

ECONOMIC-TECHNOLOGICAL MODELING AND DESIGN CRITERIA
FOR PROGRAMMABLE ASSEMBLY MACHINES

by

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ABSTRACT

Programmable assembly is a new industrial production technology in which one piece of equipment may be programmed by computer or other means to assemble many different parts to one or more products. The versatility of programmable assembly equipment will allow it to compete with alternate assembly methods--manual and special purpose mechanized methods--under certain circumstances. These circumstances typically include those where the required production volume of a product is too low to allow economical special purpose automation or where variation between different styles of the same product produces assembly problems that are difficult to solve by special purpose automation. Manual and special purpose automation assembly have certain characteristics and limitations which determine their economic and technological applicability. Programmable assembly shares some of the characteristics of each.

In this thesis the properties of all three assembly methods are modeled using a common base of assumptions and modeling techniques. Sources of costs and benefits are identified and quantified where possible. This model:

- 1) Allows programmable assembly methods to be compared to the other two methods.
- 2) Is extended to hybrid systems consisting of manual and special purpose stations together as

well as programmable and special purpose stations together.

- 3) Leads to the derivation of a numerical measure of the economic performance of a programmable assembler. This numerical measure is the product of the average assembly time for a single part and the total cost of the assembler (the price-time product).
- 4) Permits estimation of bounds on the price-time product that should be met so that designs of programmable assemblers will be economic in comparison to the alternative assembly methods and permits study of how these bounds are affected by important parameters.
- 5) Establishes a design criterion for programmable assemblers in terms of the price-time product.

Under the given assumptions, the model not only predicts that programmable assembly has economic promise, but also identifies key research needs to fulfill that promise.

An example assembler design process is presented to show how the price-time product may be used to resolve tradeoff issues when used with models for the cost and performance of an assembler. A sensitivity study based on this example is used to show how areas for further research with maximum potential impact on the price-time product may be identified.

Finally, the economic modeling can be used as a basic component of the assessment of the impact of programmable assembly on the national economy.

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1. INTRODUCTION

Programmable assembly is a new production technology in which one piece of equipment may be programmed by computer or other means to assemble many different parts to one or more products. The anticipated virtues of programmable assembly stem from its ability to be taught different assembly tasks, in contrast to conventional automatic assembly equipment. The latter is built to do one assembly task for all of its economic life. Programmable assembly equipment can assemble different products at different phases of its economic life. Thus, the economic and technological characteristics of programmable assembly can be expected to differ from current automatic or manual assembly methods.

This thesis work relates the performance of programmable assembly equipment to the economics of its application in order to develop a criterion for design and research in programmable assembly technology. The need for design and research in programmable assembly technology is related to the national need for increased assembly productivity.

Some economists have noted the recent decline in the rate of increase of productivity in the United States and have associated with it many of the present economic troubles. Productivity can be defined as the total output of goods and services provided by a country divided by the

total quantity of labor, capital, and material resources used to produce those goods and services.

The rate of increase of productivity measures the speed with which an economic system is learning to make more and better products from a given quantity of resources; it is an important factor in the economic health of an industrialized country and has been an important factor in the rise of real wages of the people in this country. Long term trend data over the period since 1900 indicates that the fraction of the total national output that goes to wages has remained relatively constant (1). However, the total national output has grown faster than the labor force in large part due to improved productivity of production technology and methods. The result has been a steady increase in the real wages for each worker over the long term. Improving economic productivity is an important process, and improving assembly productivity is a part of it.

At the present time assembly is a labor intensive process, and a significant fraction of the direct labor in many industries is occupied in the assembly process. Table 1.1 lists a number of industries of widely divergent type showing the fraction of direct production workers that are involved in assembly. For these industries assembly took a larger share of the total direct labor than any other manufacturing process. Thus, the rewards for improving assembly productivity are potentially very great.

Table 1.1: Fraction of Production Workers
in Assembly in Sample Industries

<u>Industry</u>	<u>Assembly Worker Fraction</u>
Motor Vehicles	45.6%
Aircraft	25.6%
Telephone and Telegraph	58.9%
Farm Machinery	20.1%
Household Refrigerators and Freezers	32.0%
Typewriters	35.9%
Household Cooking Equipment	38.1%
Motorcycles, Bicycles and Parts	26.3%

Source: 1967 Census of Manufactures,
U.S. Bureau of the Census

On the level of individual firms, increased assembly productivity means reduced production costs, especially if assembly is a large fraction of the direct labor. Hence, if new methods are developed which improve assembly productivity, then they will be readily accepted by those firms.

Previously, assembly has been a difficult process to automate from a technological point of view. The difficulty in automating assembly stems mainly from two sources. First, the assembly process itself is complex, involving a number of fairly complicated motions and decisions. These complex motions are often necessary because of the inherent variation in the dimensions and quality of the parts that must be assembled. Second, the human assembler is very well adapted to the requirements of the assembly process (including inspection and testing), making it difficult for automated assembly to compete directly with manual assembly, except in certain limited cases.

The emergence of programmable assembly means that manufacturers will be able to choose among three principal types of assembly: manual, automated by mechanical equipment, and automated by programmable equipment, each with its own advantages and disadvantages. How should the supplier of programmable assembly equipment design it so that it has the best possible chance in competition with the other methods of assembly? How can the purchaser of programmable assembly equipment choose among competing types? What are

the principal economic factors influencing the application of programmable assembly?

The fundamental way in which a firm will choose among the three alternatives will be to analyze each alternative and then to apply an economic criterion to indicate which method will maximize the firm's profits. This selection may take the form of choosing the system with the lowest assembly cost per unit, or the highest "return on investment." These methods are not the same, but they are intended to have the same result -- maximization of the profits.

To evaluate the operation and application of programmable assembly, it is necessary to understand what variables of the alternate assembly technologies, especially programmable assembly, will influence the results of the selection process. The results can be influenced by economic variables, such as wage scales, tax rates, cost of equipment, and cost of capital; by technological variables, such as time to complete an assembly, accuracy of assembly motions, and reproducibility of the assembly process from one assembly to the next; and by product variables, such as size, weight, part clearances, number of styles of product, and life of the product.

The problem of understanding the implications of this selection process for programmable assembly will be attacked by developing a consistent set of models and assumptions for the three alternative methods of assembly. This framework

of models and assumptions will have two sides: an economic side and a technological side. On the economic side will be models and assumptions concerning labor rates, capital rates, tax rates, cost of equipment needed, and so on. On the technological side will be models and assumptions concerning what is required to accomplish assembly by each of the different methods in terms of equipment, capacity, number of man-hours, and so on.

The topics of this thesis are organized as follows: The motivation and purpose for the research is discussed in Chapter 1. Background material concerning present assembly technology and research work related to programmable assembly is contained in Chapter 2, along with a review of the literature. Chapters 3 through 7 develop the model of programmable assembly, beginning with the assembly process (Chapter 3), and proceeding to the nature of programmability (Chapter 4), models of programmable assembly system configurations (Chapter 5), economic models of assembly methods (Chapter 6), and the development of a design criterion for programmable assembly equipment (Chapter 7). The use of the design criterion developed in Chapter 7 is illustrated by example in Chapter 8. The extension of the economic modeling of Chapter 6 to a national impact analysis of programmable assembly technology is discussed in Chapter 9, and the conclusions and recommendations for further research are given in Chapter 10.

2. BACKGROUND OF ASSEMBLY TECHNOLOGY

2.1 Present Assembly Technology

This section examines the principal methods of assembly today -- manual and transfer machine methods. These methods are first described, the important characteristics of each are detailed, and the advantages and disadvantages of each are discussed. Finally, a general outline of the factors affecting the cost of each method is presented.

2.1.1 Manual Assembly

Manual assembly was the first method of assembly and was the first method to be studied scientifically. This section describes the characteristics of the human assembler, the time and motion study approach for manual assembly, and the cost of manual assembly.

2.1.1.1 The Human Assembler

When the human assembler assembles a product, he by nature performs more than simple assembly; he also performs inspection of the parts being assembled and inspection of the quality of the completed product. If two parts are to be assembled and the human assembler finds that one is

faulty and cannot be assembled, then he can quickly reject that part and try a new one. To make this decision, the human assembler uses inputs from his senses -- touch, sight, and sound -- and he applies judgment, using what his senses tell him.

The human assembler can adapt easily to small changes in the assembly process. For example, if a new part is added to the product design, it is easy to retrain the assembly worker to add that part. This is conscious retraining. The human assembler also adapts in an unconscious way when he adjusts his assembly motions to accommodate drift in the part dimensions and other slowly varying influences on the assembly process.

However, the assembly worker is subject to errors and variations to which assembly machines are not subject. He may occasionally "forget" to perform part of his task sequence without realizing it. His performance is influenced by a host of factors that affect his state of mind and his individual assembly times will vary from one unit to the next. The very versatility of the human assembler gives him the ability to make errors that a machine cannot.

2.1.1.2 Time and Motion Study

Manual manufacturing processes of all kinds, including manual assembly, have been analyzed by means of time and

motion studies since the early part of this century. Probably the most widely used and freely published method of this type is the Methods - Time Measurement (MTM) approach developed in the late 1940's. For a detailed description of MTM see Karger and Bayha (2).

The basic assumption of MTM and the methods like it is that any manual operation or process can be separated into basic motions, that each basic motion can be assigned a pre-determined execution time, and that these basic motion times can be used to compute an overall manual operation time. Some of the basic motions include reach, move, turn, crank, apply pressure, grasp, release, position, and disengage.

The execution time of each basic motion is assigned based on certain important variables describing that motion. For example, one of the important variables influencing the MTM estimate for a "reach" motion is the length of the reach. Another example concerns the MTM operation "position" which involves placing one object in a specific position relative to another. Some of the important variables that affect the MTM estimate of position time would be the tightness of fit of the parts, the degree of symmetry, and the ease of handling. These variables do not all have scientific, quantifiable definitions. Hence, application of MTM and similar methods depends on judgment to some degree.

2.1.1.3 The Cost of Manual Assembly

Any particular manual assembly task will take a fairly predictable amount of time to be accomplished by an average assembly worker. Since direct labor is usually paid by the hour, the cost of manual labor for a simple manual operation can be estimated by multiplying the labor rate by the total man-hours required.

The labor rate is the cost incurred for one worker for a given time period. This rate is greater than the wages received by the worker because it must include other payments the company makes, such as those to Social Security, pension funds, and fringe benefits, for the benefit of that worker.

The number of man-hours necessary for the assembly of a product unit is roughly proportional to the number of parts being assembled. This means that, generally, a product with ten parts will take approximately twice as long to assemble as a product with five parts (assuming products and parts of comparable size and assembly difficulty). This is a rough model, which will be used throughout this thesis. It must be used with caution, however, and it is best used in combination with similar models for the alternate assembly methods to assess relative differences in assembly methods for the same product. For example, factors which will tend to affect the assembly difficulty for a particular

product will tend to affect the absolute assembly costs for all three methods in a similar way. Therefore, the relative costs of the three assembly methods will be less affected.

Other labor payment systems, such as a piece rate system, may not explicitly be related to the assembly time. However, even in these systems the labor cost per unit of product is relatively constant and is related to the nominal assembly time for the product.

2.1.2 Transfer Assembly Machines

Transfer assembly machines represent the currently available technology for replacing manual assembly labor. In this section their physical construction and method of design will be discussed and the cost of the transfer machine will be related to the design and construction process.

2.1.2.1 Description of Transfer Assembly Machines

In current transfer machine technology the assembly process is divided into a series of simple motions of approximately equal duration. Simple mechanisms are built to accomplish each of these motions and are arranged in sequence as stations along a transfer mechanism. This transfer mechanism carries each product unit in an indexing motion past every station where each simple assembly task is performed

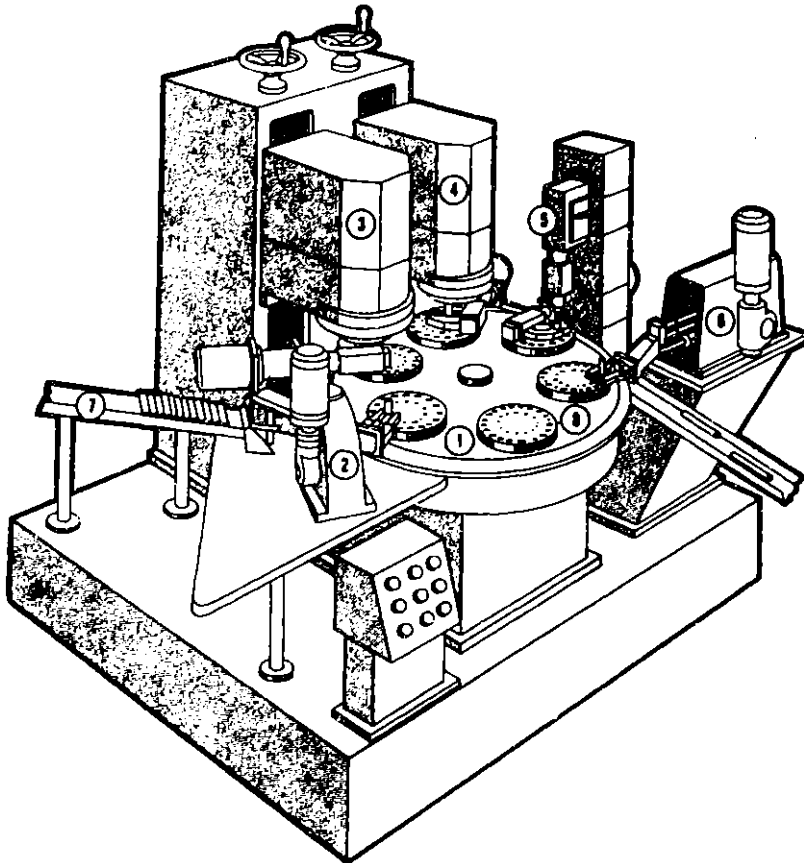
in sequence. Examples of transfer machines are the rotary index table (see Figure 2.1) and the in-line indexing table (see Figure 2.2).

Current transfer assembly machines are special purpose devices, usually one of a kind. They may be partially constructed of standard components, but the total machine is unique to the product being assembled.

The fine division of assembly tasks of the transfer machine is an important factor in its high rate of production. Because all the assembly motions are performed simultaneously, each at a separate work station, a completed product unit is produced at the end of the machine every index cycle -- the time from the beginning of one operation at a station to the beginning of the same operation on the next product unit. Index cycle times between one and five seconds are very common.

