7$ $N_d = 3$ | 0.1 | MA | 0.3810 | MA | 0.3766 |
| | 0.5 | AR | 0.3585 | MA | 0.3766 * |
| | 1.0 | AP | 0.2614 | AF | 0.2719 * |
| for MA & MM $\rho = 1.2$ | | | | | |
| for AI & AF $\rho = 1.5$ | | | | | |
| for AP $\rho = 1.8$ | | | | | |
| for AR $\rho = 2.5$ | | | | | |

Table 6.10: Summary of results of different number of shifts in the comparison of assembly systems when costs increase

| | Sys | $S_h = 1$ $V_s = 0.6$ | | $S_h = 2$ $V_s = 0.3$ | | $S_h = 3$ $V_s = 0.2$ | |
|----------------------------------|-----|--------------------------|-------|--------------------------|------|--------------------------|--|
| | | Cost | V_t | Sys | Cost | V_t | |
| $N_a = 35$ $N_t = 45$ $N_d = 10$ | AP | 1.5149 | AP | 1.5226 | AP | 1.6636 | |
| $N_a = 35$ $N_t = 55$ $N_d = 20$ | AP | 1.5232 | AP | 1.5309 | AP | 1.6719 | |
| $N_a = 12$ $N_t = 15$ $N_d = 3$ | AP | 0.7826 | MA | 0.9037 | MM | 1.0386 | |
| $N_a = 12$ $N_t = 19$ $N_d = 7$ | AP | 0.7859 | MA | 0.9037 | MM | 1.0799 | |
| $N_a = 4$ $N_t = 5$ $N_d = 1$ | AI | 0.3799 | MA | 0.3873 | MM | 0.4154 | |
| $N_a = 4$ $N_t = 7$ $N_d = 3$ | AI | 0.4478 | MA | 0.3873 | MM | 0.4402 | |

- Ratio of faulty parts to acceptable parts (P_q) = 1%
- Investment horizon (h) = 6
- Minimum attractive rate of return (r) = 0.25
- Plant efficiency (e) = 69%
- Hourly cost for one machine operator (w_a) = 18 (\$)
- Hourly cost for one machine supervisor (w_s) = 78 (\$)

In Table 6.10, since each chosen assembly system has higher capacity (V_t) than the required production volume per shift (V_s), fewer number of shifts are more economical. Alternatively, if V_t is less than V_s , the results could vary. Table 6.11 shows some examples where the unit cost of 2 shifts is lower than the unit cost of 1 shift indicated by the symbol “*.”

Table 6.11: Summary of results of different number of shifts in the comparison of assembly systems when costs decrease

| | | | $S_h = 1$ $V_s = 1.0$ | | | $S_h = 2$ $V_s = 0.5$ | | | |
|------------|------------|------------|--------------------------|--------|--------|--------------------------|--------|--------|---|
| | | | Sys | Cost | V_t | Sys | Cost | V_t | |
| $N_a = 35$ | $N_t = 45$ | $N_d = 10$ | AF | 2.7667 | 0.9374 | AP | 1.1009 | 0.9374 | * |
| $N_a = 35$ | $N_t = 55$ | $N_d = 20$ | AP | 2.8377 | 0.9374 | AP | 1.1059 | 0.9374 | * |
| $N_a = 12$ | $N_t = 15$ | $N_d = 3$ | AI | 0.6598 | 0.5777 | AI | 0.5999 | 0.5777 | * |
| $N_a = 12$ | $N_t = 19$ | $N_d = 7$ | AI | 0.8226 | 0.5777 | AP | 0.6636 | 0.9374 | * |
| $N_a = 4$ | $N_t = 5$ | $N_d = 1$ | AI | 0.3359 | 0.8013 | AI | 0.3840 | 0.8013 | |
| $N_a = 4$ | $N_t = 7$ | $N_d = 3$ | AI | 0.4173 | 0.8013 | MM | 0.4183 | 0.5465 | |

Change the Number of Different Products

When a greater number of different products (N_p) are required, “flexible” machines, such as a programmable machine (AP), tend to be selected. Some results are shown in Table 6.12. The parameters used in the table are:

- The factor ρ is 1.5 for each system
- Number of shifts (S_h) = 2
- Ratio of faulty parts to acceptable parts (P_q) = 1%
- Investment horizon (h) = 6
- Minimum attractive rate of return (r) = 0.25
- Plant efficiency (e) = 69%

Table 6.12: Summary of results of different number of products in the comparison of assembly systems

| | V_s | Sys | $N_p = 1$ | | $N_p = 2$ | | $N_p = 3$ | |
|----------------------------------|-------|-----|-----------|-----|-----------|-----|-----------|-----|
| | | | Cost | Sys | Cost | Sys | Cost | Sys |
| $N_a = 35 \ N_t = 45 \ N_d = 10$ | 1.0 | AF | 1.4979 | AP | 1.5502 | AP | 1.5726 | |
| | 0.5 | AP | 1.1009 | AP | 1.1233 | AP | 1.1456 | |
| $N_a = 35 \ N_t = 55 \ N_d = 20$ | 1.0 | AP | 1.5328 | AP | 1.5601 | AP | 1.5874 | |
| | 0.5 | AP | 1.1059 | AP | 1.1332 | AP | 1.1605 | |
| $N_a = 12 \ N_t = 15 \ N_d = 3$ | 1.0 | AI | 0.4439 | AI | 0.5854 | AP | 0.7117 | |
| | 0.5 | AI | 0.5999 | AP | 0.6690 | AP | 0.6765 | |
| $N_a = 12 \ N_t = 19 \ N_d = 7$ | 1.0 | AI | 0.5253 | AP | 0.7082 | AP | 0.7176 | |
| | 0.5 | AP | 0.6636 | AP | 0.6730 | AP | 0.6824 | |
| $N_a = 4 \ N_t = 5 \ N_d = 1$ | 1.0 | AI | 0.2640 | AI | 0.3111 | AI | 0.3583 | |
| | 0.5 | AI | 0.3840 | MM | 0.4270 | MM | 0.4481 | |
| $N_a = 4 \ N_t = 7 \ N_d = 3$ | 1.0 | AI | 0.3047 | AI | 0.3826 | AP | 0.4159 | |
| | 0.5 | MM | 0.4183 | MM | 0.4518 | MM | 0.4853 | |

- Hourly cost for one machine operator (w_a) = 18 (\$)
- Hourly cost for one machine supervisor (w_s) = 78 (\$)

In Table 6.12, when N_p is more than 1, automatic special-purpose machines, such as AI and AF, are less likely to be selected. For example, when N_a is 12, N_t is 19, and N_d is 7, and N_p is 1, AI is the most economical assembly system. Yet when N_p changes to 2 or 3, AP is selected instead.

Summary

Based on the explanation in this chapter, the modified proposed methodology is superior to other methodologies such as Boothroyd's and Gustavson's in that it takes capacity into account and allows various values of the ratio of actual installation cost to hardware cost (ρ). Allowing a system to be modified or accepting more than one type of assembly system might lead to more reasonable and economical results which could be the focus of further research.

CHAPTER 7. SUMMARY AND CONCLUSION

The objective of this research is to develop a conceptual manufacturing system design model, which is stated in Chapter 4, and to provide an assembly system selection methodology that can be demonstrated on a workstation. Basically, the proposed methodology for assembly system selection in this research is based upon the following:

- ✓ • Boothroyd's classification of assembly systems and time and cost factors in assembly cost equations.
- ✓ • Gustavson's unit cost equations for choosing the most economical assembly system.

In our modified proposed methodology, capacity is taken into account, and in addition it allows various values of the ratio of actual installation cost to hardware cost (ρ) to be used for each assembly system. According to the comparison of assembly systems provided in Chapter 6, the results can be summarized as follows:

1. The results for the initial proposed methodology without concern for capacity is consistent with Boothroyd's methodology of dimensionless assembly cost.
2. The unit costs in the modified proposed methodology tend to decrease when the required production volume per shift (V_S) increases. But the unit costs

“jump” when V_s is over the maximum capacity (V_t). That is, when another assembly system is added for capacity shortage, the equipment becomes under utilized therefore unit costs increase.

3. Higher plant efficiency (e) leads to lower unit cost.
4. The factor ρ is used to express the ratio of equipment installation cost and hardware cost. For example, the installation cost of a sophisticated assembly system such as a robot is much higher than the basic hardware cost. Therefore the ratio (ρ) must be taken into account when selecting the most economical assembly system.
5. According to annual required production volume, changing the number of shifts might influence the choice of assembly equipment.
6. Flexible assembly systems such as automatic programmable systems become more economical when a variety of different products are produced.

Further work in manufacturing system selection can focus on the following:

1. When required production volume (V_s) is not an integer multiple of the maximum capacity (V_t) for an assembly system, a method for a modified system such as adding machines, allowing certain percent of extra volume to be accomplished by manual stations, or employing another assembly system.
2. Considering the availability and constraints of resources (i.e., the supply of assembly parts) and the probability of demand changes.

3. Allowing for a variety of assembly system types to be selected when V_s is over V_t (i.e., utilizing both a special-purpose automatic machine and a robot).
4. Allowing temporary capacity shortage at a certain shortage cost or accumulating inventory at a certain inventory cost to allow for periods in which demand exceeds capacity.
5. Applying similar methodologies to fabrication systems.

Further work in the manufacturing system design model could be:

1. Interpreting methodologies for all submodels related to manufacturing system design into programs.
2. Integrating these submodels.
3. Implementing the manufacturing system design model.

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APPENDIX A. NOMENCLATURE**Variable Parameters**

C_e equipment investment cost

C_f fixed unit cost

C_t total unit cost

C_v variable unit cost

h the number of years savings are assumed to accumulate for economic analysis

N_a number of parts in the assembly

N_d number of part design changes expected during first three years

N_p number of different products to be assembled during three years

N_t total number of parts available for building different product style

Q_e capital expenditure to replace one assembly operator on one shift

q_h hourly production rate

Q_y yearly production rate

r minimum attractive rate of return

S_h number of shifts

T_p production time obtainable for a particular assembly system

V_s annual production volume per shift

W_a annual cost of one assembly operator

w_a hourly cost of one assembly operator

W_s annual cost of one machine supervisor

w_s hourly cost of one machine supervisor

W_t annual total labor cost

w_t hourly total labor cost

ρ the ratio of actual installation cost to hardware cost

Derived Parameters

E_f integer part of $\frac{V_s}{V_t}$

f_a annualized cost factor

N_m integer part of $\left(\frac{N_a}{N_s} + 1\right)$

N_s number of parts in a station

R_d design stability, $R_d = \frac{N_d}{N_a}$

S_v design variations, $S_v = \frac{N_t}{N_a}$

T_b greater value of T_p and T_q , $T_b = \max(T_p, T_q)$

T_q required production time, $T_q = \frac{7.2e}{V_s}$

v retained value of equipment (in percent)

V_m smaller volume of V_s and V_t , $V_m = \min(V_s, V_t)$

V_t annual production volume per shift obtainable from an assembly facility

Other Parameters

D number of the available working days per year = 250

e plant efficiency; average time worked divided by time available = 69%

N_i number of operators additional to machine supervisor on in-line indexing machin
= 1

N_r number of operators additional to machine supervisor on rotary indexing machine
= 0

P_q ratio of fault parts to acceptable parts = 1 %

Constant Factors

Equipment

C_1 basic cost of robot or programmable workhead = 25 k\$

C_2 additional cost of robot or programmable workhead per degree of freedom = 8
k\$

C_b cost of transfer device per work station or buffer space on free-transfer machine
= 1 k\$

C_c cost of work carrier = 1 k\$

C_{fd} cost of automatic feeding device and delivery track = 5 k\$

C_g cost gripper divided by N_a = 0.5 k\$

C_m cost of manually loaded magazine = 0.5 k\$

C_{tr} cost of transfer device per work station for an indexing machine = 10 k\$

C_w cost of special-purpose workhead = 10 k\$

Time

T_a manual assembly time per part = 10 s

T_d machine downtime due to each defective part = 30 s

T_m manual assembly time per part when mechanical assistance is provided = 9 s

T_r assembly time per part with robot or programmable workhead = 5 s

T_w assembly time per part with special-purpose workhead = 5 s

3600 seconds per hour

8 working hours per day

7.2 working seconds per year (in million) derived by 250 working days

APPENDIX B. BOOTHROYD'S METHODOLOGY

Program List

```

C   Dimensionless Assembly Cost
C   based on the economic analysis done by
C   G. Boothroyd
C
C   Define all variables used in this program.
C
REAL VS,NA,QE,SH,NT,ND,NP,WA,WS,C1,C2,CB
REAL CC,CF,CG,CM,CP,CT,CU,CW,TA,TD,TM,TR,TW
REAL PE,PQ,NI,NR,SV,RD,TQ,NS,TP,WT,WR,CE,CD
REAL GAME
DIMENSION CD(6)

C
C   Define output file "assem.dat".
C
OPEN(UNIT=2,FILE='assem.dat',STATUS='NEW')
WRITE(*,*)'Assembly System Selection'
WRITE(2,1)
1  FORMAT('Assembly System Selection by Boothroyd Method')
C
C   Use "GAME" to check if need one more run (1=yes 0=no).
C   The initial value is 1.
C
GAME=1
100 IF(GAME .EQ. 0) THEN
GO TO 200
ENDIF

C
C   Collect the input data for system selection.

```

```

C      WRITE(*,*)'Number of different products'
      READ(*,*)NP
      WRITE(2,2)NP
2     FORMAT('Number of different products',F6.0)
      WRITE(*,*)'Annual volume per shift ? by million'
      READ(*,*)VS
      WRITE(2,3)VS
3     FORMAT('annual volume',F10.2)
      WRITE(*,*)'Number of shifts ?'
      READ(*,*)SH
      WRITE(2,4)SH
4     FORMAT('number of shift',F10.0)
      WRITE(*,*)'Number of parts ?'
      READ(*,*)NA
      WRITE(2,5)NA
5     FORMAT('number of parts',F10.0)
      WRITE(*,*)'Total number of parts for different styles ?'
      WRITE(2,6)NT
6     FORMAT('total number of parts',F10.0)
      WRITE(*,*)'Number of design changes in the first three :
      READ(*,*)ND
      WRITE(2,7)ND
7     FORMAT('number of design change',F10.0)
      WRITE(*,*)'QE by ?K$'
      READ(*,*)QE
      WRITE(2,8)QE
8     FORMAT('QE',F6.0)
      WRITE(*,*)'Annual rate for one operator?'
      READ(*,*)WA
      WRITE(2,9)WA
9     FORMAT('Annual rate for one operator',F6.0)
      WRITE(*,*)'Annual rate for one supervisor'
      READ(*,*)WS
      WRITE(2,10)WS 10
C
C      Define the value for time and cost parameters.
C
C1=25

```

C2=8
 CB=5
 CC=1
 CF=5
 CG=0.5
 CM=0.5
 CP=1
 CT=10
 CU=10
 CW=10
 TA=10
 TD=30
 TM=9
 TR=5
 TW=5
 PE=69
 PQ=0.01
 NI=1
 NR=0

C
 C
 C

Use input data to derive these parameters.

$SV = NT/NA$
 $RD = ND/NA$
 $TQ = 0.072 * PE / VS$

C
 C
 C
 C

Calculate CD for "AI".

$TP = TW + NA * PQ * TD$
 $WT = NI * WA + WS$
 IF (NA .LT. 7) THEN
 $WT = NR * WA + WS$
 ENDIF
 $CE = NA * (SV * CT + NP * (SV * CC + (SV + RD) * (CF + CW)))$
 IF (TP .LT. TQ) THEN
 $TP = TQ$
 ENDIF
 $WR = WT / (WA * NA)$

```

CD(1)=(TP/TA)*(WR+(CE/NA)/(SH*QE))
C
C Calculate CD for "AF".
C
TP=TW+PQ*TD
CE=NA*(SV*(1+TD/TW)*(CB+NP*CC/2)+NP*(SV+RD)*(CF+CW))
IF (TP .LT. TQ) THEN
TP=TQ
ENDIF
WR=(NI+WS/WA)/NA
CD(2)=(TP/TA)*(WR+(CE/NA)/(SH*QE))
C
C Calculate CD for "AP".
C
NS=INT(TQ/(TR+PQ*TD)+0.5)
IF(NS .EQ. 0) THEN
NS=1
ENDIF
TP=NS*(TR+PQ*TD)
CR=C1+6*C2
IF (NS .LT. 6) THEN
CR=C1+NS*C2
ENDIF
CE=NA*((CR+(1+TD/TR)*CB)/NS)
CE=CE+NP*((SV+RD)*CM+CG+(1+TD/TR)*CC/2/NS))
IF (TP .LT. TQ) THEN
TP=TQ
ENDIF
WR=(NI+WS/WA)/NA
CD(3)=(TP/TA)*(WR+(CE/NA)/(SH*QE))
C
C Calculate CD for "AR".
C
TP=NA*(TR/2+PQ*TD)
CR=C1+6*C2
IF (NA .LT. 6) THEN
CR=C1+NA*C2
ENDIF

```

```

CE=2*CR+NP*(CC+NA*CG+NA*(SV+RD)*CM)
IF (TP .LT. TQ) THEN
TP=TQ
ENDIF
WR=WS/WA/NA
CD(4)=(TP/TA)*(WR+(CE/NA)/(SH*QE))

```

C

C

C

```

Calculate CD for "MA".