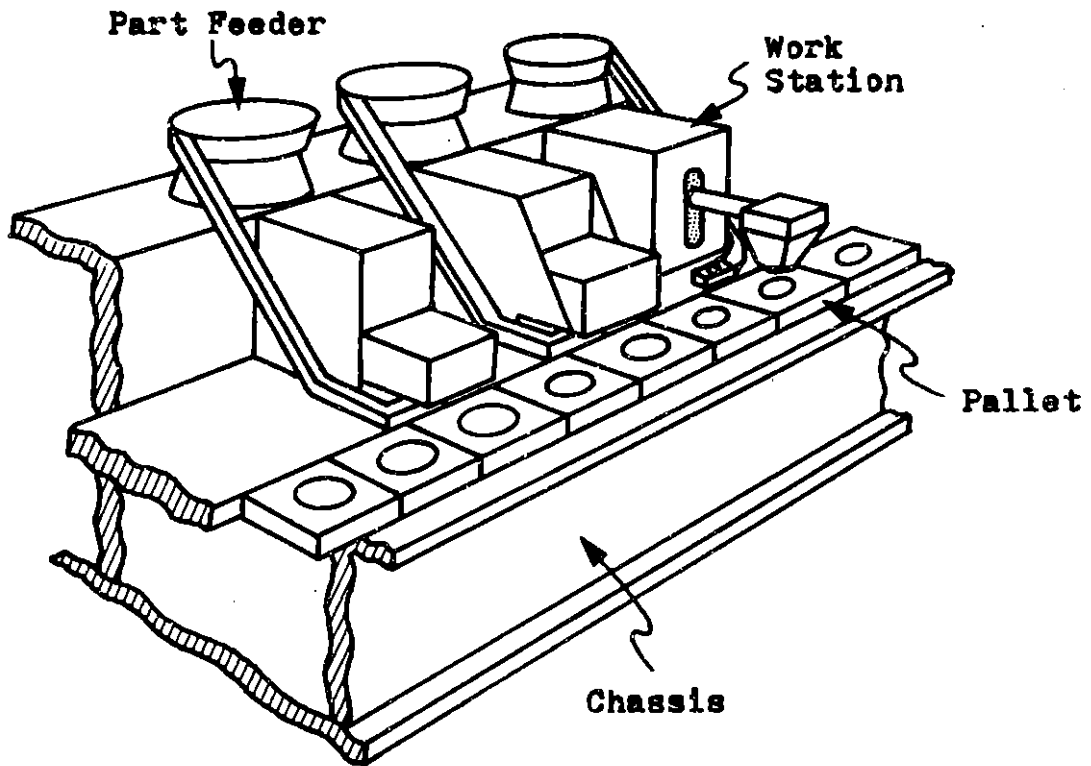
There are two categories of transfer machines: synchronous and non-synchronous. The conveying system of a synchronous transfer machine moves all of the product units in process from one station to the next simultaneously, while in a non-synchronous machine the products move from one station to the next independently. The two types of synchronous transfer machines are the rotary index (or "dial") table and the in-line indexing table. General descriptions of these two machines and of a non-synchronous machine are given following:

Figure 2.1: Rotary Index Table



- (1) Six station index table
- (2) - (6) Work stations
- (7) Parts feeding equipment
- (8) Pallet or nest

Figure 2.2: In-line Index Machine



Rotary Index Table

The size of the rotary table varies from one to five feet in diameter. The chief factor limiting the size of the table is its rotary inertia. As the diameter of the table increases, the inertia also increases and eventually becomes too large for rapid indexing rates.

The indexing motion of the table is usually provided by a cam drive. The positioning accuracy of the indexing equipment is such that accuracies of $\pm .001$ inch can be maintained at the outer radius of the table, and the indexing device can provide a range of index angles allowing from four to thirty-six index positions around the circumference. Index times from one half second to two seconds are common.

In-Line Indexing Table

The in-line indexing table may vary in length from a few feet to several yards. Often the driving mechanism and chassis structure of the transfer machine are made up of standard components. The products being assembled are mounted on pallets fixed to a chain or steel band which is moved by the cam drive. The pallet size, which usually runs from four to eight inches, is fixed in the original design of the set of standard components from which the individual machines are constructed. These individual machines are then restricted to that pallet size. However, any one machine may be designed with many or few stations by using the appropriate number of chassis modules, or "bays", and a corresponding length of

pallet chain.

The positioning accuracy for a pallet at a station is usually about ± 0.003 inches, although methods exist for obtaining greater accuracy. Index times from one to five seconds are common, although much shorter times are possible.

Non-Synchronous Machine

In non-synchronous transfer machines the parts are mounted on pallets which travel along conveyors connecting the individual stations. Each station contains its own indexing mechanism. When the station is finished with its assembly operations on a particular product unit, the indexing mechanism ejects that product unit and brings in the next product unit waiting in line at the station.

The major components of a transfer assembly machine for the assembly of a single part to the subassembly are shown schematically in Figure 2.3. Their function and interaction will now be discussed.

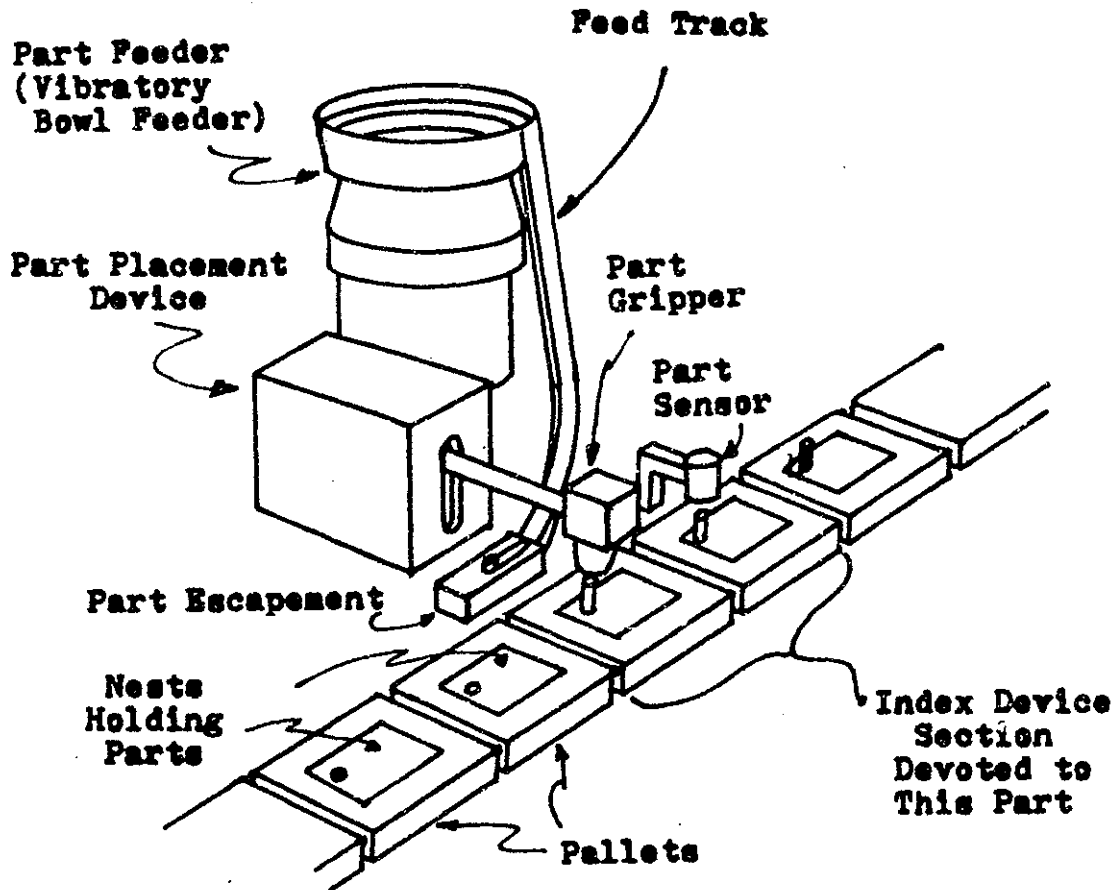
1) Nest

The nest is the space that is provided to hold the partially completed assembly on the index device; for example, it may be a jig which holds the base part of the product. In the case of rotary index tables, the nest is sometimes cut directly out from the metal of the dial.

2) Pallet

In non-synchronous systems and in-line systems the nest is part of or connected to a pallet. The pallet is connected

**Figure 2.3 : Schematic of Transfer Assembly
Machine Components**



to the indexing chain or band in the in-line system, and rides on a conveyor path in the non-synchronous system.

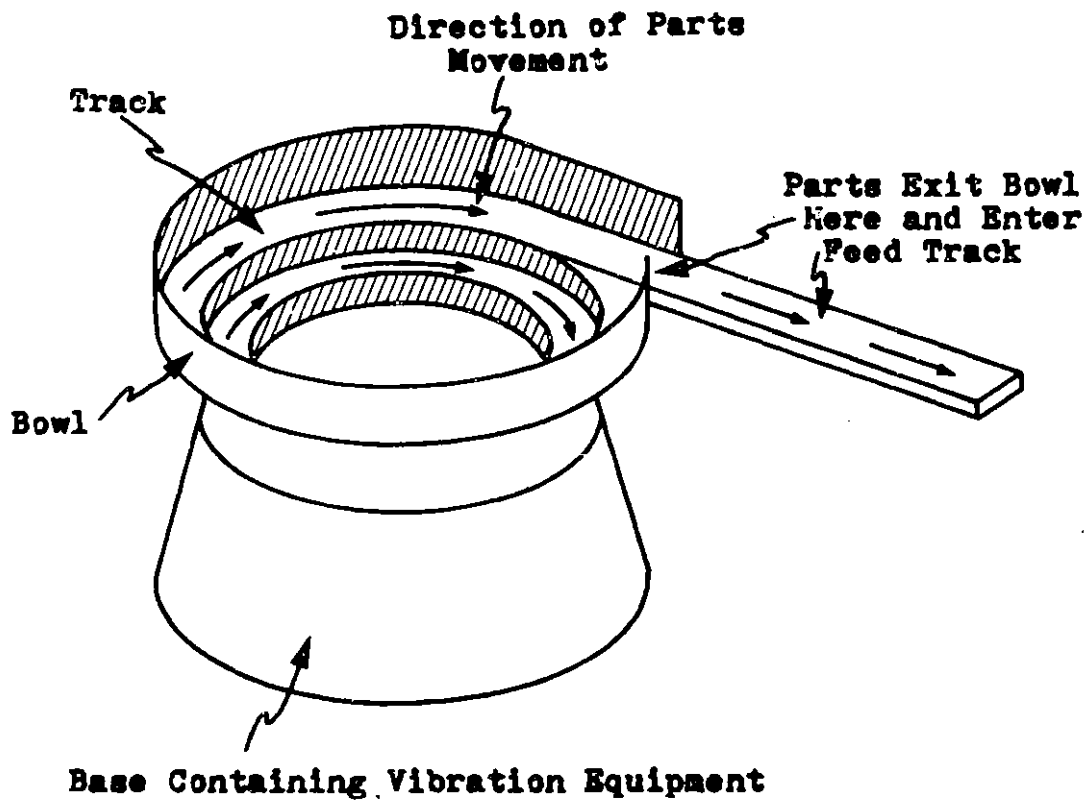
3) Parts Feeding Equipment

The parts feeding equipment may vary greatly in its sophistication and may incorporate a wide variety of devices. The function of the feeding equipment is to move part units from storage positions near the machine to a presentation site at the station where the part assembly is to take place. Other equipment takes the part unit from the presentation site and assembles it.

There are two main approaches to parts feeding. In one approach parts are taken in a bulk form with random orientations in boxes or bins. These parts are then dumped into devices that orient them and then present them to the assembly equipment. In the other approach the parts are stored in an oriented form, such as in egg crates, on tapes, or in magazines or stacks. In this case all the parts feeding equipment must do is hold the stored parts or perhaps move them serially toward the station. The problems of designing feeding equipment to orient the parts is avoided in the second approach, although this savings in equipment may be offset by the additional expense of storing the parts in a preoriented fashion.

The most common example of parts feeding equipment for small parts is the vibratory bowl feeder, shown sketched in Figure 2.4. The bowl is vibrated in a helical fashion so

Figure 2.4: Vibratory Bowl Feeder



that the parts "dance" up the inclined spiral tracks on the inside of the bowl. The parts begin at the bottom of the bowl disoriented. Special metal shapes, or "tooling," mounted along the spiral track cause the parts to emerge oriented from the top edge. The feeding of screws and fasteners is a typical application of a bowl feeder; an operator will pour a box of screws into a bowl feeder which then orients the screws and feeds them to automatic screw driving equipment. The feeder must not only be provided with special features to orient the screws, but to reject or divert sub-standard parts and foreign bodies that are often mixed in with the good parts. Although very significant progress has been made by Boothroyd (3) and others in the analysis of the performance of bowl feeders, the practice of bowl feeder design is more of an art than a science at present.

The vibratory feeder track operates on a principle similar to the vibratory bowl feeder. It is typically used to move the oriented parts from the exit of the bowl feeder to the part escapement equipment described below.

4) Escapement

The escapement is a device that discharges one (or more) parts at a time from the feeder track. It is a gating mechanism that separates the one part that is needed from the rest lined up behind it in the part unit queue. It also locates the part in a precise position so that the assembly equipment can take it.

5) Part Gripper

The part gripper grasps the part that is gated by the escapement. The gripper is often specially tooled so that its "fingers" conform to the shape of the part so that the part is held precisely while it is being assembled to the product.

6) Placement Device

The placement device carries the part gripper and the part that the gripper is holding on a predetermined trajectory. A typical placement, or "pick and place," unit executes a trajectory in the shape of an inverted U: a sequence consisting of a lift, swing, drop, lift, swing back, and drop again. One end of this trajectory corresponds to the location of the part held in the escapement, and the other end corresponds to the assembled position of the part in the product. The path of the device is controlled by cams, links, and certain adjustments. Some devices have no adjustment; the only way to change the path is to cut a new cam to replace the old one. Other units allow some adjustment of certain segments of the path without requiring replacement of the cam.

7) Sensor

It is good assembly machine design practice to install a sensor to check for the successful assembly of the part. Although this can sometimes be done at the same station that does the assembly, usually it is done at an inspection station following the assembly station.

This concludes the listing of the major assembly machine components. In practice, the components vary in the specifics of size, use, and complexity depending on the type of machine and the type of assembly operation. Transfer machines, in general, have their own advantages and disadvantages, and these are now discussed briefly.

If a transfer machine is used two or three shifts per day, annual production volumes in the millions are easily obtained. For example, a transfer machine with a two second cycle time can assemble roughly three million parts per shift per year. However, the transfer machine is expensive. This expense is partially due to the fine division of tasks, which means that hardware and design work are needed for each of many simple assembly motions. The cost of a single work station can be tens of thousands of dollars. As a result, transfer machines are an economic alternative to manual assembly only for products which require a high production volume. When a high production volume exists, the cost of the entire machine is spread out over enough product units to bring down the assembly cost per unit to a level competitive with manual assembly. For a simple example, a transfer machine with a two second cycle time working two shifts for two years could assemble about 12 million units. If the machine were required to "pay for itself" in those two years, then, even if the machine cost one million dollars, the assembly cost for one product unit, excluding operating expenses, would be only

about eight cents. (In Chapter 6 a more quantitative model for the unit assembly cost for a transfer machine will be developed along these lines.)

Transfer machines have certain drawbacks. First of all, they are not easily changed to accommodate significant changes in the product design. This means that the transfer machine is not a good investment if the product design is not stable for a sufficient number of years to repay the cost of the machine. This important issue, calculating repayment, is discussed in detail in Chapter 6. Secondly, they are restricted to products in which the individual assembly motions are sufficiently simple. The recognition of this fact has led to the design of the assembly machine and product together as a system in some firms. However, designing transfer assembly machines for existing products is often difficult or impossible because the product design does not lend itself to mechanized assembly and, for other reasons, this design cannot be changed.