```

```

NS=INT(TQ/(TA*(1+PQ))+0.5)
IF(NS .EQ. 0) THEN
NS=1
ENDIF
TP=NS*TA*(1+PQ)
WR=1/NS
CE=(NA/NS)*(2*CB+NP*CC)
IF (TP .LT. TQ) THEN
TP=TQ
ENDIF
CD(5)=(TP/TA)*(WR+(CE/NA)/(SH*QE))

```

C

C

C

```

Calculate CD for "MM".

```

```

NS=INT(TQ/(TM*(1+PQ))+0.5)
IF(NS .EQ. 0) THEN
NS=1
ENDIF
TP=NS*TM*(1+PQ)
WR=1/NS
CE=(NA/NS)*(2*CB+NP*CC+NS*(NP*(SV+RD)*CF))
IF (TP .LT. TQ) THEN
TP=TQ
ENDIF
CD(6)=(TP/TA)*(WR+(CE/NA)/(SH*QE))

```

C

C

C

C

```

Print results for each system.

```

```

WRITE(2,11)CD(1),CD(2),CD(3)

```

```
11  FORMAT(1X,'AI',F8.4,' AF',F8.4,' AP',F8.4)
    WRITE(2,12)CD(4),CD(5),CD(6)
12  FORMAT(1X,'AR',F8.4,' MA',F8.4,' MM',F8.4)
    WRITE(2,13)
13  FORMAT("//)
C
C  Check if need one more run.
C
    WRITE(*,*)'NEED MORE ? 0=NO, 1=YES'
    READ(*,*)GAME
    GO TO 100
200 STOP
    END
```

APPENDIX C. INITIAL UNIT COST METHODOLOGY

Program List

```

C
C   Unit Assembly Cost
C   based on the economic analysis done by
C   G. Boothroyd and Gustavson
C
C   Define all variables used in this program.
C
REAL R,H,V,D,RHO,QH,FA,RR,C,DR
REAL MACRS,X,TYPE,TQ,GAME
REAL VS,NA,SH,NT,ND,NP,WA,WS,C1,C2,CB
REAL CC,CF,CG,CM,CP,CT,CU,CW,TA,TD,TM,TR,TW
REAL PE,PQ,NI,NR,SV,RD,NS,TP,WT,CE,VT
DIMENSION C(6),MACRS(30),X(6),TYPE(6)
DIMENSION VT(6),CE(6),WT(6)
C
C   Define input file "unr.dat" and output file "unw.dat".
C
OPEN(UNIT=2,FILE='unr.dat',STATUS='old')
OPEN(UNIT=3,FILE='unw.dat',STATUS='new')
WRITE(3,1)
1  FORMAT('Selection of Assembly Systems by Unit Cost')
   READ(2,2)TYPE
2  FORMAT(6A2)
   GAME=1
100 IF(GAME .EQ. 0) THEN
    GO TO 200
   ENDIF
   WRITE(*,*)'Number of different products'

```

```

READ(*,*)NP
WRITE(3,3)NP
3  FORMAT('Number of different products',F6.4)
   WRITE(*,*)'Annual volume per shift ? by million'
   READ(*,*)VS
   WRITE(3,4)VS
4  FORMAT('Annual volume (by ms)',F6.2)
   WRITE(*,*)'Number of shifts ?'
   READ(*,*)SH
   WRITE(3,5)SH
5  FORMAT('Number of shift ',F6.0)
   WRITE(*,*)'Number of parts ?'
   READ(*,*)NA
   WRITE(3,6)NA
6  FORMAT('Number of parts ',F6.0)
   WRITE(*,*)'Total number of parts for different styles ?'
   READ(*,*)NT
   WRITE(3,7)NT
7  FORMAT('Total number of parts ',F6.0)
   WRITE(*,*)'Number of design changes in the first three'
   READ(*,*)ND
   WRITE(3,8)ND
8  FORMAT('Number of design change',F6.0)
   WRITE(*,*)'Minimum attractive rate of return ?'
   READ(*,*)R
   WRITE(3,9)R
9  FORMAT('Minimum A. R. R. ',F6.2)
   WRITE(*,*)'Investment horizon ?'
   READ(*,*)H
   WRITE(3,10)H
10 FORMAT('Investment horizon ',F6.0)
   WRITE(*,*)'Hourly rate for operator ?'
   READ(*,*)WA
   WRITE(3,11)WA
11 FORMAT('Rate for operator',F6.0)
   WRITE(*,*)'Hourly rate for supervisor ?'
   READ(*,*)WS
   WRITE(3,12)WS
12 FORMAT('Rate for supervisor',F6.0)

```

```
WRITE(*,*)'Plant efficiency ?'  
READ(*,*)PE  
WRITE(3,13)PE  
13  FORMAT('Plant efficiency',F6.2)  
WRITE(*,*)'Quantity ?'  
READ(*,*)PQ  
WRITE(3,14)PQ  
14  FORMAT('Quality',F6.2)  
D=250  
MACRS(1)=0.8571  
MACRS(2)=0.6122  
MACRS(3)=0.4373  
MACRS(4)=0.3124  
MACRS(5)=0.2232  
MACRS(6)=0.1340  
MACRS(7)=0.0448  
MACRS(8)=0.0002  
DO 20 I=1,22  
MACRS(I+8)=0  
20  CONTINUE  
C1=25  
C2=8  
CB=5  
CC=1  
CF=5  
CG=0.5  
CM=0.5  
CP=1  
CT=10  
CU=10  
CW=10  
TA=10  
TD=30  
TM=9  
TR=5  
TW=5  
NI=1  
NR=0  
SV=NT/NA
```

```

RD=ND/NA
TQ=7.2*PE/VS
DO 25 I=1,h
V=MACRS(I)
25 CONTINUE
C
C Calculate unit cost for AI.
C
TP=TW+NA*PQ*TD
VT(1)=7.2*PE/TP
WT(1)=NI*WA+WS
IF(NA .LT. 7) THEN
WT(1) = WA*NR+WS
ENDIF
IF (VT(1) .GT. VS) THEN
VT(1)=VS
ENDIF
CE(1)=NA*(SV*CT+NP*(SV*CC+(SV+RD)*(CF+CW)))
RHO=1.5
RR=(1+R)**H
FA=(1-V/RHO/RR)*(R*RR/(RR-1))
QH=1000000*VT(1)/D/8
C(1)=(WT(1)/QH)+(RHO*CE(1)*FA)*1000/(SH*8*D*QH)
C
C
C Calculate unit cost for AF.
C
TP=TW+PQ*TD
VT(2)=7.2*PE/TP
WT(2)=WA*NI+WS
IF (VT(2) .GT. VS) THEN
VT(2)=VS
ENDIF
CE(2)=NA*(SV*(1+TD/TW)*(CB+NP*CC/2)+NP*(SV+RD)*(CF+CW))
RHO=1.5
RR=(1+R)**H
FA=(1-V/RHO/RR)*(R*RR/(RR-1))
QH=1000000*VT(2)/D/8
C(2)=(WT(2)/QH)+(RHO*CE(2)*FA)*1000/(SH*8*D*QH)

```

C
C
C
C

Calculate unit cost for AP.

```

NS=INT(TQ/(TR+PQ*TD)+0.5)
IF (NS .EQ. 0) THEN
NS=1
ENDIF
TP=NS*(TR+PQ*TD)
VT(3)=7.2*PE/TP
CR=C1+6*C2
IF(NS .LE. 6) THEN
CR=C1+NS*C2
ENDIF
WT(3)=WA*NI+WS
IF (VT(3) .GT. VS) THEN
VT(3)=VS
ENDIF
DR=1+TD/TR
CE(3)=NA*((CR+DR*CB)/NS+NP*((SV+RD)*CM+CG+DR*CC/2/NS))
RHO=1.5
RR=(1+R)**H
FA=(1-V/RHO/RR)*(R*RR/(RR-1))
QH=1000000*VT(3)/D/8
C(3)=(WT(3)/QH)+(RHO*CE(3)*FA)*1000/(SH*8*D*QH)

```

C
C
C
C

Calculate unit cost for AR.

```

TP=NA*(TR/2+PQ*TD)
VT(4)=7.2*PE/TP
CR=C1+6*C2
IF(NA .LT. 6) THEN
CR=C1+NA*C2
ENDIF
WT(4)=WS
IF (VT(4) .GT. VS) THEN
VT(4)=VS
ENDIF

```

```

CE(4)=2*CR+NP*(CC+NA*CG+NA*(SV+RD)*CM)
RHO=1.5
RR=(1+R)**H
FA=(1-V/RHO/RR)*(R*RR/(RR-1))
QH=1000000*VT(4)/D/8
C(4)=(WT(4)/QH)+(RHO*CE(4)*FA)*1000/(SH*8*D*QH)