In short, transfer machines make good economic sense in many applications, especially for high volume products for which the product assembly process can be accomplished by existing transfer machine technology and where the product design is relatively stable over time. However, as will be discussed in later chapters, where the production volume is not high, where the needs of the product assembly process tax the presently available transfer machine technology, or

where the product design is subject to change, programmable assembly may be competitive with the transfer machine.

2.1.2.2 The Design and Manufacture of Transfer Assembly Machines

The transfer assembly machine design and manufacturing process has three distinct phases: first, the initial planning and engineering stage; second, the assembly of the basic equipment; and, third, a testing and debugging process that may involve redesigning parts of the transfer machine. A typical design and manufacturing process is described below:

The initial planning and engineering stage is a layout process in which the basic components of the system are chosen and arranged. The designers of the transfer machine are supplied with drawings of all of the parts in the product to be assembled which provides them with nominal dimensional information. Using their experience they may be able to make reasonable assumptions concerning the type of part variations to expect because explicit data is rarely available -- even the manufacturer does not have this information. The designers then develop an assembly task sequence for the assembly of the product and lay out the arrangement of the transfer machine stations using an appropriate indexing device.

If the transfer machine is to be built on a synchronous

indexing chassis such as an in-line indexing table or a rotary index table, then the allocation of the stations on the index device is fairly routine. The initial station is usually the loading station for the base part of the assembly. It is good practice to allow two stations for the assembly of each additional part -- one station to assemble the part and the second station to check to see that the assembly operation was completed satisfactorily. It is also good design practice to leave some station locations empty to allow room for future modifications of the machine. Usually, the last station is allocated for the unloading of the finished product unit, but sometimes one more station is used to unload rejects.

The initial planning and engineering stage may take anywhere from two weeks for a very simple assembly machine to several months for a more complex system.

The second stage is the construction of the machine from basic components. Depending on many factors, this may be a straightforward process that can often be done within a matter of weeks, frequently a fraction of the time required to design the system.

The third stage is the tryout and debugging stage. This stage begins with a trial run of the machine. This trial run identifies the problems of the completed machine which must be corrected for proper operation.

The principal difficulties lie in the variation of the

parts that must be assembled. These supposedly identical parts actually vary slightly one from the next in dimension, or they can have rough edges, flashing, and dirt attached. Occasionally, there are foreign bodies mixed in with the good parts. All of these irregularities can affect the performance of the equipment that must feed and assemble the parts. It is this unpredictable irregularity that makes reliable parts feeding and assembly so difficult to analyze -- it is nearly impossible to predict and plan for the many possible types of irregularities. In practice experimentation is the only way currently in use to discover which variations of the parts will actually affect the performance of an assembly machine. Once the problems are identified, the process of analyzing the difficulties and redesigning can begin. The time necessary for this debugging and redesign process is highly variable, but it can easily take six months for an in-line synchronous machine that assembles six to ten parts.

Transfer assembly machine builders are roughly divided into three classes. First are the standard chassis manufacturers who construct their machines from a stock chassis and standard components. This reduces the amount of design time and machine shop effort, but there is still a considerable amount of special engineering and debugging left to be done. The second class is the non-standard chassis builders. Their designs may vary greatly from machine to machine. The third

class consists of the in-house automation groups of the major manufacturing companies.

Of the independent makers of automatic assembly machines, or transfer assembly machines, eighteen belong to the assembly machines group of the National Machine Tool Builders Association. These represent most of the large assembly machine makers, but it is difficult to determine exactly what fraction of the transfer assembly machine market they represent. Their total orders for automatic assembly machines for calendar 1975 were between \$10 and \$15 million. This contrasts to an estimated purchase of \$839.9 million worth of assembly equipment of all kinds (including manual equipment) in calendar 1976 (4). This means that automatic assembly machines account for only a small fraction of the total assembly equipment business.

2.1.2.3 The Cost of Transfer Assembly Machines

The cost of a transfer machine (its purchase price) can be broken down into two components: hardware costs and labor costs associated with the design and construction of the machine. This section first discusses the typical breakdown of these costs. Then, the effect of number of product parts and product size on these costs is considered.

Data concerning the major costs of a transfer assembly machine was collected in discussions with various firms

presently making automatic assembly machines. This data is summarized in Table 2.1. The data is in rough agreement with similar data from Prenting (5) who reported component costs from 25 to 35 percent; engineering, machine shop, and system building at 40 to 50 percent; and debugging expense anywhere from 10 to 50 percent of the total cost.

The engineering design cost is a significant fraction of the total cost because each transfer assembly machine is designed for a specific product. This means that each transfer assembly machine is unique, and therefore the full engineering design cost is charged to only one machine. Like the engineering design cost, debugging costs also are applied to only one machine. However, debugging costs are hard to predict because debugging is, by definition, the solving of unforeseen problems.

The breakdown of hardware costs for one type of transfer machine (an in-line indexing table) is given in Table 2.2. Because the cost ranges of several of the components are large, and because any given part assembly may not use all of the components listed, the hardware costs for the assembly of two different parts assembled on one machine may vary greatly.

The number of parts being assembled into the product unit affects the total cost of both the hardware and the design and construction labor. A machine that assembles a product with twice as many parts as the product of a second

Table 2.1 Cost Breakdown for Transfer Assembly
Machine

	Nominal <u>Percentage</u>	Percentage <u>Range</u>
Component Costs	40	30 - 50
Engineering Labor	20	15 - 25
Machine Shop Labor	20	15 - 25
Machine Assembly and Tryout (Debugging)	20	15 - 25

Table 2.2 Cost Ranges for Typical Hardware Components of a Transfer Assembly Machine Station (assumes in-line indexing table -- product size up to eight inches)

Section of index table (for one part assembly)	\$535 - \$4770
Bowl feeder (tooled)	\$1800 - \$7000
Feeder track	\$165 - \$300
Vibratory feeder track (tooled)	\$500 - \$700
Part escapement	\$100 - \$200
Placement device	\$860 - \$3290
Part detector	\$50 - \$200
Pick up device	\$115 - \$125
Control wiring	\$100 - \$500

machine will have approximately twice as many work stations and will cost approximately twice as much as the second machine (assuming comparable product and part sizes). Therefore, it is reasonable to consider the cost of a transfer machine on a per part cost basis.

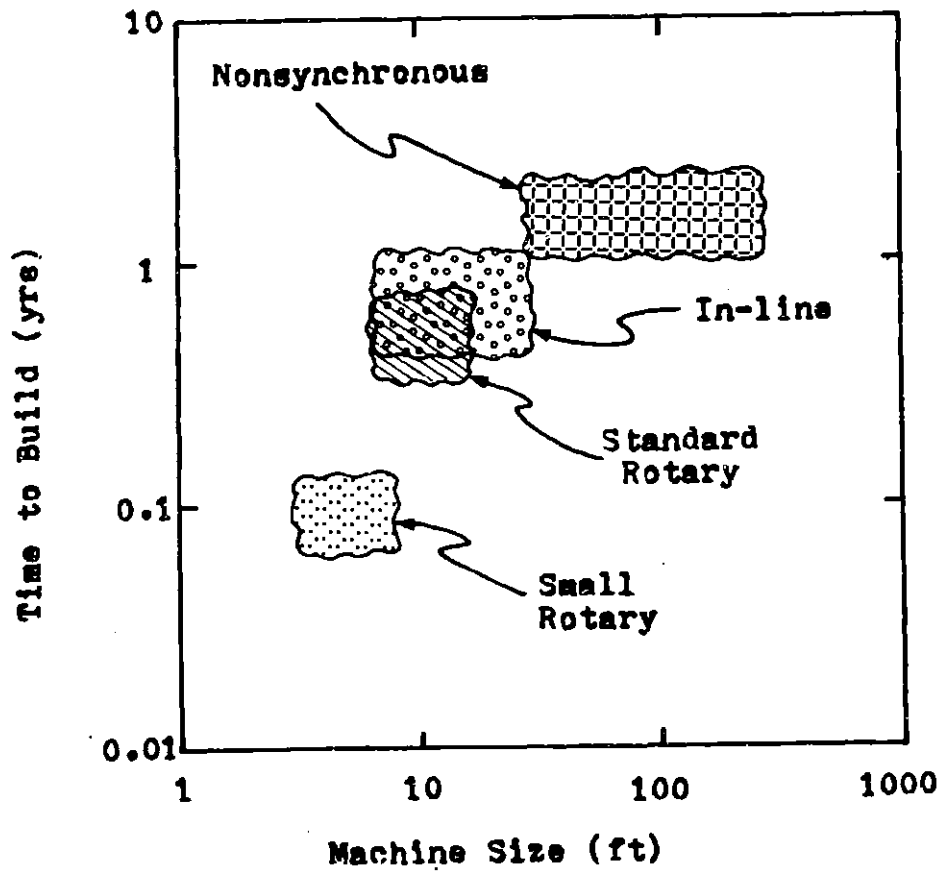
The cost of the assembly machine is also a function of the size of the product. As product parts become larger, larger and more expensive equipment is required to handle them, and longer periods of time are required to design, build, and debug them. Rough data on machine design, build, and debug time versus machine size (obtained by surveying machine builders) is given in Figure 2.5.

The cost per part of the assembly machine as a function of the size of the product is illustrated in Figure 2.6. As indicated, different types of assembly machines are used depending upon the size of the product. Rotary index tables are the cheapest transfer machine method, followed by in-line indexing machines, and finally by non-synchronous systems.

2.2 Highlights of Programmable Assembler Technology Research at the Charles Stark Draper Laboratory

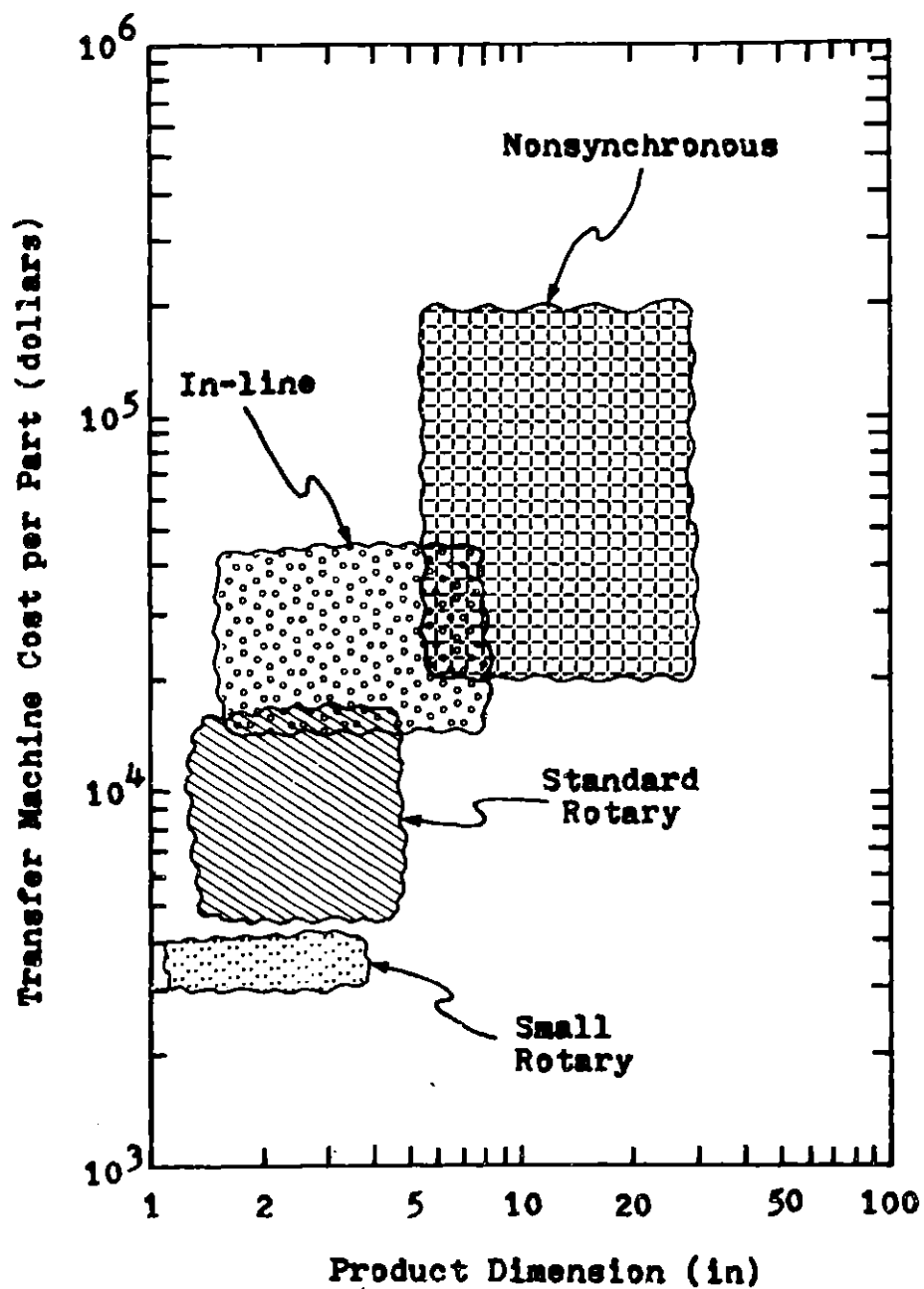
During the assembly process there is a large amount of information processing required for the assembly motions. This information processing is handled very easily in manual assembly by the human assembler. Transfer assembly machines

Figure 2.5: Transfer Machine Size and Time to Build



Source: Survey of Machine Builders

Figure 2.6: Transfer Machine Cost per Part versus Product Dimension



Source: Survey of Machine Builders

are constructed so that the part motion information is stored in the geometry of the cams and levers of the machine itself. The advent of relatively low cost and physically compact computing equipment offers a new approach for handling this information processing; the result is programmable assembly.

Besides the availability of microcomputers and microprocessors, programmable assembly requires the availability of suitable assembler technology; that is, equipment that can be directed to do assembly under computer control. Research on assembler technology has been conducted at the Charles Stark Draper Laboratory for the past several years, and this section will report some of the highlights of this research. For more detail concerning this work see Nevins et al (6), (7), and (8).

The research at Draper Lab in this area grew out of an investigation of manipulators being used in the space program. A manipulator is an arm-like structure which is usually controlled by a person from a remote position. However, when manipulators in space are controlled from the ground, the transmission delays caused by the long distances involved often make manipulation difficult. Therefore, the concept of supervisory control was introduced -- a certain level of intelligence is assigned to the remote manipulator so that continuous control between earth and space is unnecessary. From this research grew an appreciation for

quantitative definition of manipulation tasks and of the sensory information and control algorithms required to carry them out. This appreciation has been applied to the industrial assembly problem for the last four years.

Work has since been carried on in the development of computer control of assembly hardware. The design of a high performance six axis hydraulic assembler was carried out on paper and provided information on the potential performance capacity of a range of assembler hardware. A force sensor design which mounts at the "wrist" of an assembler device and provides strain gage readings which are "resolved" into three force components and three torque components within a computer has been developed.

The concept of resolution of motions and forces into appropriate coordinate systems is an important problem for remote manipulators. General purpose manipulators usually have at least six degrees of freedom of motion. They are usually constructed so that a simple straight line of motion of the end point, or "hand," of the manipulator may require various motions by all of the axes.

D. E. Whitney (9) developed "resolved motion rate control" as a means of controlling remote manipulators by commands to be interpreted in a coordinate system fixed to the hand of the remote manipulator. Thus, in order to achieve forward motion of the hand, the operator of a remote manipulation system need only issue a command to move forward,

rather than attempt to issue many commands to the various joint actuators of the remote manipulator. Resolved motion rate control requires computer processing in order to accomplish the coordinate transformations.

Resolved motion rate control can be combined with "wrist" force sensor information resolved in the same hand coordinate system to guide the assembler hand motion. This process has been designated "accommodation" and can be used to control the manipulator when contact is made with a fixed object. Frequently in the assembly of parts, such as a peg into a hole, force information obtained in this way can be used to modify the motion of the assembler so that smoother and more effective assembly motions take place.

Work is currently being done to develop computer software systems with expanded capacity for dealing with the different aspects of information processing in programmable assembly.

2.3 Review of the Literature

There is very little literature in the area of economic criteria for the design of programmable assembly systems or component assembly equipment. There has, however, been work done in related areas that is well worth mentioning.

Boothroyd has done work in the area of automatic assembly. In particular, his 1968 book Mechanized Assembly, with

co-author A. H. Redford (3), discusses many of the components of transfer assembly machines. The strength of the book is the detail of analysis of the construction and performance of the important components of the transfer assembly machine, particularly the parts feeding and orienting equipment. He discusses the performance and economics of transfer assembly machines insofar as they are dominated by the quality of the parts being assembled. The cost/performance process he models is the effect of downtime associated with machine stoppage caused by poor quality parts, and he addresses the problem of how much of the assembly process to mechanize based on the part quality and machine performance at a given part quality. There is no general economic model or analysis, however.

An Introduction to Mechanical Assembly, by Tipping (10), is a descriptive book about the major components of transfer assembly machines. The book is particularly oriented toward the user of the transfer assembly machine and emphasizes that a detailed feasibility study and economic analysis be done for the particular installation to determine the best way to mechanize the assembly process. It does not address models that relate cost and performance.

T. O. Prenting has addressed the economics of transfer assembly machines in a series of papers and articles in the 1960's. In particular, "Automatic Assembly -- the Economic Considerations" (5) describes the cost sources in construc-

ting a transfer assembly machine and provides some data on the cost composition. With co-author M. D. Kilbridge in the article "Assembly: Last Frontier of Automation," (11), Prenting discusses in general terms principal characteristics of transfer assembly machines and their economics.

A series of reports from the Stanford Research Institute entitled "Exploratory Research in Advanced Automation", (12), (13), and (14), concern work on automation based on programmable computer controlled manipulators. The work concerns the use of vision systems to locate and identify parts and products in random positions, the development of end effectors and sensors to aid in the manipulation, and the development of hardware and software to aid in the teaching and controlling of the manipulators by various means such as joysticks and voice control. Their work does not include any analysis of the potential economics of these experimental systems.

Work at the Stanford Artificial Intelligence Laboratory of the Computer Science Department of Stanford University has included the development of a programming language for programmable assembly reported in "AL: A Programming System for Automation" (15). This work assumes the existence of very general purpose assembly manipulators and an unstructured assembly environment. The purpose of the development of this language is to aid in the programming and set up of assembly tasks, thereby reducing the time and cost of imple-

mentation of individual assembly processes. The scope of the work does not include an analysis of the economic impact of the reduced set up time.

Heginbotham (16) has considered the problem of the economics of the application of industrial robots, but did not specifically include the performance of the robots in his analysis. Heginbotham is chief editor of and a regular contributor to "The Industrial Robot" (17), a journal published in Great Britain which reports developments in the field of industrial robot technology including assembly applications.

Abraham, Yaroshuk, and Beres (18) have analyzed the problem of selecting suitable products for a hypothetical programmable assembly system. Their method depends on certain key variables related to the candidate product and hypothetical assembly system. These variables include man-hours per unit of assembly, batch size, number of different styles, annual volume per style, automation equipment cost, setup time, and setup cost. Their analysis includes the development of graphical aides to help identify candidate products for assembly on flexible automated assembly systems.

At the Charles Stark Draper Laboratory a programmable assembly automation project sponsored by the National Science Foundation is in progress. The reports issued to date from the project cover a range of work relating to programmable assembly systems. The reports are titled "Exploratory

Research in Industrial Modular Assembly" (6), (7), and (8). All three reports cover work progress in the areas of the description of the assembly tasks and analysis of task geometry; the development of control systems for programmable assembly hardware; the development of sensor technology suitable for assembly tasks and programmable hardware control; and the development of computer software to control the programmable assembler equipment, to organize the execution of the assembly task sequence, and to teach the assembly task sequence to the system. Both theoretical and experimental work has been done in these areas. Progress in the analysis of the economics of programmable assembly systems -- part of the work leading to this thesis -- has also been described in these reports.

In general, assembly is not an area where there is much ongoing research. What there is tends to be technical in nature, with technical feasibility, rather than economic viability, being the guide.

3. DESCRIPTION OF THE ASSEMBLY PROCESS

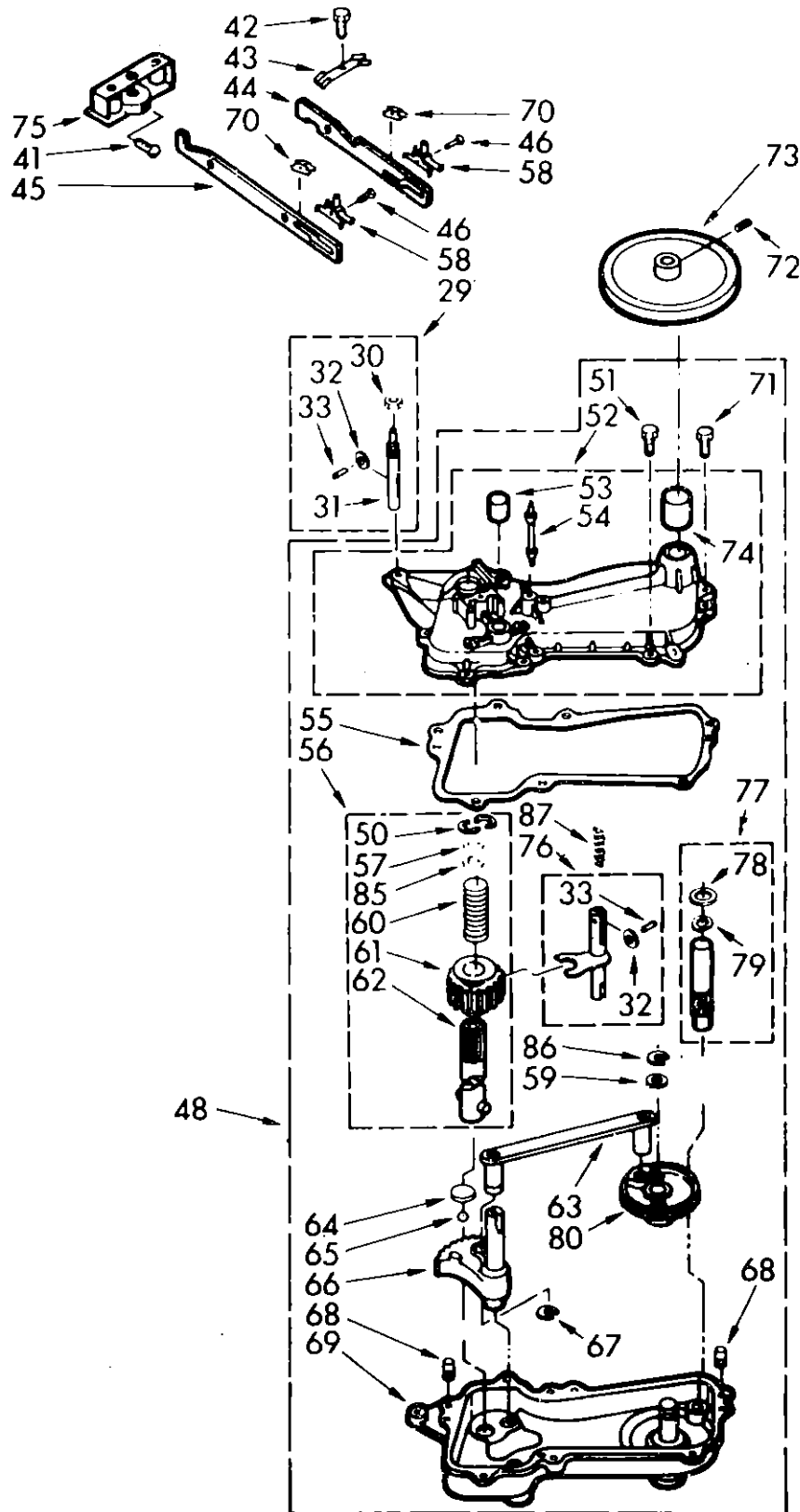
Assembly is the process by which a collection of parts is transformed into a product unit. It is a process in which objects are moved in relation to each other and often in contact with each other. The assembly process can be viewed in terms of assembly tasks and an assembly sequence.

An assembly sequence is an ordered set of steps which, when executed in order, will assemble the parts into the final unit. Each of these steps is the execution of an assembly task. Examples of assembly task steps are: Place a part in a specified position; push part A against part B with specified force; and, insert part A into part B. Examples of assembly tasks are: position, push, and fetch. The function of an assembly task is essentially the same each time it is performed, but the exact details of its execution may vary from time to time, and the identity of the parts involved will change. In general, an assembly sequence is not unique because one can think of more than one way of assembling most products.

To investigate the nature of assembly tasks, a case study was performed with a washing machine gearcase (see Figure 3.1). The objective of the study was to go through the process of specifying an assembly sequence for the gearcase that could conceivably be done by a programmable assembly machine. No attempt was made to optimize the assembly sequence.

Two conditions were imposed: First, the sequence was restricted to one which could be executed by a "one-armed" assembly device. The purpose of this constraint was to force consideration of the simpler one-armed assembler rather than some device that was more complex (and therefore more distant in the future). Second, any tools were

Figure 3.1: Gear Case Assembly



allowed so long as they could be used by a single arm assembler. The intent of this assumption was to avoid the problem of having to conceive of a universal part gripper that could be used to manipulate all the parts. The purpose of the study was to examine assembly tasks; the design details of the tools used in the tasks was of lesser importance.

There were a total of 34 parts involved, and the part size ranged from about 1/4 inch to 1 foot. The resulting assembly sequence contained a total of 221 steps. There were a total of 17 different tasks used.

Of the 17 tasks used, 9 were very similar in their method of execution. Specifically, they used "accommodation," a process which uses contact force to modify the motion of the parts in such a way as to facilitate assembly. These 9 tasks have been lumped together under the title "Accommodation" in Table 3. This table shows the frequency of the tasks in the assembly sequence as a count, a percentage of total steps in sequence, and also as a count normalized with respect to the number of parts in the assembly. On the average, 6.5 task steps were performed per part. The corresponding task definitions are given in Table 3.2.

Certain tasks such as "fetch" and "position" have normalized frequency counts approximately equal to one, which means they are performed an average of once for each part. Therefore, these particular tasks are probably required in

Table 3.1 Breakdown of Assembly Task Steps
for Washer Gearcase (34 parts)

<u>Task</u>	<u>Number</u> <u>of Steps</u>	<u>Percent of</u> <u>Total</u>	<u>Operations</u> <u>per Part</u>
Fetch	33	14.9	.97
Grasp	21	9.5	.62
Position	36	16.3	1.06
Interface	33	14.9	.97
Release	17	7.7	.50
Return	34	15.4	1.00
Cycle	15	6.8	.44
Detect	1	.5	.03
"Accommodation"	31	14.0	.91
Total	221	100.0	6.50

the assembly of each part regardless of the specific part identity. This means that they are essential functions of any general assembly operation, and any programmable assembly machine would be required to perform them.

Table 3.3 shows a breakdown of the accommodation tasks used in the sequence specification, and Table 3.4 provides brief definitions of the tasks. "Complex accommodation" refers to relatively complicated motions using accommodation that were hard to name. The other accommodation tasks were simpler motions that were more specific and consequently easier to name.

There were 36 tools, jigs, and fixtures needed for the process, approximately one tool or fixture per part. Many of the tools were special shapes that allowed accurate location and gripping of parts. The tools used fell into three general categories.

The first category contained tools with grasping surfaces that were designed to grasp parts in a particular way. These grasping surfaces were designed to locate the part accurately in the gripper or hand because the assembly process will be simplified if the part is held accurately.

A second tool category was one of special, rigid, one-piece jigs designed to reduce the degrees of freedom of assembly. These tools were "invented" when a subassembly of loosely connected parts had to be fitted to the main assembly. This tool would hold the various connected parts

Table 3.3 Breakdown of "Accommodation" Task
Steps for Washer Gearcase (34 parts)

<u>Task</u>	<u>Number of Steps</u>	<u>Percent of Total</u>	<u>Operations per Part</u>
Complex Accomodate	8	25.8	.23
Insert	11	35.5	.32
Rotate	3	9.7	.09
Depress	1	3.2	.03
Search motion	2	6.5	.06
Slide	2	6.5	.06
Seat	1	3.2	.03
Move	1	3.2	.03
Remove	2	6.5	.06
<u>Total</u>	<u>31</u>	<u>100.0</u>	<u>.91</u>

Table 3.4 Accommodation Task Definitions

Complex Accommodate:	Accommodation executed during a complex motion. No convenient name to describe motion.
Insert:	Pushing a shaft-or-peg-like part into a hole. Nominal trajectory is a straight line.
Rotate:	Rotation of part about an axis with accommodation.
Depress:	Deflect a part in its compliant direction.
Search motion:	Move along surface while maintaining contact force normal to it.
Slide:	Move part along grooved or channeled surface in direction of channel.
Seat:	Place very wide peg-like part in very shallow hole.
Move:	Insertion or similar accommodation executed over very long trajectory.
Remove:	Withdraw a peglike part or tool from a hole.

rigid so that the assembly would become easier for a one-armed assembly machine.

The third tool category was currently available automatic feeding tools. These tools include feeding mechanisms which automatically supply the tool with the parts. An example is a power screwdriver with automatic feeding of the screw fasteners.

Based on the experience of this case study, the same general procedure is used for the assembly of each part, assuming a special tool must be used for each part. This procedure is:

- 1) Assembler moves to location of tool storage site.
- 2) Assembler engages tool.
- 3) Assembler carries tool to part storage or presentation site.
- 4) Tool engages part.
- 5) Assembler carries tool with part to assembly site.
- 6) Assembler with tool assembles part to subassembly.
- 7) Tool releases part.
- 8) Assembler carries tool to tool storage site.
- 9) Assembler releases tool.