```

C
C
C

Calculate unit cost for MA.

```

NS=INT(TQ/(TA*(1+PQ))+0.5)
IF(NS .EQ. 0) THEN
NS=1
ENDIF
TP=NS*TA*(1+PQ)
VT(5)=7.2*PE/TP
WT(5)=(NA/NS)*WA
IF (VT(5) .GT. VS) THEN
VT(5)=VS
ENDIF
CE(5)=(NA/NS)*(2*CB+NP*CC)
RHO=1.5
RR=(1+R)**H
FA=(1-V/RHO/RR)*(R*RR/(RR-1))
QH=1000000*VT(5)/D/8
C(5)=(WT(5)/QH)+(RHO*CE(5)*FA)*1000/(SH*8*D*QH)

```

C
C
C
C

Calculate unit cost for MM.

```

NS=INT(TQ/(TM*(1+PQ))+0.5)
IF(NS .EQ. 0) THEN
NS=1
ENDIF
TP=NS*TM*(1+PQ)
VT(6)=7.2*PE/TP
WT(6)=NA/NS*WA
IF (VT(6) .GT. VS) THEN
VT(6)=VS
ENDIF

```

```

CE(6)=(NA/NS)*(2*CB+NP*CC+NS*(NP*(SV+RD)*CF))
RHO=1.5
RR=(1+R)**H
FA=(1-V/RHO/RR)*(R*RR/(RR-1))
QH=1000000*VT(6)/D/8
C(6)=(WT(6)/QH)+(RHO*CE(6)*FA)*1000/(SH*8*D*QH)
C
C
C   Sorting Assembly Systems. C
DO 30 I=1,6
X(I)=1/C(I)
30  CONTINUE
C
DO 35 I=1,6
SMALL=0
DO 40 J=1,6
IF(X(J)-SMALL)40,50,50
50  SMALL=X(J)
M=J
40  CONTINUE
WRITE(3,15)I,TYPE(M),VT(M),WT(M),CE(M),C(M)
15  FORMAT('Pr ',I1,2X,A2,' VT',F8.4,' WT',F7.1,' CE',F8.1,' C',F7.4)
X(M)=0
35  CONTINUE
C
C
C   Check if one more run. C
WRITE(*,*)'NEED MORE ? 0=NO, 1=YES'
READ(*,*)GAME
GO TO 100
200 STOP
END

```

APPENDIX D. MODIFIED UNIT COST METHODOLC

The Main Menu of the Program

```

*****
*
* SELECTION OF ASSEMBLY SYSTEMS *
* by total unit cost *
*
*****
*
* Please Key in the Number of Topics *
*
* 1. Description of Assembly systems *
* 2. Description of input data *
* 3. Description of Constant *
* 4. Format of Input Data *
* 5. Sample output *
* 6. Begin Input Data *
* 7. Quit *
*
*****
Key in the number

```

The Sample Output of the Program

```

*****
*
* 5. Sample output
*
* RHO for AI 1.50 RHO for AF 1.50
* RHO for AP 1.80 RHO for AR 2.50
* RHO for MA 1.20 RHO for MM 1.20
* Number of parts = 4
* Total number of parts = 5
* Number of design change = 1
* Number of products = 1
* Number of shift = 2
* Annual volume (by ms) = 0.50
* Minimum A. R. R. = 0.25
* Investment horizons = 6
* Rate for operator = 18
* Rate for supervisor = 36
* Plant efficiency = 0.69
* Ratio of faulty to acceptable parts = 0.01
* Working days per year = 250
* Pr 1 AI unit cost = 0.2160
* Pr 2 AF unit cost = 0.3562
* Pr 3 AP unit cost = 0.3585
* Pr 4 MM unit cost = 0.3965
* Pr 5 AR unit cost = 0.4884
* Pr 6 MA unit cost = 0.7634
*
*****
Back to main menu ?
(yes=0 no=9, begin input data)

```

Program List

```

C   Assembly System Selection
C   based on total unit cost
C
C
C   Define all variables used in this program.
C
INTEGER SYS,YN
REAL R,H,V,D,RHO,QH,FA,RR,C,DR
REAL MACRS,X,TYPE,TQ,GAME
REAL VS,NA,SH,NT,ND,NP,WA,WS,C1,C2,CB
REAL CC,CF,CG,CM,CP,CT,CU,CW,TA,TD,TM,TR,TW
REAL PE,PQ,NL,NR,SV,RD,NS,TP,WT,CE,VT
DIMENSION C(6),MACRS(30),X(6),TYPE(6)
DIMENSION VT(6),CE(6),WT(6),RHO(6)
C   Define output file 'unr.dat'
OPEN(UNIT=2,FILE='unr.dat',STATUS='old')
READ(2,1)TYPE
1   FORMAT(6A2)
999 DO 2 I=1,40
    WRITE(*,*)"
2   CONTINUE
C
C
C   Main menu for the program.
C
WRITE(*,*)'***** *'
WRITE(*,*)'* SELECTION OF ASSEMBLY SYSTEMS *'
WRITE(*,*)'* by total unit cost *'
WRITE(*,*)'***** *'
WRITE(*,*)'* Please Key in the Number of Topics *'
WRITE(*,*)'* 1. Description of Assembly systems *'
WRITE(*,*)'* 2. Description of input data *'
WRITE(*,*)'* 3. Description of Constant *'
WRITE(*,*)'* 4. Format of Input Data *'
WRITE(*,*)'* 5. Sample output *'
WRITE(*,*)'* 6. Begin Input Data *'
WRITE(*,*)'* 7. Quit *'
WRITE(*,*)'***** *'

```

```

WRITE(*,*)'Key in the number'
READ(*,*)SYS
GO TO (111,222,333,444,555,666,200),SYS
111 DO 3 I=1,40
    WRITE(*,*)"
3    CONTINUE
C
C
C    Description of assembly systems.
C
WRITE(*,*)'***** *'
WRITE(*,*)'* 1. Description of Assembly systems *'
WRITE(*,*)'* AI: automatic, using indexing machines *'
WRITE(*,*)'* AF: automatic, using free-transfer machines *'
WRITE(*,*)'* AP: automatic, using programmable machines *'
WRITE(*,*)'* AR: automatic, using two-arm robot *'
WRITE(*,*)'* MA: manual assembly *'
WRITE(*,*)'* MM: manual, with mechanical assistance *'
WRITE(*,*)'***** *'
WRITE(*,*)'Back to main menu ?'
WRITE(*,*)' (yes=0 no=9 begin input data)'
READ(*,*)YN
IF(YN .EQ. 0) THEN
GO TO 999
ENDIF
GO TO 666
222 DO 4 I=1,40
    WRITE(*,*)"
4    CONTINUE
C
C
C    Description of input data.
C
WRITE(*,*)'***** *'
WRITE(*,*)'* 2. Description of Input Data *'
WRITE(*,*)'* D : number of working days per year *'
WRITE(*,*)'* H : investment of horizon *'
WRITE(*,*)'* NA: number of parts in the assembly *'
WRITE(*,*)'* NT: total number of parts for product styles *'

```

```

WRITE(*,*)' ND: number of design changes          *'
WRITE(*,*)' NP: number of different products      *'
WRITE(*,*)' PE: plant efficiency                 *'
WRITE(*,*)' PQ: ratio of faulty of acceptable parts *'
WRITE(*,*)' R : minimum attractive rate of return *'
WRITE(*,*)' SH: number of shifts                 *'
WRITE(*,*)' VS: required annual production volumes *'
WRITE(*,*)' WA: hourly cost for a machine operator *'
WRITE(*,*)' WS: hourly cost for a machine supervisor *'
WRITE(*,*)' RHO:the ratio of actual installation cost *'
WRITE(*,*)' to hardware cost                     *'
WRITE(*,*)'***** *'
WRITE(*,*)'Back to main menu ?'
WRITE(*,*)' (yes=0 no=9 begin input data) '
READ(*,*)YN
IF(YN .EQ. 0) THEN
GO TO 999
ENDIF
GO TO 666
333 DO 5 I=1,40
WRITE(*,*)'
5 CONTINUE
C
C
C Description of constants.
C
WRITE(*,*)'***** *'
WRITE(*,*)' 3. Description of Constants          *'
WRITE(*,*)' C1 basic cost of robot or programmable *'
WRITE(*,*)' workhead = 25 k$                    *'
WRITE(*,*)' C2 additional cost of robot or programmable *'
WRITE(*,*)' workhead per degree of freedom = 8 k$ *'
WRITE(*,*)' CB cost of transfer device          *'
WRITE(*,*)' per work station or buffer space on *'
WRITE(*,*)' free-transfer machine = 1 k$        *'
WRITE(*,*)' CC cost of work carrier = 1 k$      *'
WRITE(*,*)' CFD cost of automatic feeding device *'
WRITE(*,*)' and delivery track = 5 k $         *'
WRITE(*,*)' CG cost gripper divided by Na = 0.5 k$ *'