The motions of the assembler can be divided into two types: gross and fine. During a gross motion the assembler arm travels from one location to another, usually without being in contact with the product being assembled. For example, a gross motion occurs in step 3 above. During a fine motion

the assembler arm makes small movements in a localized area and is usually in contact with either the product or the parts feeding unit. For example, fine motions occur when a part is actually being assembled to the product unit or when a part is being grasped initially. Step 6 above requires a fine motion.

Using a different tool for each part represents one extreme in the specialization of tools for assembly. The other extreme is to specify as few tools as possible, or even to require the use of only one general purpose tool. This general purpose tool would need to be quite complex in order to satisfy the requirement for versatility, and therefore, it would probably be more expensive than any of the other tools used for only one part. However, if it were not necessary to change tools for every part, then a great deal of time can be saved. Then, the general procedure for assembling a part would look like this:

- 1) Assembler with gripper makes a gross motion to part storage or presentation site.
- 2) Assembler with gripper engages part.
- 3) Assembler with gripper carries part to assembly site in gross motion.
- 4) Assembler with gripper assembles part to subassembly in a fine motion operation.
- 5) Gripper releases part.

The extra expense and complexity of a general purpose tool

may or may not be rewarded by the time saved. This is only one of many technical issues which can be resolved only by the ultimate economic test.

Summary

The assembly sequence is an ordered set of steps, each of which is the execution of an assembly task. Two interesting facts concerning these tasks are:

- 1) Several tasks are similar in their execution; they use contact force to modify their motion during assembly. Such tasks are designated "accommodation" tasks.
- 2) Certain tasks, such as "position," are necessary for the assembly of each part, and, therefore, are a necessary function for any programmable assembler.

A range of options exists in the use of assembly tools, with the following two extremes: a special tool can be designed for each individual part assembly, or a universal part gripper which can perform each assembly step for each part can be designed. The first extreme would require as many as four extra steps in the assembly sequence for a single part, but the individual tool cost would probably be lower than the cost of the universal part gripper.

There are two types of assembly motions: gross and fine. The gross motions are "traveling" motions, such as a motion used for the assembly task "position." The fine

motions are used, for example, during the actual assembly of the part to the product unit.

The concepts of assembly tasks and tools are important because they play a part in the economic evaluation of a programmable assembly system. Gross and fine motions are necessary functions in assembly, and each requires a certain amount of time to be performed by the assembly equipment. Task execution time will influence production rates which, in turn, influence the economic evaluation. Tools, whether general purpose or specialized, cost money and will also influence execution time; hence, the tools also will affect the economic evaluation. In the next chapter a closer examination of these and other characteristics of programmable assembly systems that will influence the economics of their application is begun.

4. EMERGING PROGRAMMABLE ASSEMBLY TECHNOLOGY

In this chapter the application of programmability to assembly technology will be discussed. First, the basic definitions and concepts of a programmable assembly system as they are applied in this research are presented. The remainder of the chapter discusses the economic advantages that are possible with programmable assembly.

Since programmable assembly is not, in fact, a practiced reality, it should be kept in mind that these advan-

tages are projected advantages, and their truth will be proven or disproven only after programmable assembly is actually put into use.

4.1 Basis Concepts of Programmable Assembly Systems

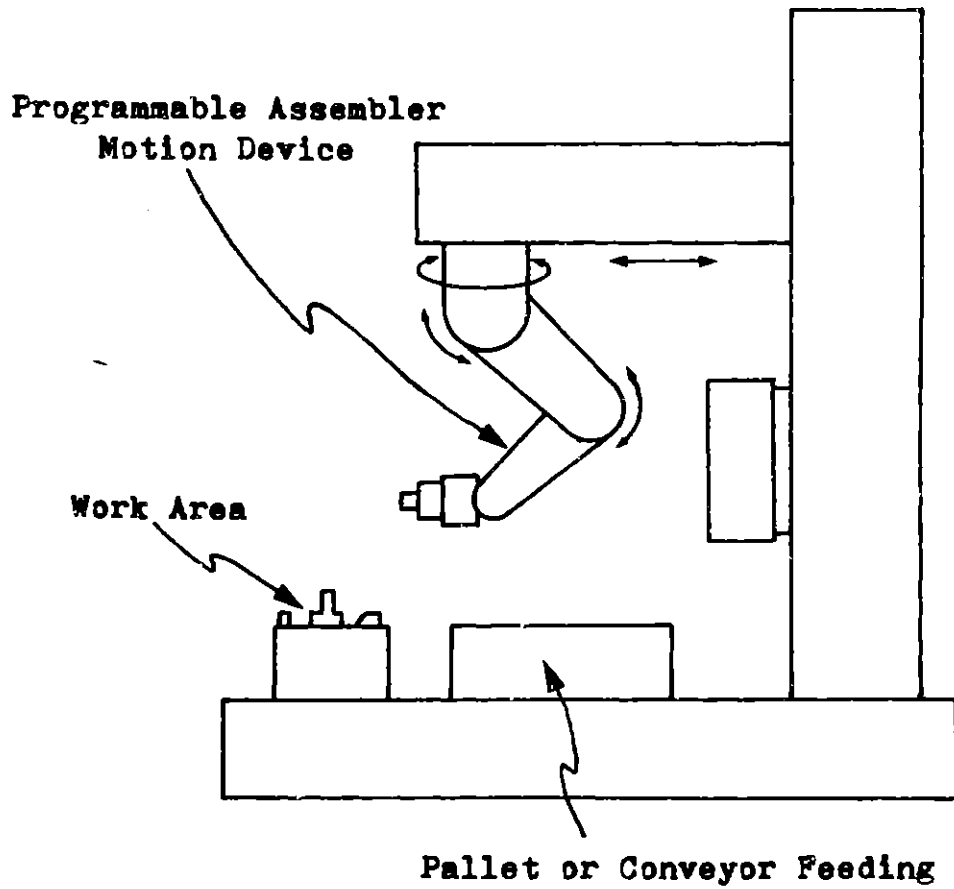
The words "programmable assembly" have been used in this thesis to refer to the general concept of assembly equipment that can be programmed to execute a sequence of assembly tasks. In this section the specific concepts of programmable assembly as they are applied in this research are presented.

It is important to define specifically the terms programmable assembler, programmable assembly system, programmable assembly station, and programmability and to discuss their interrelations.

Programmable Assembler

A programmable assembler is a device which assembles products and which consists of 1) a motion device capable of positioning a part in many different positions and 2) a control unit that directs the motions of the motion device and which may be programmed. The motion device may resemble a remote manipulator, but that is not necessary. One conceptualization of the motion device of a programmable assembler is shown in Figure 4.1. The motion device hardware consists of an end effector (part gripper or tool) and po-

Figure 4.1: Example Design for Programmable Assembler Station



sitioning equipment (the links and axes) to move and orient the end effector.

The programmable control unit may be a minicomputer or microprocessor, or it may be a device of less sophistication. The control unit must be capable of storing enough information to execute the necessary tasks. The degree of sophistication required of the programmable control unit depends on the capabilities of the motion device and the requirements of the application of the assembler.

A programmable assembler includes not only the programmable control unit and the motion device, but also sensory equipment that is required for the completion of the assembly task. Position sensors located on the motion device provide information about the location of the part carried by the assembler. These sensors are also used in the servo control of the motion device. Force sensors may be included to monitor contact forces between parts during assembly. Other sensors may be used in more sophisticated systems. For example, visual sensors may be used to locate parts and assembly sites, or tactile sensors located in part grippers may be used to identify just where the part is being held in the gripper.

Programmable Assembly System

A programmable assembly system is a collection of programmable assemblers working together on the assembly of a product. The system includes not only a set of assemblers

but also a conveying system which moves the in-process assemblies from one assembler to the next; and a set of parts feeding equipment, which presents parts to the assemblers in known orientation and position.

Programmable Assembly Station

A programmable assembly station consists of a programmable assembler and the portion of the conveying system associated with that assembler.

Programmability

"Programmability" as used here is the ability of a device to be taught different tasks. This is in contrast to the methods of conventional assembly technology in which a task is defined by the geometry of the hardware and is not easily changed. This kind of programmability does not require a computer, but the use of a minicomputer or microprocessor is an easy way to implement it in assembly technology.

4.2 Economic Advantages of Programmable Assembly

As reported in Chapter 2, presently employed assembly technology consists of manual assembly and transfer machine assembly. Each of these methods has its own strong points; circumstances exist where one method is clearly preferred over the other. What are these circumstances for programmable assembly? In particular, in which cases will program-

mable assembly prove to be economically superior to manual assembly and transfer machine assembly and why? This section discusses in general terms some of the assembly situations where programmable assembly is seen to be potentially advantageous. The advantages of programmable assembly are discussed for multipart assembly, multiproduct assembly, and adaptive assembly. The possible reduction in engineering time associated with setting up a programmable system instead of a transfer assembly machine system is also discussed.

4.2.1 Multipart Assembly

The chief economic measure by which different assembly methods are compared is the assembly cost per unit of product. When capital equipment is built to assemble a product, the assembly cost per unit is proportional to the cost of the capital equipment divided by the number of units made on the equipment. (Modeling and calculating costs will be discussed in Chapter 6). The assembly cost per unit can be reduced either by reducing the cost of the equipment or by increasing the number of product units that are assembled on the equipment.

A distinction is drawn here between the terms product and product unit and the terms part and part unit. A product is a set of identical product units. Hence, a pump is

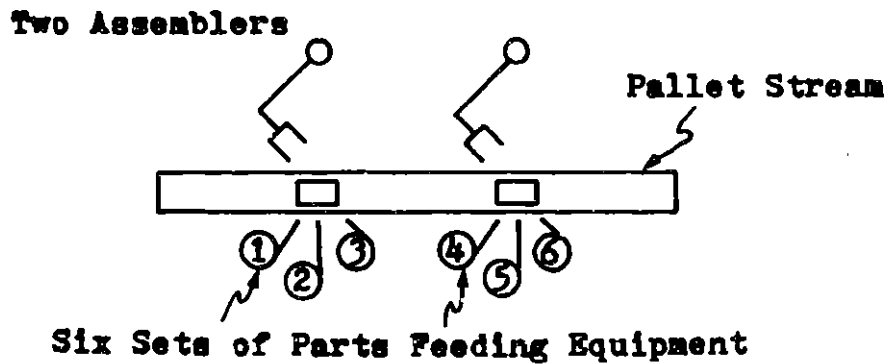
an example of a product, and there are many units of the pump made per year. Similarly, a part is a set of identical part units. For example, a bowl feeder is designed to handle a single part, but it may have a certain feeding rate of so many part units per minute. Finally, the term volume, or annual production volume, is used to mean the number of product units that are assembled in one year.

Because a programmable assembler can execute more than one assembly task, it can assemble a number of different parts. This multipart assembly capability of a programmable assembly station is in direct contrast with the transfer assembly machine station where one part at most is assembled per station (some stations may be used for nonassembly functions). A single programmable station may be more complex and expensive than a single transfer machine station, but the fact that fewer programmable stations may be required for a system to assemble a given product raises the prospect of an assembly system whose original cost is less than that of the corresponding transfer machine. This comparison is illustrated in Figure 4.2. However, as the number of parts assembled per station increases, the maximum production rate of a programmable system decreases. This means that a programmable system in which each assembler performs multipart assembly can be designed with the appropriate number of stations for the needed production volume. If the cost of programmable stations is comparable to that of transfer machine stations,

Figure 4.2: Multipart Assembly

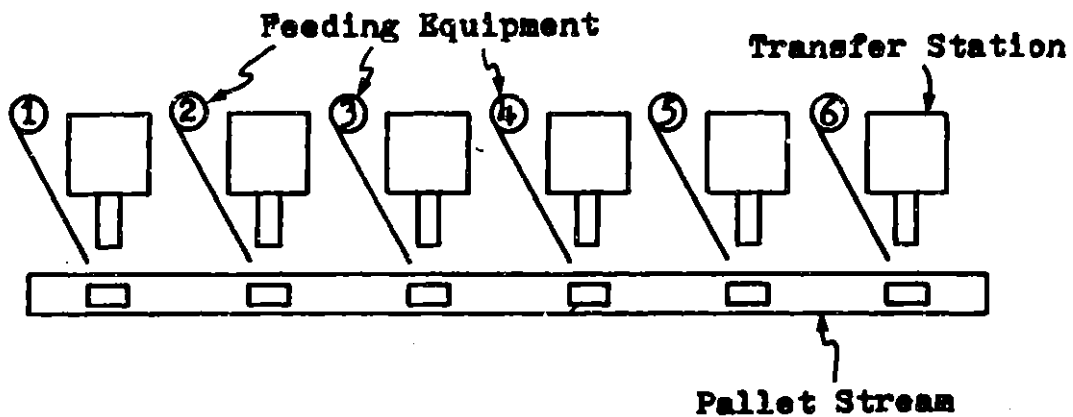
Assumes product with six parts

Programmable System:



Transfer Machine System:

Six Transfer Stations and Six Sets of Parts



then, in general, programmable systems will be economically more attractive than transfer machines for lower production volumes.

4.2.2 Multiproduct Assembly

We have seen that the versatility of a programmable assembler allows it to assemble more than one part of a product and that this can lead to unit assembly cost savings by reducing the number of assembly stations required. This versatility can also be used to spread the cost of the system over many product units in another way. One programmable assembly system can be designed to assemble the parts of different products.

For multiproduct assembly, versatility is required not only for the assemblers, but also for the other parts of the system, i.e., the conveying system and the parts feeding equipment. For example, programmable assembly systems may be designed to assemble product families -- groups of products that have common or related parts and assembly processes. One product may have a "deluxe model" which requires the assembly of extra parts, and this would require versatility in the conveying system so that the deluxe model product unit could be routed to extra assemblers. Or, one product may differ from another simply by the size of one of its parts. This would require versatility in one set of parts feeding

equipment so that it could handle two different size parts.

The degree of specialization or generalization of such programmable assembly systems in specific cases will be the result of a trade-off decision between the expense of the added assembly generality and the unit assembly cost savings this generality introduces as a result of the application of the system to a larger number of product units.

4.2.3 Adaptive Assembly

Adaptive assembly is the use of a sensor system to monitor and modify the progress of the assembly task. Adaptive assembly requires one or more sensors which collect force, touch, or image information during the assembly and a processor which can use this information to modify the fine assembly motions. Adaptive assembly may be used in combination with a programmable assembly system, and it has many advantages.

Much of the downtime of the present transfer machines is associated with clearing jams of parts in the assembly mechanism caused by variations in part dimensions and quality. A programmable assembler with adaptive assembly can detect the onset of certain kinds of jams and could immediately repeat the assembly operation either with the same part or with a new one. Because the system could automatically recover from assembly jams, there is a corresponding reduction in downtime.

Quick recovery from potential jams is only one of the

uses for adaptive assembly. Force and position readings obtained from the sensors attached to the assembler can be used in fine motion assembly tasks. In other words, the assembler station could use the sensor information to feel its way through the assembly process. This can be particularly helpful in two cases: first, when the part dimensions have large variation and secondly, when the part tolerance is very small. Generally, present assembly machines work best when there is relatively little part dimensional variation and the part clearance is greater than .005 in. Adaptive assembly can reduce the required quality and expense of the supporting equipment. For example, transfer machines must be made very accurately in order to reduce the chances of jamming the parts during assembly. The dimensional variation that the machine must overcome results from both the parts and the machine itself. Transfer machines are made very accurately to reduce some of this variation. Programmable adaptable assembly can be specifically designed to correct for variations in the part positions and dimensions as they appear to the assembler from one assembly operation to the next. Using adaptable assembly to deal with variations in part dimension and tooling dimension can allow looser standards for both the parts and the supportive machine system tooling, such as the conveyors and pallets. These lower standards mean that cheaper system tooling can be used, and part manufacturing costs may be reduced.

Finally, by taking readings over a series of units, production data can be developed on the value and drift rate of important dimensions, the number of faulty parts, the average assembly rate, and other important production variables. This data can then be used to improve the system and make it more economic. At present almost no data, of even the most rudimentary kind, is available to assess assembly processes and machine performance.

4.2.4 Reduction of Engineering Time

The fact that the programmable assembler is programmable means that the trajectory of its motions is controlled by easily changed data in the processor memory. This simplifies the engineering problems in developing a system to assemble a product and will result in a cost savings in building the system.

The programmable assembler can be used as a standard component in the construction of an assembly system but in a wider sense than the "standard" components of a transfer system. The standard component in the construction of a transfer machine system can perform only a limited set of tasks, and it must be mounted accurately with respect to other equipment on the system (such as the pallet position). A programmable assembler can perform a much wider range of tasks and motions, and these motions need not be accurately

specified until after the system is assembled. This relieves many of the requirements for accurate relative positioning of the components and the corresponding design and machine shop time. The wide applicability and ease of incorporation of a programmable assembler raise the assembler salvage value because it can be easily converted to use in a new system.

Programmable assembly could reduce the costs of debugging. In the development of a transfer machine, the motions of the assembler equipment are determined by the physical geometry of the hardware. It is much more difficult to adjust and modify these motions during the debugging process than it is to modify the motions of a programmable assembler. This means that the debugging time for the programmable system is greatly shortened with a corresponding decrease in this portion of the cost of the system. This can represent a considerable savings since, as reported in Chapter 2, the cost of debugging the system can be almost half the total price of the transfer machine. If the programmability of the system includes adaptive assembly, then the information from the force sensors can be used to speed the debugging process by helping to identify the troublesome assembly tasks. This will also help to reduce the debugging time and cost.

4.3 Summary

The basic concepts of programmable assembly systems are

important ideas which are used in the modeling of later chapters:

- 1) A programmable assembler consists of a motion device and a control unit.
- 2) A programmable assembly system is a collection of programmable assemblers working together on the assembly of a product and includes a conveying system and a set of parts feeding equipment.
- 3) A programmable assembly station consists of the programmable assembler and a portion of the conveying system.
- 4) Programmability is the ability of a device to be taught different tasks.

The potential advantages of programmable assembly include multipart assembly, multiproduct assembly, adaptive assembly, and a reduction in engineering time for the set-up of the system. The versatility of the programmable assembler leads to its ability to assemble more than one part, while the versatility of the programmable assembly system leads to its ability to assemble more than one product. Adaptive assembly may be used in combination with programmable assembly and will add advantages, such as the ability to clear certain jams, the ability of the assembler to "feel" its way through the assembly process, and a reduction in equipment expense. Because a programmable assembly system does not require accurate positioning of the assem-

blers in many cases and because the assembly motions and tasks are easy to change, the system will require less engineering time for setup than a similar transfer machine assembly system.

Next, in Chapter 5, the modeling process begins with an examination of the characteristics and requirements for programmable assemblers and assembly systems. Then, certain of the economic advantages of programmable assembly that have been discussed in this chapter will be quantified in the economic model to be developed in Chapter 6.

5. CONFIGURATIONS OF PROGRAMMABLE ASSEMBLY TECHNOLOGY

In Chapter 4 the economic advantages of programmable assembly were presented in general terms. In Chapter 6 the economic advantages of programmable assembly are investigated from a different, more quantitative, point of view: Economic models of programmable assembly systems, transfer machine systems, and manual assembly are derived and compared. This chapter presents the characteristics of programmable assembly systems upon which the modeling of Chapter 6 is based.

The programmable assembler is the "center" of the programmable assembly system. This chapter begins with a discussion of programmable assembler configurations: What are some of the possible designs of programmable assemblers and what are their characteristics?

The second section of the chapter is concerned with the possible configurations of programmable assembly systems. The principal components of a programmable assembly system are programmable assemblers, a conveying system, and a set of parts feeding equipment. The possible types of arrangements for the programmable assemblers in the system and the characteristics of each arrangement are discussed.

The economic model developed in Chapter 6 for programmable assembly systems depends partially on the "efficiency" of the system configuration.

The concept of system efficiency is discussed in the third section of the chapter.

5.1 Programmable Assembler Configurations

The specific configuration of the programmable assembler is now considered in greater detail. How versatile should a programmable assembler be? Should every programmable assembler be able to position a part in any arbitrary location? This section shows that there can be a wide range of versatility for an assembler (in particular for the motion device), and that due to the existence of principal assembly axes on many products the less versatile (and therefore less costly) assemblers may have many applications.

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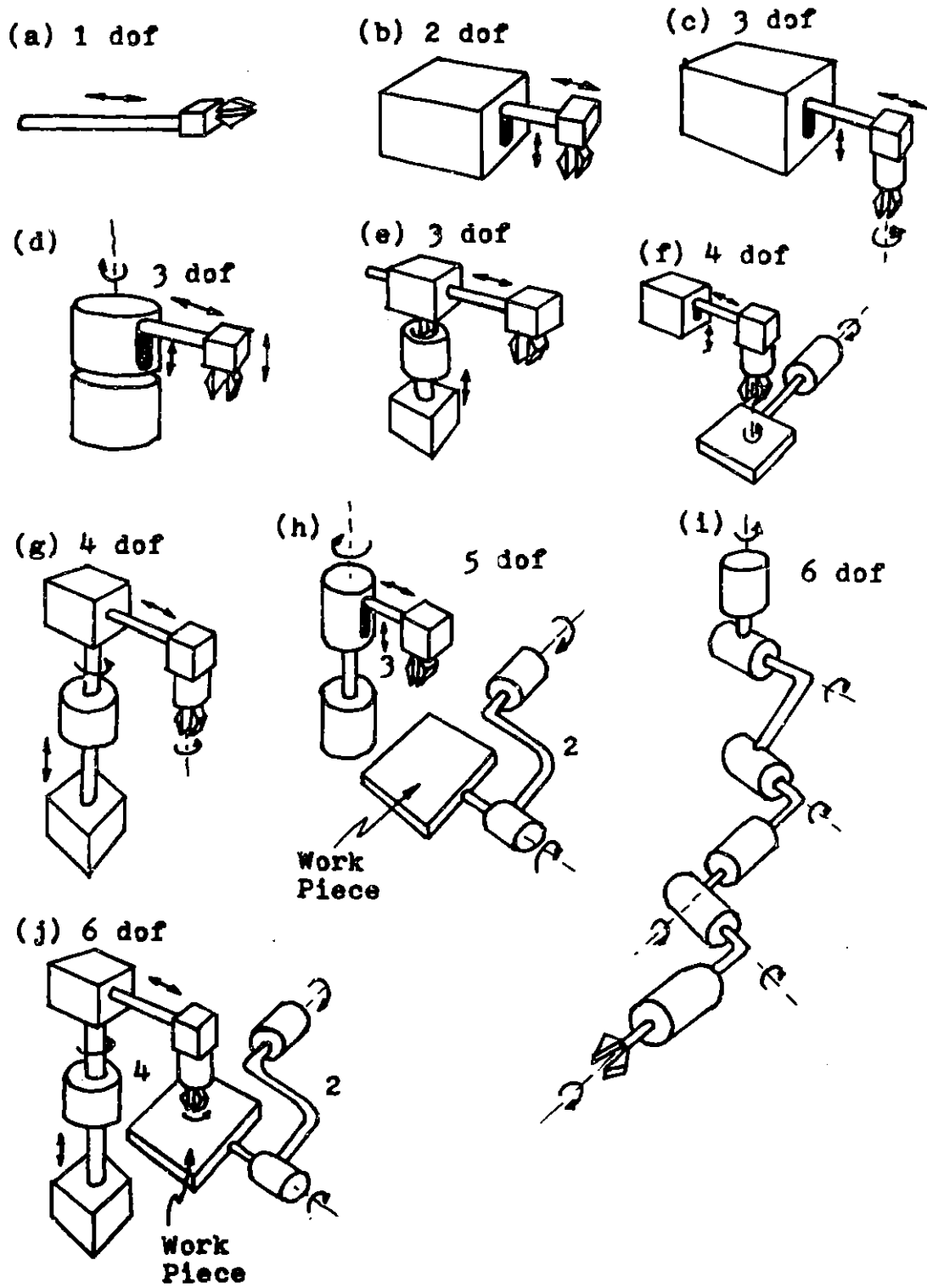
5.1.1 Degrees of Freedom of Motion Device

A programmable assembler device must have the ability to move a part unit through space over a range of motions. The number of degrees of freedom of this motion is an important measure of the versatility of the assembler.

Figure 5.1 shows a set of potential assembler motion device configurations illustrating the concept of the number of degrees of freedom. (They are sketched so that the location and action of each degree of freedom is plainly visible.) A single degree of freedom device has motion along a path in space or rotation about a single axis. A two degree of freedom device may be designed to move in two independent directions (and so move over a surface in space), or it may be designed to move along a path and rotate about an axis, or it may be designed to rotate about two independent axes. All two degree of freedom devices are not equivalent or even similar. One possible three degree of freedom device might move a part unit to any point in its working volume but not control the angular orientation of that part unit at that point.

The position of a part can be completely described by six numbers: for example, three numbers indicating its displacement in three dimensional space and three numbers indicating its angular orientation about the three major axes. Therefore, to position an object to an arbitrary location and orientation an assembler motion device would require six in-

Figure 5.1: Assemblers with Various Degrees of Freedom



dependent degrees of freedom.

However, in order to control part assembly positioning it is not necessary to hold the basic assembly fixed and to position the part with six degrees of freedom. The assembler motion device may actually consist of two motion devices: one to hold the product unit and one to position the part. For arbitrary relative positioning of part and product unit the two motion devices must have six degrees of freedom between them. For example, an assembler may have its degrees of freedom divided as in assembler (j) of Figure 5.1 where three displacements and one rotation are controlled by the assembler mechanism that carries the part and the two remaining rotations are controlled by the table that holds the product assembly.

More degrees of freedom for the assembler necessitate more complex and costly equipment. Consequently, when designing a programmable assembler or assembly system, it is important to determine the minimum number of degrees of freedom required to accomplish the necessary assembly tasks.

5.1.2 Principal Assembly Directions and Axes

Many products have principal axes along which many of their parts are assembled. These axial alignments occur partly for functional reasons and partly because manufacturing processes tend to create them. For example, the use of

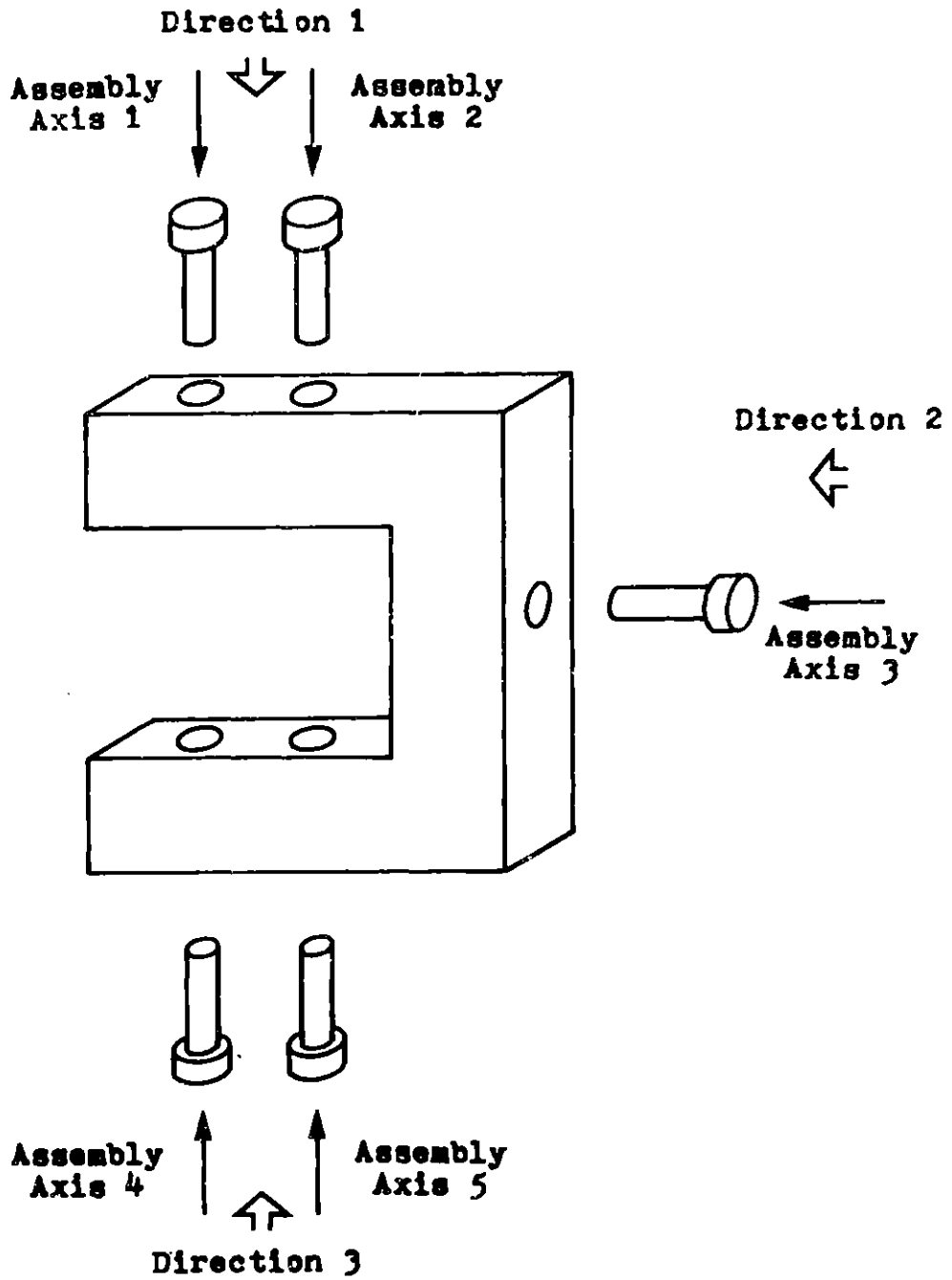
simple three axis milling machines tends to create parts that have three principal directions at right angles to each other. Turning and drilling equipment tends to create parts that interface with axial symmetry.

We now define axis and direction with respect to a product. Imagine the product attached to a fixed reference frame. An axis is defined as a directed straight line passing through the product (see Figure 5.2). The direction of an axis is simply the angular orientation of the line in space without regard to its physical displacement with respect to the coordinate frame. Thus, several axes may have common directions. An axis of assembly is an axis along which a part is moved to assemble it to the product.