```

```

WRITE(*,*)'* CM cost of manually loaded                                *'
WRITE(*,*)'* magazine = 0.5 k$                                        *'
WRITE(*,*)'* CTR cost of transfer device per work                    *'
WRITE(*,*)'* station for an indexingmachine = 10 k$                 *'
WRITE(*,*)'* CW cost of special-purpose workhead = 10 k$           *'
WRITE(*,*)'* TA manual assembly time per part = 10 s               *'
WRITE(*,*)'* TD machine downtime due to                             *'
WRITE(*,*)'* each defective part = 30 s                             *'
WRITE(*,*)'* TM manual assembly time per part when                 *'
WRITE(*,*)'* mechanical assistance is provided = 9 s               *'
WRITE(*,*)'* TR assembly time per part with robot                  *'
WRITE(*,*)'* or programmable workhead = 5 s                        *'
WRITE(*,*)'* TW assembly time per part with                         *'
WRITE(*,*)'* special-purpose workhead = 5 s                         *'
WRITE(*,*)'* 3600 seconds per hour                                  *'
WRITE(*,*)'* 8 working hours per day                                *'
WRITE(*,*)'* 7.2 working seconds per year (in million)            *'
WRITE(*,*)'* derived by 250 working days                            *'
WRITE(*,*)'***** *'
WRITE(*,*)'Back to main menu ?'
WRITE(*,*)' (yes=0 no=9 begin input data)'
READ(*,*)YN
IF(YN .EQ. 0) THEN
GO TO 999
ENDIF
GO TO 666
444 DO 6 I=1,40
WRITE(*,*)"
6 CONTINUE
C
C
C Format of input data.
C
WRITE(*,*)'***** *'
WRITE(*,*)'* 4. Format of Input Data                                *'
WRITE(*,*)'* Variable type limit                                  *'
WRITE(*,*)'* D integer  $0 < D$                                     *'
WRITE(*,*)'* H integer  $0 < H$                                     *'
WRITE(*,*)'* NA integer  $0 < NA$                                     *'

```

```

WRITE(*,*)' NT integer 0 < NT                                *'
WRITE(*,*)' ND integer 0 ≤ ND                                *'
WRITE(*,*)' NP integer 0 < NP                                *'
WRITE(*,*)' PE real 0 < PE < 1                              *'
WRITE(*,*)' PQ real 0 < PQ < 1                              *'
WRITE(*,*)' R real 0 < R < 1                                *'
WRITE(*,*)' SH integer 0 < SH < 4                            *'
WRITE(*,*)' VS real 0 < VS                                  *'
WRITE(*,*)' RHO real 1 ≤ RHO ≤ 5                             *'
WRITE(*,*)' WA real 0 < WA                                  *'
WRITE(*,*)' WS real 0 < WS                                  *'
WRITE(*,*)'*****'
WRITE(*,*)'Back to main menu ?'
WRITE(*,*)' (yes=0 no=9 begin input data)'
READ(*,*)YN
IF(YN .EQ. 0) THEN
GO TO 999
ENDIF
GO TO 666
555 DO 7 I=1,40
WRITE(*,*)'
7 CONTINUE
C
C
C Sample output.
C
WRITE(*,*)'*****'
WRITE(*,*)' 5. Sample output                                *'
WRITE(*,*)' RHO for AI 1.50 RHO for AF 1.50                *'
WRITE(*,*)' RHO for AP 1.80 RHO for AR 2.50                *'
WRITE(*,*)' RHO for MA 1.20 RHO for MM 1.20                *'
WRITE(*,*)' Number of parts = 4                             *'
WRITE(*,*)' Total number of parts = 5                       *'
WRITE(*,*)' Number of design change = 1                     *'
WRITE(*,*)' Number of products = 1                          *'
WRITE(*,*)' Number of shift = 2                             *'
WRITE(*,*)' Annual volume (by ms) = 0.50                    *'
WRITE(*,*)' Minimun A. R. R. = 0.25                          *'
WRITE(*,*)' Investment horizone = 6                          *'

```

```

WRITE(*,*)' Rate for operator = 18          *'
WRITE(*,*)' Rate for supervisor = 36       *'
WRITE(*,*)' Plant efficiency = 0.69        *'
WRITE(*,*)' Ratio of faulty to acceptable parts = 0.01 *'
WRITE(*,*)' Working days per year = 250    *'
WRITE(*,*)' Pr 1 AI unit cost = 0.2160     *'
WRITE(*,*)' Pr 2 AF unit cost = 0.3562     *'
WRITE(*,*)' Pr 3 AP unit cost = 0.3585     *'
WRITE(*,*)' Pr 4 MM unit cost = 0.3965     *'
WRITE(*,*)' Pr 5 AR unit cost = 0.4884     *'
WRITE(*,*)' Pr 6 MA unit cost = 0.7634     *'
WRITE(*,*)'***** *'
WRITE(*,*)'Back to main menu ?'
WRITE(*,*)' (yes=0 no=9 begin input data)'
READ(*,*)YN
IF(YN .EQ. 0) THEN
GO TO 999
ENDIF

```

C

C

C

Initial values of variables.

C

```

666 GAME=0
RHO(1)=1.5
RHO(2)=1.5
RHO(3)=1.8
RHO(4)=2.5
RHO(5)=1.2
RHO(6)=1.2
NP=1
WA=18
WS=36
PE=0.69
PQ=0.01
D=250
SH=2
H=6
R=0.25
VS=0.5

```

```

100 IF(GAME .EQ. 9) THEN
      GO TO 200
      ENDIF
      DO 8 I=1,40
      WRITE(*,*)"
8     CONTINUE
C
C
C     Begin input data. Check with initial values first. If need
C     any change, answer "yes".
C
      WRITE(*,*)'Begin input data'
      WRITE(*,*)"
      WRITE(*,9)RHO(1),RHO(2)
9     FORMAT(' RHO for AI = ',F4.2,' RHO for AF = ',F4.2)
      WRITE(*,10)RHO(3),RHO(4)
10    FORMAT(' RHO for AP = ',F4.2,' RHO for AR = ',F4.2)
      WRITE(*,11)RHO(5),RHO(6)
11    FORMAT(' RHO for MA = ',F4.2,' RHO for MM = ',F4.2)
      WRITE(*,*)"
      WRITE(*,*)' ( minimum = 1 maximum = 5 )'
      WRITE(*,*)"
      WRITE(*,*)' Need change (yes=9, no=0)?'
      WRITE(*,*)"
      READ(*,*)YN
      IF(YN .EQ. 9) THEN
      WRITE(*,*)"
12    WRITE(*,*)' RHO for AI is ?'
      READ(*,*)RHO(1)
      IF ( RHO(1) .GT. 5 .OR. RHO(1) .LT. 1) THEN
      WRITE(*,*)'RHO is out of limit, Try again !!'
      WRITE(*,*)"
      ENDIF
      IF ( RHO(1) .GT. 5 .OR. RHO(1) .LT. 1) GO TO 12
13    WRITE(*,*)' RHO for AF is ?'
      READ(*,*)RHO(2)
      IF ( RHO(2) .GT. 5 .OR. RHO(2) .LT. 1) THEN
      WRITE(*,*)'RHO is out of limit, Try again !!'
      WRITE(*,*)"

```

```

ENDIF
IF ( RHO(2) .GT. 5 .OR. RHO(2) .LT. 1) GO TO 13
14 WRITE(*,*)' RHO for AP is ?'
   READ(*,*)RHO(3)
   IF ( RHO(3) .GT. 5 .OR. RHO(3) .LT. 1) THEN
   WRITE(*,*)'RHO is out of limit, Try again !!'
   WRITE(*,*)"
   ENDF
   IF ( RHO(3) .GT. 5 .OR. RHO(3) .LT. 1) GO TO 14
15 WRITE(*,*)' RHO for AR is ?'
   READ(*,*)RHO(4)
   IF ( RHO(4) .GT. 5 .OR. RHO(4) .LT. 1) THEN
   WRITE(*,*)'RHO is out of limit, Try again !!'
   WRITE(*,*)"
   ENDF
   IF ( RHO(4) .GT. 5 .OR. RHO(4) .LT. 1) GO TO 15
16 WRITE(*,*)' RHO for MA is ?'
   READ(*,*)RHO(5)
   IF ( RHO(5) .GT. 5 .OR. RHO(5) .LT. 1) THEN
   WRITE(*,*)'RHO is out of limit, Try again !!'
   WRITE(*,*)"
   ENDF
   IF ( RHO(5) .GT. 5 .OR. RHO(5) .LT. 1) GO TO 16
17 WRITE(*,*)' RHO for MM is ?'
   READ(*,*)RHO(6)
   IF ( RHO(6) .GT. 5 .OR. RHO(6) .LT. 1) THEN
   WRITE(*,*)'RHO is out of limit, Try again !!'
   WRITE(*,*)"
   ENDF
   IF ( RHO(6) .GT. 5 .OR. RHO(6) .LT. 1) GO TO 17
   ENDF
   WRITE(*,*)"
18 WRITE(*,*)' Number of parts ?'
   READ(*,*)NA
   IF ( NA .LT. 1) THEN
   WRITE(*,*)'NA is out of limit, Try again !!'
   WRITE(*,*)"
   ENDF
   IF ( NA .LT. 1) GO TO 18