The actual assembly process may involve general large scale motion along the axis of assembly plus much smaller accommodation motions in other directions. An assembler must have the appropriate degrees of freedom to move the part along the principal assembly axes. The small accommodation motions must also be made, but they may or may not be made with a controlled degree of freedom. For example, if the part is held with a certain compliance in the part gripper, then the small accommodation motions may be made passively under favorable conditions.

Kondoleon (19) has found for a small set of products consisting of rigid machined or molded plastic parts that roughly two thirds of the parts of these products are assem-

Figure 5.2: Product Assembly Axes and Directions



bled in one principal direction and that over 80 percent of the parts are assembled in only two principal directions. Thus, even though a station in a given system may be required to add many parts to a product unit, only a few product axes may be involved, and so that station may need only a few degrees of freedom. This is important since an assembler with a reduced number of degrees of freedom will certainly be cheaper than one with more degrees of freedom.

For example, for the product illustrated in Figure 5.2, the four axis device (a) illustrated in Figure 5.1 would be adequate for the assembly of the bolts along assembly axes 1 and 2 in assembly direction 1. The device could reach to a bolt feeder, pick up a bolt, assemble it along assembly axis 1, reach for another bolt and assemble it along assembly axis 2. This device would not be able to assemble the bolts along assembly axes 3, 4, or 5.

The three degree of freedom assembler (c) in Figure 5.1 could assemble the bolts along axes 1 and 2 if the bolts were fed directly to the part gripper through a tube (a common fastener feeding method) or if the bolt feeding site were in the same plane as the assembly axes. This device also could not assemble the bolts along assembly axes 3, 4, or 5 because of its restricted set of degrees of freedom. Assembler (f) with four degrees of freedom has the right degrees of freedom to assemble all bolts along all five assembly axes. The six degree of freedom assemblers (i) and (j) could also assemble

the entire product because their degrees of freedom allow arbitrary motion.

This organization of the assembly of a product into principal assembly axes can affect the kind of assembler required in a given system configuration. For example, for a system configuration in which one assembler must assemble all the parts of the product in all the principal assembly directions, the single assembler may need six degrees of freedom. Consider another system configuration in which several assemblers each assemble a few parts of the product so that together they assemble the entire product. Each assembler in the second configuration may need fewer than six degrees of freedom if each is oriented so that it has the proper degrees of freedom to assemble a subset of the parts with a common axis or assembly direction.

5.2 Programmable Assembly System Configurations

In this section the possible arrangements of programmable assemblers in the assembly system are examined. There are three principal arrangements, or configuration modes, which can be used: serial, parallel, and overlap. First, each mode is described. Then, the important characteristics of each mode are discussed. Finally, the use of combinations of modes in an assembly system is discussed.

5.2.1 Principal Configuration Modes

This section describes the three principal configuration modes for programmable assemblers: serial, parallel, and overlap. Many simplifying assumptions are made in order to present the modes with as little complication as possible. In the next section the operating characteristics of the three modes are discussed without considering the simplifying assumptions used here.

The principal modes of assembler arrangement into a system can be illustrated by a pair of assemblers working together to assemble a product (see Figure 5.3).

To simplify the comparison it will be assumed that both assemblers in the assembly system cost the same amount and that the time spent during the part assembly cycle is constant for all parts and the same for each assembler.

The time spent by an assembler during the part assembly cycle is called the single part assembly time. It includes the time spent in fetching parts or tools, the grasping and release time, and the time spent in fine motion assembly activity. In the example of the two assemblers, the assumption that the single part assembly time is constant for all parts and the same for each assembler means that the part assembly time for part A is the same as for part B and that the speed of each assembler is the same.

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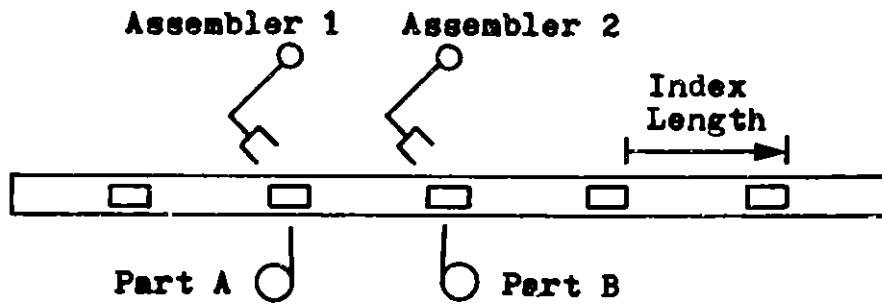
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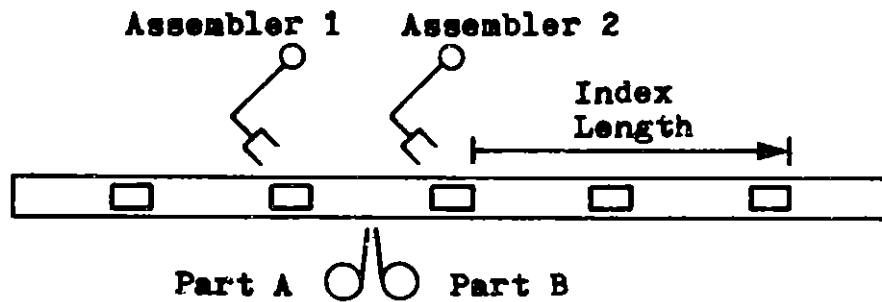
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Figure 5.3: Principal Configuration Modes

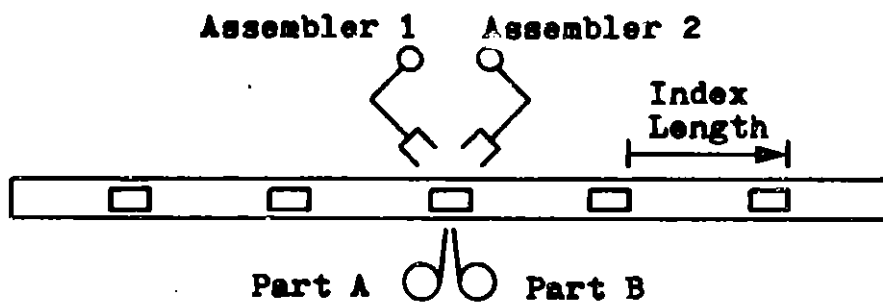
Serial Mode:



Parallel Mode:



Overlap Mode:



sentation equipment is so constructed and situated that two or more assemblers can share the same parts feeding equipment. The partially completed product units will be assumed to be on pallets passing in front of the assemblers in an indexing motion. The distance that the pallets are moved along the stream in one index cycle will be called the index length and will be measured in number of pallet lengths.

In the serial arrangement, both assemblers function simultaneously but on different product units. Each assembler adds a different part to the product. If two parts are assembled by these two stations, then assembler 1 adds part A and assembler 2 adds part B. The effective time between completed assemblies from the pair is the assembly time for one part by one assembler. In the arrangement shown in Figure 5.3, each pallet stops at both assemblers. The index length of the pallet stream is one pallet spacing, and the price of the pair of assemblers is twice the price of the individual assemblers.

In the parallel arrangement, both assemblers function simultaneously and on different product units. However, both assemblers add the same parts to different product units. Once a product unit is finished at assembler 1 it does not go to assembler 2. Each assembler works on only every other product unit in the stream. The index length of the product stream is two pallet spacings. The time for each individual assembler to complete its operations on a given product unit

is twice the single part assembly time since it must assemble two parts, but, because the two stations are operating in parallel, the effective time between completed assemblies is still equal to the single part assembly time. Notice that the parts feeding equipment is shared between the individual assemblers. The price of the pair of stations is twice the price of an individual station, and, hence, the total costs and production rates of the serial and parallel systems are equivalent.

In the overlap arrangement, the two assemblers operate simultaneously on the same product unit. Assembler 1 adds part A and assembler 2 adds part B. If the geometry and timing of their motions permit, the assembler motions are simultaneous. Each pallet stops in front of the assembler pair. The index length of the pallet stream is one pallet spacing. In this case the time between completed assemblies is equal to the part assembly time for an individual assembler since the assembly motions are simultaneous. Again, the price of this system of stations is twice the price of a single assembler.

All three of the above arrangements are equivalent in terms of production rate and cost in this ideal example. This equivalence is due to the assumption that both assemblers are always kept busy -- there is no waiting time for any assembler. This is due to the fact that the single part assembly time is assumed to be equal for parts A and B and

equal for assemblers 1 and 2. If these assumptions are not true (as indeed they are not, in general), differences in the production rate and system cost for the three modes do exist, and these are discussed in the next section.

The examples presented here of the two assembler systems are intended simply to define the different modes clearly. Many more issues are actually involved when the system becomes more complicated, and these are left to later discussion.

The discussion so far has centered on the arrangement of assemblers within a system. In some circumstances entire programmable assembly systems may be duplicated. This may occur if the production rate of one system is not sufficient to meet the annual production requirements. If there are two duplicate systems, then there are twice as many assembler stations and twice as many sets of parts feeding equipment as in the single system. We will consider the economics of this duplicate system to be the same as the economics of a single system working on one half of the production volume of the product.

5.2.2 Operating Characteristics of the Principal Modes

Although the principal modes are equivalent in an ideal sense, there are differences in operating characteristics in practical systems.

One important factor is that, in general, single part assembly times vary. The same assembler will take different times to assemble different parts because of variations in part weight, fit characteristics, and distance between part presentation site and assembly site. Different models of assemblers will take different times to assemble the same part because of differences in load and speed capabilities.

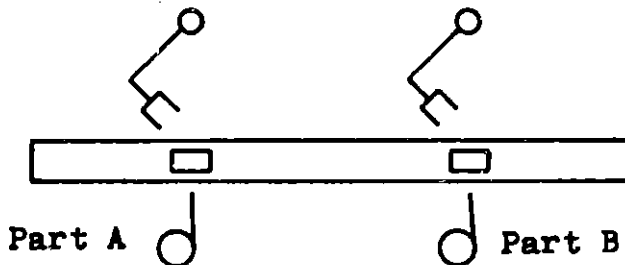
If two equivalent assemblers are operating in a serial mode, and if the part assembly times differ for the two different parts, then the longer assembly time will dominate. The slower station will pace the pair because the faster station must wait for the completion of the slower one. The waiting time of the faster station represents unusable capacity.

If the same two stations were placed in parallel, so that each station assembled both parts A and B, then there need not be any waiting time. As soon as either assembler is finished with part A it may proceed to part B. Both assemblers will finish at about the same time because they have identical tasks to perform. Figure 5.4 illustrates this effect. Under these conditions, the parallel arrangement allows a higher production rate.

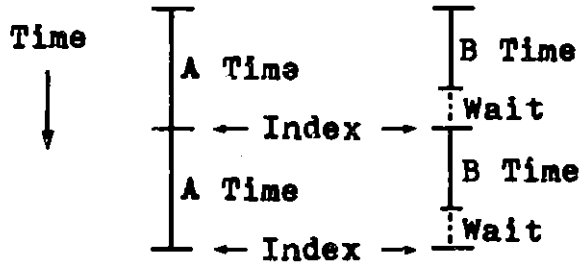
The applicability of the parallel arrangement is dependent upon the ability of the assemblers to assemble more than one part in sequence. If the parts that must be assembled are such that special tools must be used for each of

Figure 5.4: Serial versus Parallel Modes

Serial Mode:



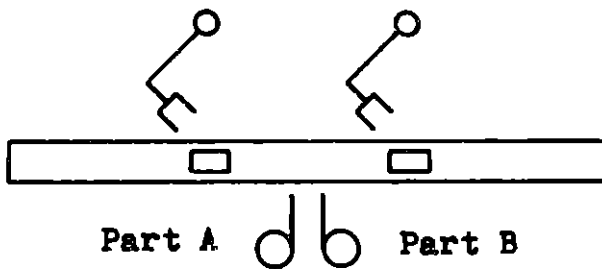
Timing Diagram



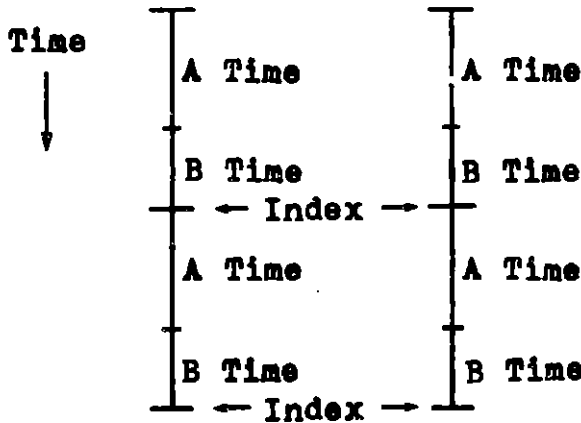
$A \text{ Time} > B \text{ Time}$

Product Interval
= A Time

Parallel Mode:



Timing Diagram



$A \text{ Time} > B \text{ Time}$

Product Interval
= $\frac{A \text{ Time} + B \text{ Time}}{2}$

them, then the parallel arrangement would suffer because of the extra time the assemblers must devote to the tool changing. In the serial arrangement where each assembler must handle a smaller variety of parts, the amount of tool changing would be reduced.

In the parallel arrangement the need to assemble a greater number of parts at one station may require more complex and expensive assemblers. For example, extra degrees of freedom may be required in the assembler motion device.

In the example given here only two assemblers operate in parallel, and the two share the same parts feeding equipment. As the number of assemblers operating in parallel increases, the requirement for shared parts feeding equipment becomes more difficult to satisfy. In order to have three or four assemblers operating in parallel, it would probably be necessary to modify portions of the parts feeding equipment, at extra expense. For five or more assemblers it would probably be necessary to duplicate the feeding equipment of the parts, at even greater added expense.

In the overlap mode, two or more assemblers add parts to a single product unit simultaneously. Under ideal conditions this mode could be as efficient a use of individual assemblers as the serial or parallel modes. However, it is likely that a large fraction of waiting time would occur in this arrangement because of the sequential nature of assembly and because geometric interference will prevent true simul-

taneous operation of the assemblers.

However, an advantage of the overlap arrangement is that it allows the execution of two-handed assembly tasks. Typically, parts that require two-handed assembly are not stable in their final assembled position until succeeding parts or fasteners are added. For example, a bolt will not hang unheld upside-down in a hole waiting for a nut to be attached. The unstable part must be held in position with one assembler while the other adds the next part or fastener. Serial and parallel modes are generally restricted to single-handed operation.

An assembly system may be constructed according to one of the principal configuration modes or a combination of them. Each mode has its own advantages and disadvantages. These were outlined generally above, but which of these are most important in the design of a particular assembly system will depend on the individual constraints of the application. These are discussed more completely in the next section.

5.2.3 Combinations of the Modes

An entire system need not be completely of the serial, parallel, or overlap type. Combinations of these modes may be used throughout the assembly system. The mode actually used at any particular point in the system will depend on special considerations peculiar to the part, the product,

and the production volume.