```

```

19  WRITE(*,*)' Total number of parts for different styles ?'
    READ(*,*)NT
    IF ( NT .LT. NA) THEN
    WRITE(*,*)'NT is out of limit, Try again !!'
    WRITE(*,*)"
    ENDIF
    IF ( NT .LT. NA) GO TO 19
20  WRITE(*,*)' Number of design changes ?'
    READ(*,*)ND
    IF ( ND .LT. 0) THEN
    WRITE(*,*)'ND is out of limit, Try again !!'
    WRITE(*,*)"
    ENDIF
    IF ( ND .LT. 0) GO TO 20
    WRITE(*,*)"
    WRITE(*,21)NP
21  FORMAT(' Number of products is ',F3.0)
    WRITE(*,*)"
    WRITE(*,*)' need change? (yes=9 no=0)'
    WRITE(*,*)"
    READ(*,*)YN
    IF(YN .EQ. 9) THEN
22  WRITE(*,*)' Number of products ? '
    READ(*,*)NP
    IF ( NP .LE. 0) THEN
    WRITE(*,*)'NP is out of limit, Try again !!'
    WRITE(*,*)"
    ENDIF
    IF ( NP .LE. 0) GO TO 22
    ENDIF
    WRITE(*,*)"
    WRITE(*,*)' Factory related data'
    WRITE(*,*)"
    WRITE(*,23)SH
23  FORMAT(' Number of shifts is ',F2.0)
    WRITE(*,24)VS
24  FORMAT(' Annual volume per shift (in million) is ',F6.2)
    WRITE(*,*)"
    WRITE(*,*)' need change? (yes=9 no=0)'

```

```

WRITE(*,*)"
READ(*,*)YN
IF(YN .EQ. 9) THEN
WRITE(*,*)"
25 WRITE(*,*)' Number of shifts is'
READ(*,*)SH
IF ( SH .LT. 1 .OR. SH .GT. 3) THEN
WRITE(*,*)'SH is out of limit, Try again !!'
WRITE(*,*)"
ENDIF
IF ( SH .LT. 1 .OR. SH .GT. 3) GO TO 25
26 WRITE(*,*)' Annual production volume is'
READ(*,*)VS
IF ( VS .LE. 0) THEN
WRITE(*,*)'VS is out of limit, Try again !!'
WRITE(*,*)"
ENDIF
IF ( VS .LE. 0) GO TO 26
ENDIF
WRITE(*,*)"
WRITE(*,27)H
27 FORMAT(' Investment horizon is ',F2.0)
WRITE(*,28)R
28 FORMAT(' Minimum attractive rate of return is ',F5.2)
WRITE(*,*)"
WRITE(*,*)' need change? (yes=9 no=0)'
WRITE(*,*)"
READ(*,*)YN
IF(YN .EQ. 9) THEN
29 WRITE(*,*)' Investment horizon is'
READ(*,*)H
IF ( H .LT. 1) THEN
WRITE(*,*)'H is out of limit, Try again !!'
WRITE(*,*)"
ENDIF
IF ( H .LT. 1) GO TO 29
30 WRITE(*,*)' Minimum attractive rate of return is'
READ(*,*)R
IF ( R .LE. 0 .OR. R .GE. 1) THEN

```

```

WRITE(*,*)'R is out of limit, Try again !!'
WRITE(*,*)"
ENDIF
IF ( R .LE. 0 .OR. R .GE. 1) GO TO 30
ENDIF
WRITE(*,*)"
WRITE(*,31)WA
31  FORMAT(' Hourly cost for an operator = ',F6.1)
WRITE(*,32)WS
32  FORMAT(' Hourly cost for a supervisor = ',F6.1)
WRITE(*,*)"
WRITE(*,*)' Need change (yes=9, no=0)'
WRITE(*,*)"
READ(*,*)YN
IF(YN .EQ. 9) THEN
33  WRITE(*,*)' Hourly cost for an operator ?'
READ(*,*)WA
IF ( WA .LE. 0) THEN
WRITE(*,*)'WA is out of limit, Try again !!'
WRITE(*,*)"
WRITE(*,*)"
ENDIF
IF ( WA .LE. 0) GO TO 33
34  WRITE(*,*)' Hourly cost for a supervisor ?'
READ(*,*)WS
IF ( WS .LE. 0) THEN
WRITE(*,*)'WS is out of limit, Try again !!'
WRITE(*,*)"
ENDIF
IF ( WS .LE. 0) GO TO 34
ENDIF
WRITE(*,*)"
C
WRITE(*,*)"
WRITE(*,35)PE
35  FORMAT(' Plant efficiency is = ',F4.2)
WRITE(*,36)PQ
36  FORMAT(' Ratio of faulty to acceptable parts = ',F4.2)
WRITE(*,37)D

```

```

37  FORMAT(' Working days per year = ',F4.0)
    WRITE(*,*)"
    WRITE(*,*)' Need change (yes=9, no=0)? '
    WRITE(*,*)"
    READ(*,*)YN
    IF(YN .EQ. 9) THEN
38  WRITE(*,*)' Plant efficiency is?'
    READ(*,*)PE
    IF ( PE .LE. 0 .OR. PE .GE. 1) THEN
    WRITE(*,*)'PE is out of limit, Try again !!'
    WRITE(*,*)"
    ENDIF
    IF ( PE .LE. 0 .OR. PE .GE. 1) GO TO 38
39  WRITE(*,*)' Ratio of faulty to acceptable parts is?'
    READ(*,*)PQ
    IF ( PQ .LE. 0 .OR. PQ .GE. 1) THEN
    WRITE(*,*)'PQ is out of limit, Try again !!'
    WRITE(*,*)"
    ENDIF
    IF ( PQ .LE. 0 .OR. PQ .GE. 1) GO TO 39
40  WRITE(*,*)' Working days per year is?'
    READ(*,*)D
    IF ( D .LE. 0) THEN
    WRITE(*,*)'D is out of limit, Try again !!'
    WRITE(*,*)"
    ENDIF
    IF ( D .LE. 0) GO TO 40
    ENDIF
    WRITE(*,*)"

C
C
C  Initial values of time and cost factors. C
    MACRS(1)=0.8571
    MACRS(2)=0.6122
    MACRS(3)=0.4373
    MACRS(4)=0.3124
    MACRS(5)=0.2232
    MACRS(6)=0.1340
    MACRS(7)=0.0448

```

```

MACRS(8)=0.0002
DO 41 I=1,22
MACRS(I+8)=0
41 CONTINUE
C1=25
C2=8
CB=5
CC=1
CF=5
CG=0.5
CM=0.5
CP=1
CT=10
CU=10
CW=10
TA=10
TD=30
TM=9
TR=5
TW=5
NI=1
NR=0
SV=NT/NA
RD=ND/NA
TQ=7.2*PE/VS
DO 42 I=1,H
V=MACRS(I)
42 CONTINUE
C
C Calculate unit cost for AI
C
TP=TW+NA*PQ*TD
VT(1)=7.2*PE/TP
WT(1)=NI*WA+WS
IF(NA .LT. 7) THEN
WT(1) = WA*NR+WS
ENDIF
CE(1)=NA*(SV*CT+NP*(SV*CC+(SV+RD)*(CF+CW)))
RR=(1+R)**H

```

```

FA=(1-V/RHO(1)/RR)*(R*RR/(RR-1))
IF (VS .GT. VT(1)) THEN
CE(1)=CE(1)*INT(VS/VT(1)+1)
WT(1)=WT(1)+INT(VS/VT(1))*WA
ENDIF
QH=1000000*VS/D/8
C(1)=(WT(1)/QH)+(RHO(1)*CE(1)*FA)*1000/(SH*8*D*QH)

```

C
C
C
C

Calculate unit cost for AF

```

TP=TW+PQ*TD
VT(2)=7.2*PE/TP
WT(2)=WA*NI+WS
CE(2)=NA*(SV*(1+TD/TW)*(CB+NP*CC/2)+NP*(SV+RD)*(CF+CW))
RR=(1+R)**H
FA=(1-V/RHO(2)/RR)*(R*RR/(RR-1))
IF (VS .GT. VT(2)) THEN
CE(2)=CE(2)*INT(VS/VT(2)+1)
WT(2)=WT(2)+INT(VS/VT(2))*WA
ENDIF
QH=1000000*VS/D/8
C(2)=(WT(2)/QH)+(RHO(2)*CE(2)*FA)*1000/(SH*8*D*QH)

```

C
C
C
C

Calculate unit cost for AP

```

NS=INT(TQ/(TR+PQ*TD)+0.5)
IF (NS .EQ. 0) THEN
NS=1
ENDIF
TP=NS*(TR+PQ*TD)
VT(3)=7.2*PE/(TR+PQ*TD)
CR=C1+6*C2
IF(NS .LE. 6) THEN
CR=C1+NS*C2
ENDIF
WT(3)=WA*NI+WS
DR=1+TD/TR

```

```

CE(3)=INT((NA/NS)+1)*(CR+DR*CB)
CE(3)=CE(3)+NP*(NA*((SV+RD)*CM+CG))
CE(3)=CE(3)+INT((NA/NS)+1)*(DR*CC/2/NS)
RR=(1+R)**H
FA=(1-V/RHO(3)/RR)*(R*RR/(RR-1))
IF(VS .GT. VT(3)) THEN
CE(3)=CE(3)*INT(VS/VT(3)+1)
WT(3)=WT(3)+INT(VS/VT(3))*WA
ENDIF
QH=1000000*VS/D/8
C(3)=(WT(3)/QH)+(RHO(3)*CE(3)*FA)*1000/(SH*8*D*QH)

```

C
C
C
C

Calculate unit cost for AR

```

TP=NA*(TR/2+PQ*TD)
VT(4)=7.2*PE/TP
CR=C1+6*C2
IF(NA .LT. 6) THEN
CR=C1+NA*C2
ENDIF
WT(4)=WS
CE(4)=2*CR+NP*(CC+NA*CG+NA*(SV+RD)*CM)
RR=(1+R)**H
FA=(1-V/RHO(4)/RR)*(R*RR/(RR-1))
IF (VS .GT. VT(4)) THEN
CE(4)=CE(4)*INT(VS/VT(4)+1)
WT(4)=WT(4)*INT(VS/VT(4)+1)
ENDIF
QH=1000000*VS/D/8
C(4)=(WT(4)/QH)+(RHO(4)*CE(4)*FA)*1000/(SH*8*D*QH)

```

C
C
C
C

Calculate unit cost for MA

```

NS=INT(TQ/(TA*(1+PQ))+0.5)
IF(NS .EQ. 0) THEN
NS=1
ENDIF

```

```

TP=NS*TA*(1+PQ)
VT(5)=7.2*PE/(TA*(1+PQ))
WT(5)=INT((NA/NS)+1)*WA
CE(5)=INT((NA/NS)+1)*(2*CB+NP*CC)
RR=(1+R)**H
FA=(1-V/RHO(5)/RR)*(R*RR/(RR-1))
IF (VS .GT. VT(5)) THEN
CE(5)=CE(5)*INT(VS/VT(5)+1)
WT(5)=WT(5)*INT(VS/VT(5)+1)
ENDIF
QH=1000000*VS/D/8
C(5)=(WT(5)/QH)+(RHO(5)*CE(5)*FA)*1000/(SH*8*D*QH)
C
C
C   Calculate unit cost for MM
C
NS=INT(TQ/(TM*(1+PQ))+0.5)
IF(NS .EQ. 0) THEN
NS=1
ENDIF
TP=NS*TM*(1+PQ)
VT(6)=7.2*PE/(TM*(1+PQ))
WT(6)=INT((NA/NS)+1)*WA
CE(6)=INT((NA/NS)+1)*(2*CB+NP*CC+NS*(NP*(SV+RD)*CF))
RR=(1+R)**H
FA=(1-V/RHO(6)/RR)*(R*RR/(RR-1))
IF (VS .GT. VT(6)) THEN
CE(6)=CE(6)*INT(VS/VT(6)+1)
WT(6)=WT(6)*INT(VS/VT(6)+1)
ENDIF
QH=1000000*VS/D/8
C(6)=(WT(6)/QH)+(RHO(6)*CE(6)*FA)*1000/(SH*8*D*QH)
DO 43 I=1,6
X(I)=1/C(I)
43 CONTINUE
C
C
C   Check if need printout. C
WRITE(*,*)”

```

```

WRITE(*,*)'Need print out (yes=9, no=0)?'
WRITE(*,*)"
READ(*,*)YN
IF(YN .EQ. 9) THEN
OPEN(UNIT=3,FILE='unw.dat',STATUS='new')
WRITE(*,*)'Results '
WRITE(*,*)"
WRITE(3,44)RHO(1),RHO(2)
44  FORMAT( // 'RHO for AI',F5.2,'RHO for AF',F5.2)
WRITE(3,45)RHO(3),RHO(4)
45  FORMAT('RHO for AP',F5.2,'RHO for AR',F5.2)
WRITE(3,46)RHO(5),RHO(6)
46  FORMAT('RHO for MA',F5.2,'RHO for MM',F5.2)
WRITE(3,47)NA
47  FORMAT('Number of parts ',F6.0)
WRITE(3,48)NT
48  FORMAT('Total number of parts ',F6.0)
WRITE(3,49)ND
49  FORMAT('Number of design change',F6.0)
WRITE(3,50)NP
50  FORMAT('NP',F5.0)
WRITE(3,51)VS
51  FORMAT('Annual volume (by ms)',F6.2)
WRITE(3,52)SH
52  FORMAT('Number of shift ',F6.0)
WRITE(3,53)R
53  FORMAT('Minimun A. R. R. ',F6.2)
WRITE(3,54)H
54  FORMAT('Investment horizone ',F6.0)
WRITE(3,55)WA
55  FORMAT('Rate for operator',F6.0)
WRITE(3,56)WS
56  FORMAT('Rate for supervisor',F6.0)
WRITE(3,57)PE
57  FORMAT('Plant efficiency',F6.2)
WRITE(3,58)PQ
58  FORMAT('Ratio of faulty parts to acceptable parts',F6.2)
WRITE(3,59)PQ
59  FORMAT('Working days per year',F5.1)

```

```

C
C
C   Sorting assembly systems.
C
      DO 60 I=1,6
      SMALL=0
      DO 70 J=1,6
      IF(X(J)-SMALL)70,80,80
80    SMALL=X(J)
      M=J
70    CONTINUE
      WRITE(3,90)I,TYPE(M),VT(M),WT(M),CE(M),C(M)
90    FORMAT('Pr ',I1,2X,A2,' VT',F8.4,' WT',F7.1,' CE',F8.1,' C',F7.4)
      WRITE(*,91)I,TYPE(M),C(M)
91    FORMAT('Pr',I1,2X,A2,2X,'unit cost =',F7.4)
      X(M)=0
60    CONTINUE
      ENDIF
C
      IF(.NOT.(YN .EQ. 9)) THEN
      DO 92 I=1,6
      X(I)=1/C(I)
92    CONTINUE
      DO 93 I=1,6
      SMALL=0
      DO 94 J=1,6
      IF(X(J)-SMALL)94,95,95
95    SMALL=X(J)
      M=J
94    CONTINUE
      WRITE(*,96)I,TYPE(M),C(M)
96    format('Pr',I1,2X,A2,2X,'unit cost =',F7.4)
      X(M)=0
93    CONTINUE
      ENDIF
C
C
C   Check if one more run. C
      WRITE(*,*)"

```

```
WRITE(*,*)'Need more ? (yes=0 no=9)'  
WRITE(*,*)"  
READ(*,*)GAME  
GO TO 100  
200 STOP  
END
```

APPENDIX E. ANNUALIZED FACTOR (f_a)

As stated in Chapter 5, the equation for f_a is

$$f_a = \left[1 - \frac{v}{\rho(1+r)^h} \right] \left[\frac{r(1+r)^h}{(1+r)^h - 1} \right]$$

The following tables show the value of f_a when ρ is 1.2, 1.5, 1.8, and 2.5. The factors r and h are the minimum attractive rate of return and the investment horizon.

Table E.1: Annualized factor (f_a) ($\rho = 1.2$)

| r | h | | | | |
|------|--------|--------|--------|--------|--------|
| | 1 | 2 | 3 | 4 | 5 |
| 0.05 | 0.3358 | 0.2889 | 0.2516 | 0.2216 | 0.1973 |
| 0.10 | 0.3857 | 0.3333 | 0.2920 | 0.2594 | 0.2333 |
| 0.15 | 0.4358 | 0.3778 | 0.3330 | 0.2981 | 0.2707 |
| 0.20 | 0.4857 | 0.4227 | 0.3746 | 0.3378 | 0.3094 |
| 0.25 | 0.5358 | 0.4677 | 0.4167 | 0.3783 | 0.3492 |
| 0.30 | 0.5858 | 0.5130 | 0.4593 | 0.4196 | 0.3900 |
| 0.35 | 0.6358 | 0.5584 | 0.5023 | 0.4615 | 0.4318 |
| 0.40 | 0.6858 | 0.6041 | 0.5458 | 0.5041 | 0.4744 |
| 0.45 | 0.7358 | 0.6499 | 0.5896 | 0.5473 | 0.5177 |
| 0.50 | 0.7858 | 0.6959 | 0.6338 | 0.5910 | 0.5617 |

| r | h | | | | |
|------|--------|--------|--------|--------|--------|
| | 6 | 7 | 8 | 9 | 10 |
| 0.05 | 0.1806 | 0.1682 | 0.1547 | 0.1407 | 0.1295 |
| 0.10 | 0.2151 | 0.2015 | 0.1874 | 0.1736 | 0.1627 |
| 0.15 | 0.2515 | 0.2370 | 0.2228 | 0.2096 | 0.1993 |
| 0.20 | 0.2895 | 0.2745 | 0.2606 | 0.2481 | 0.2385 |
| 0.25 | 0.3289 | 0.3139 | 0.3004 | 0.2888 | 0.2801 |
| 0.30 | 0.3696 | 0.3548 | 0.3419 | 0.3312 | 0.3235 |
| 0.35 | 0.4115 | 0.3970 | 0.3849 | 0.3752 | 0.3683 |
| 0.40 | 0.4544 | 0.4404 | 0.4291 | 0.4203 | 0.4143 |
| 0.45 | 0.4982 | 0.4847 | 0.4743 | 0.4665 | 0.4612 |
| 0.50 | 0.5427 | 0.5299 | 0.5203 | 0.5134 | 0.5088 |

Table E.2: Annualized factor (f_a) ($\rho = 1.5$)

| r | h | | | | |
|------|--------|--------|--------|--------|--------|
| | 1 | 2 | 3 | 4 | 5 |
| 0.05 | 0.4786 | 0.3387 | 0.2747 | 0.2337 | 0.2040 |
| 0.10 | 0.5286 | 0.3818 | 0.3140 | 0.2706 | 0.2394 |
| 0.15 | 0.5786 | 0.4253 | 0.3540 | 0.3086 | 0.2762 |
| 0.20 | 0.6286 | 0.4690 | 0.3946 | 0.3475 | 0.3144 |
| 0.25 | 0.6786 | 0.5131 | 0.4358 | 0.3873 | 0.3537 |
| 0.30 | 0.7286 | 0.5573 | 0.4776 | 0.4280 | 0.3941 |
| 0.35 | 0.7786 | 0.6019 | 0.5198 | 0.4694 | 0.4355 |
| 0.40 | 0.8286 | 0.6466 | 0.5625 | 0.5114 | 0.4778 |
| 0.45 | 0.8786 | 0.6916 | 0.6056 | 0.5542 | 0.5208 |
| 0.50 | 0.9286 | 0.7367 | 0.6492 | 0.5974 | 0.5645 |

| r | 6 | 7 | 8 | 9 | 10 |
|------|--------|--------|--------|--------|--------|
| 0.05 | 0.1839 | 0.1692 | 0.1547 | 0.1407 | 0.1295 |
| 0.10 | 0.2180 | 0.2023 | 0.1874 | 0.1736 | 0.1627 |
| 0.15 | 0.2540 | 0.2377 | 0.2228 | 0.2096 | 0.1993 |
| 0.20 | 0.2917 | 0.2751 | 0.2606 | 0.2481 | 0.2385 |
| 0.25 | 0.3309 | 0.3144 | 0.3004 | 0.2888 | 0.2801 |
| 0.30 | 0.3714 | 0.3552 | 0.3419 | 0.3312 | 0.3235 |
| 0.35 | 0.4131 | 0.3973 | 0.3849 | 0.3752 | 0.3683 |
| 0.40 | 0.4558 | 0.4407 | 0.4291 | 0.4203 | 0.4143 |
| 0.45 | 0.4994 | 0.4850 | 0.4743 | 0.4665 | 0.4612 |
| 0.50 | 0.5438 | 0.5302 | 0.5203 | 0.5134 | 0.5088 |

Table E.3: Annualized factor (f_a) ($\rho = 1.8$)

| r | h | | | | |
|------|--------|--------|--------|--------|--------|
| | 1 | 2 | 3 | 4 | 5 |
| 0.05 | 0.5738 | 0.3719 | 0.2901 | 0.2417 | 0.2085 |
| 0.10 | 0.6238 | 0.4142 | 0.3287 | 0.2781 | 0.2435 |
| 0.15 | 0.6738 | 0.4569 | 0.3680 | 0.3155 | 0.2799 |
| 0.20 | 0.7238 | 0.4999 | 0.4080 | 0.3540 | 0.3177 |
| 0.25 | 0.7738 | 0.5433 | 0.4486 | 0.3933 | 0.3567 |
| 0.30 | 0.8238 | 0.5869 | 0.4897 | 0.4336 | 0.3969 |
| 0.35 | 0.8738 | 0.6308 | 0.5314 | 0.4746 | 0.4380 |
| 0.40 | 0.9238 | 0.6750 | 0.5736 | 0.5163 | 0.4800 |
| 0.45 | 0.9738 | 0.7193 | 0.6163 | 0.5587 | 0.5229 |
| 0.50 | 1.0238 | 0.7640 | 0.6594 | 0.6017 | 0.5664 |
| r | 6 | 7 | 8 | 9 | 10 |
| 0.05 | 0.1861 | 0.1698 | 0.1547 | 0.1407 | 0.1295 |
| 0.10 | 0.2200 | 0.2028 | 0.1874 | 0.1736 | 0.1627 |
| 0.15 | 0.2557 | 0.2381 | 0.2228 | 0.2096 | 0.1993 |
| 0.20 | 0.2932 | 0.2755 | 0.2606 | 0.2481 | 0.2385 |
| 0.25 | 0.3322 | 0.3147 | 0.3004 | 0.2888 | 0.2801 |
| 0.30 | 0.3726 | 0.3555 | 0.3419 | 0.3312 | 0.3235 |
| 0.35 | 0.4141 | 0.3976 | 0.3849 | 0.3752 | 0.3683 |
| 0.40 | 0.4567 | 0.4409 | 0.4291 | 0.4203 | 0.4143 |
| 0.45 | 0.5002 | 0.4852 | 0.4743 | 0.4665 | 0.4612 |
| 0.50 | 0.5445 | 0.5303 | 0.5203 | 0.5134 | 0.5088 |

Table E.4: Annualized factor (f_a) ($\rho = 2.5$)

| r | h | | | | |
|------|--------|--------|--------|--------|--------|
| | 1 | 2 | 3 | 4 | 5 |
| 0.05 | 0.7072 | 0.4184 | 0.3117 | 0.2530 | 0.2148 |
| 0.10 | 0.7572 | 0.4596 | 0.3493 | 0.2885 | 0.2492 |
| 0.15 | 0.8072 | 0.5012 | 0.3876 | 0.3252 | 0.2851 |
| 0.20 | 0.8572 | 0.5432 | 0.4267 | 0.3630 | 0.3224 |
| 0.25 | 0.9072 | 0.5856 | 0.4664 | 0.4018 | 0.3610 |
| 0.30 | 0.9572 | 0.6283 | 0.5068 | 0.4414 | 0.4007 |
| 0.35 | 1.0072 | 0.6713 | 0.5477 | 0.4819 | 0.4415 |
| 0.40 | 1.0572 | 0.7146 | 0.5892 | 0.5232 | 0.4832 |
| 0.45 | 1.1072 | 0.7582 | 0.6312 | 0.5651 | 0.5258 |
| 0.50 | 1.1572 | 0.8020 | 0.6737 | 0.6077 | 0.5691 |

| r | 6 | 7 | 8 | 9 | 10 |
|------|--------|--------|--------|--------|--------|
| 0.05 | 0.1891 | 0.1706 | 0.1547 | 0.1407 | 0.1295 |
| 0.10 | 0.2227 | 0.2035 | 0.1874 | 0.1736 | 0.1627 |
| 0.15 | 0.2581 | 0.2387 | 0.2228 | 0.2096 | 0.1993 |
| 0.20 | 0.2953 | 0.2760 | 0.2606 | 0.2481 | 0.2385 |
| 0.25 | 0.3341 | 0.3152 | 0.3004 | 0.2888 | 0.2801 |
| 0.30 | 0.3742 | 0.3559 | 0.3419 | 0.3312 | 0.3235 |
| 0.35 | 0.4155 | 0.3979 | 0.3849 | 0.3752 | 0.3683 |
| 0.40 | 0.4580 | 0.4412 | 0.4291 | 0.4203 | 0.4143 |
| 0.45 | 0.5013 | 0.4854 | 0.4743 | 0.4665 | 0.4612 |
| 0.50 | 0.5455 | 0.5305 | 0.5203 | 0.5134 | 0.5088 |