The system configuration may be designed to take advantage of part subsets. As noted in Section 5.1.2, product parts are often oriented in a few specific directions, and this is one example of how the parts of a product may be grouped into natural subsets. Another natural subset may occur when several of the parts are identical, such as fasteners.

It may prove to be convenient to have an entire subset of parts assembled by the same assembler. However, if the subset is a large fraction of the total number of parts, it may prove most efficient in terms of the balance of the system to have parallel assemblers handling the large subsets and single assemblers handling the subsets with fewer parts. Such a system would be parallel at some points and serial at others.

If some of the tasks are two-handed -- requiring two assemblers simultaneously -- then certain portions of the system may be configured in the overlap mode and the two-handed tasks assigned there. The potential configurations of even a few assemblers are many.

5.3 System Efficiencies

A designer who wishes to build a programmable assembly system wishes to reduce the cost of assembly per unit as

much as possible. Therefore, he will want to build as inexpensive a system as he can, which means using a minimum number of programmable assemblers. However, he must also fulfill the production requirements of the product to be assembled, and the fewer the programmable assemblers in a system, the lower the maximum production rate of that system. This is because each assembler must assemble more parts on the average so that the average time between completed assemblies is longer. Since the available production time is limited (for a given number of working shifts and working days per year), the total annual production volume of a given system configuration is also limited. The fewer the stations in the system, the longer the average product assembly time, and the lower the maximum production volume.

In order to estimate the cost of programmable assembly, it is important to be able to estimate the number of programmable assemblers required in a system that is designed for a given product. The net station efficiency of a system, which will be defined in this section, can be used to determine the number of assemblers required by the system and, therefore, to determine the capital equipment cost of that system. The net station efficiency is found by using the configuration efficiency and the utilization efficiency of the system. These terms will be defined precisely in this section, but, briefly, the configuration efficiency of the system is a measure of how well the system is balanced. It is low if

an assembler spends a lot of time waiting for other assemblers or if assemblers are performing nonassembly tasks. The utilization efficiency is a measure of the use of the system. It compares the actual production volume with the potential production volume of the system.

First, the concept of assembly station capacity, which is necessary in the definition of configuration efficiency, is discussed. Then, the configuration, utilization, and net system efficiencies are defined; and the expression for finding the number of assemblers needed is developed. Finally, an example is presented showing the calculations of the efficiencies.

5.3.1 Assembly Station Capacity

Assembly time is the time spent grasping parts and moving them to the assembly site, time spent retrieving and storing tools, and time spent during assembly fine motion.

The discussion in the previous section concerning assembly system configurations showed that some of the time of an assembler may be nonassembly time -- time spent waiting for another assembler to complete an assembly task. There is a second way for an assembler to have nonassembly time; when an assembler is assigned a nonassembly task, such as transporting a part from one point to another point without assembling the part, the time spent is nonassembly time because

it was not spent on an assembly task.

The capacity of an assembler, CAP, is defined as the number of parts that it can assemble during a period of time equal to the yearly operating time of the assembly system in which it will be installed. The assembler capacity is computed assuming that it is operating by itself before it is installed in the system and does not have to wait idly on any other equipment (as it may have to do when it is installed). Hence, the assembler capacity represents what the assembler could do if it were not limited in any way by the configuration or line balance of the system.

The amount of yearly operating time for the assembly system will depend on the number of shifts worked, the number of working days in the year and the amount of downtime for the system. Therefore, the capacity of assembly station i , CAP_i , is the number of part assembly tasks that station i could accomplish in one year in the allowed working time assuming that the working time of station i consists entirely of assembly time (no nonassembly tasks and no waiting). The sum of the assembly station capacities is $\sum_i CAP_i$.

The capacity of a single station i can be expressed in terms of working seconds in the year (the yearly operating time of the system in seconds) and the single part assembly time of the i^{th} station as

$$CAP_i = \frac{NSPY}{PARTTIME_i} \quad (5.1)$$

where CAP_i = number of parts that can be assembled
annually by the i^{th} station

$NSPY$ = number of working seconds per year
(yearly operating time of the system
in seconds)

$PARTTIME_i$ = single part assembly time for i^{th}
assembler as defined in section 5.2

(A list of variable definitions is contained in Appendix 1.)

$NSPY$ can be expressed analytically as follows:

$$NSPY = UT*DY*HD*3600 \quad (5.2)$$

where UT = uptime fraction

DY = number of days worked per year

HD = number of hours worked per day

The uptime fraction is simply one minus the downtime fraction; it is the fraction of the time that the system should be producing that it actually is producing. If the uptime fraction is .8, there are 250 days worked per year, and 16 hours worked per day (2 shifts), then the value of $NSPY$ is 1.152×10^7 sec/yr.

5.3.2 Configuration Efficiency

The configuration efficiency is defined as the potential number of parts that the system could assemble per year di-

vided by the sum of the assembly station capacities.

$$CEF = \frac{NPART * MAXVOL}{\sum_i CAP_i} \quad (5.3)$$

where CAP = configuration efficiency

NPART = number of parts in the product

MAXVOL = potential production volume of the
system (number of product units per year)

The potential production volume of the system is the number of product units that can be assembled during the yearly operating time of the assembly system. It is usually determined by a particular pacing station or sequence of such stations because the other stations must spend some time waiting on the pacing station to complete its tasks.

The configuration efficiency is a measure of the amount of nonassembly time that the assemblers are forced to spend as a result of the assembly system configuration. This will be illustrated by example in section 5.3.4.

For the special case in which the single part assembly time for all the assemblers in the system is the same, the configuration efficiency can be shown to be equal to the total time the assemblers are actually performing assembly operations during one index period divided by the total assembler time available in that index period as follows:

The capacity of a single station is:

$$CAP_i = \frac{NSPY}{PARTTIME} \quad (5.4)$$

Now, the sum of the assembly station capacities can be expressed as follows:

$$\sum_i CAP_i = \frac{NSTA * NSPY}{PARTTIME} \quad (5.5)$$

where NSTA = number of programmable stations in the system.

The index time for one product unit in terms of the number of working seconds per year and the maximum production volume that the system can achieve during those working seconds is

$$INDEXTIME = \frac{NSPY}{MAXVOL} \quad (5.6)$$

where INDEXTIME = average time between completed product units (in seconds)

Notice that the assumption is made here that the index time corresponds to the maximum production rate. It is assumed that the system will operate at its maximum production rate even when less than the maximum production volume is required. Then, to achieve reduced production volume, the system will be operated for a reduced amount of time during the year.

Equations 5.3, 5.5, and 5.6 can be combined together to form an alternate expression for the configuration efficiency for the case of equal single part assembly times.

$$CEF = \frac{NPART * PARTTIME}{NSTA * INDEXTIME} \quad (5.7)$$

Notice that the numerator of the expression in equation 5.7 is equal to the number of station-seconds that must be devoted to the actual assembly motions for a single product unit, whereas the denominator is equal to the number of station-seconds tied up in the index period during which one product unit is made. Hence, the configuration efficiency represents that fraction of the index period that is actually spent in assembly task execution.

5.3.3 Utilization Efficiency

The utilization efficiency of an assembly system is defined as the ratio of the actual annual production volume divided by the potential annual production volume.

$$PUEF = \frac{VOL}{MAXVOL} \quad (5.8)$$

where PUEF = utilization efficiency of the programmable system

VOL = actual production volume of the product.

Essentially, the utilization efficiency is the fraction of the capability of the system that is actually being used.

5.3.4 Net Station Efficiency

Finally, the net station efficiency is defined as follows:

$$\text{NSEF} = \frac{\text{NPART} * \text{VOL}}{\sum_i \text{CAP}_i} \quad (5.9)$$

where NSEF = net station efficiency of the system.

It can be seen by comparing equation 5.9 to equations 5.3 and 5.8 that the net station efficiency is also equal to the product of the utilization efficiency and the configuration efficiency.

$$\text{NSEF} = \text{PUEF} * \text{CEF} \quad (5.10)$$

The net station efficiency includes not only the effects of the imbalance between the stations but also the degree of use of the system: How closely does the potential production volume of the system match the production volume requirements of the product? In the special case of identical assemblers used in a system, the net station efficiency is the ratio of the number of stations needed under "ideal conditions" to the number of stations actually used. Ideal conditions consist of perfect configuration balance (configuration efficiency = 1.0) and equality between the potential production volume and the production volume requirements (utilization efficiency = 1.0).

For any particular assembly system design, the net station efficiency cannot be specified or estimated in advance. The system must first be designed and then the net station efficiency calculated. However, in later modeling it will be necessary to be able to estimate the number of stations required in a typical system for a product with a specified

production volume. In this case a net station efficiency must be estimated that is representative of the range of net station efficiencies that would occur in the actual systems designed for products with that production volume.

Combining equations 5.5 and 5.9 gives

$$NSTA = \frac{VOL * NPART * PARTTIME}{NSPY * NSEF} \quad (5.11)$$

This equation can be rewritten in terms of the configuration efficiency and the utilization efficiency.

$$NSTA = \frac{VOL * NPART * PARTTIME}{NSPY * PUEF * CEF} \quad (5.12)$$

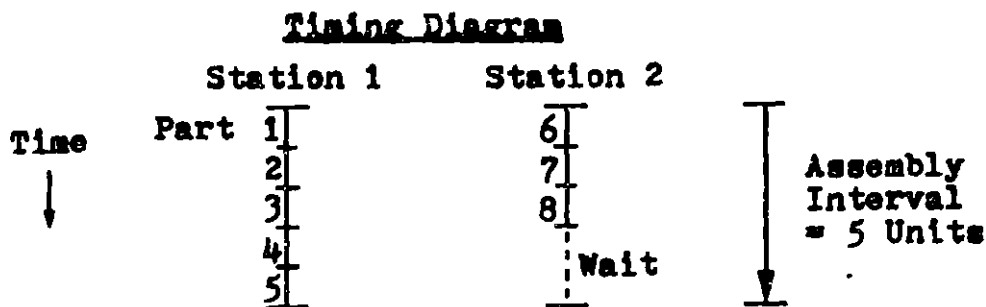
Thus the number of assembly stations needed in an assembly system can be estimated from the production volume of the product, the number of parts in the product, the single part assembly time, and estimates of the configuration and utilization efficiencies.

5.3.5 Example Calculation of System Efficiencies

To show how configuration, utilization, and net station efficiencies would be calculated for a simple system, consider the pair of assemblers illustrated in Figure 5.5. They are to be used in a system to manufacture a product with a total of eight parts. This product has two principal directions of assembly with five of the parts assembled in one direction and three assembled in the

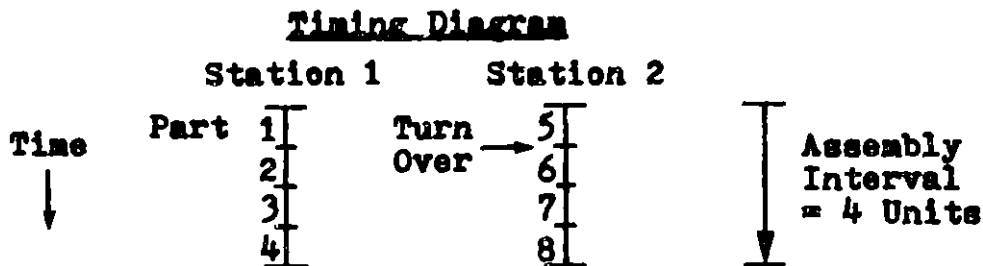
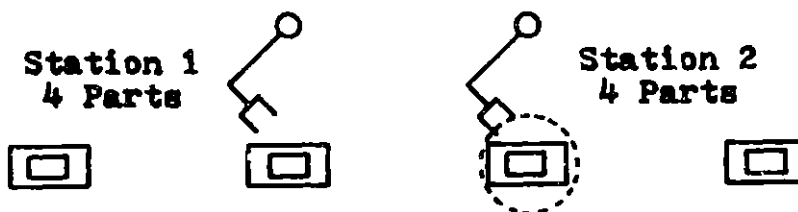
Figure 5.5: Example Configuration Efficiency Calculation

1st Case:



Configuration Efficiency = 0.8

2nd Case:



Configuration Efficiency = 1.0

other. The assemblers both have a single part assembly time equal to PARTTIME.

Assume that each assembler is aligned with a principal direction of assembly. The first assembler will have five parts to assemble and the second will have three. Since the first assembler will pace the system, its rate will determine the system rate and capacity.

$$\text{MAXVOL} = \frac{\text{NSPY}}{5 * \text{PARTTIME}}$$

Here it is assumed that the first assembler spends all of its time in assembly motions--there are no nonassembly motions and no waiting time.

The sum of assembly station capacities for the pair of assemblers is just twice their individual capacity.

$$\sum_i \text{CAP}_i = \frac{2 * \text{NSPY}}{\text{PARTTIME}}$$

The configuration efficiency is, according to equation 5.3,

$$\text{CEF} = \frac{8 * \text{NSPY}}{5 * \text{PARTTIME}} * \frac{\text{PARTTIME}}{2 * \text{NSPY}} = .8$$

The utilization efficiency depends on the actual volume demanded in the market. If the actual volume VOL produced were 750,000 but the potential production volume MAXVOL were 1,000,000, then the utilization efficiency PUEF would be .75 .

The net station efficiency of this arrangement is, according to equation 5.10, the product of the configuration and utilization efficiencies.

$$\text{NSEF} = .8 * .75 = .6$$

To continue the example, we now attempt to improve the configuration efficiency of the system by adding a device to the second assembler station to rotate the work pallet so that both principal directions are accessible from the second assembler. (It is assumed that the rotation is accomplished while the assemblers are reaching for tools or parts.) Now, four parts can be assembled at each assembler. Since each assembler is being used constantly for assembly tasks only in this new arrangement, the configuration efficiency is now equal to one. Both stations are now equal and limiting, and the potential production volume of the system has been increased.

$$\text{MAXVOL} = \frac{\text{NSPY}}{4 * \text{PARTTIME}}$$

This represents a 25 percent increase in the potential production volume of the system; that is, from 1,000,000 to 1,250,000. If the actual production volume of the

system does not change, there is a reduction in the utilization efficiency of the system.

$$PUJEF = \frac{750,000}{1,250,000} = .6$$

The net station efficiency of this arrangement is

$$NSEF = 1. * .6 = .6$$

This example illustrates that improving the balance of the system (i.e., the configuration efficiency) will not improve the overall net station efficiency if there is no reduction in the number of assemblers. The second configuration of the example was a much better balanced system, and because of its higher production rate, it will be able to satisfy the annual production requirements in less operation time. This means that other expenses associated with the length of its annual operation time (such as labor and maintenance) will be less. However, since the cost of the assembly system is the same as in the first configuration, that portion of the unit cost of assembly attributable to the capital investment in the system remains the same. (In fact, the capital investment cost will go up due to the cost of the reorientation device at the second station.)

Another alternative is available if there is another assembler on the market with longer assembly time and lower price. If a system constructed with a lower cost-longer time assembler and a rotation device can meet the production

requirements, then the balancing of the system does lead to reduced unit assembly cost.

5.4 Summary

This chapter presented the characteristics of programmable assembly which are necessary as a basis for the modeling done in Chapter 6.

The configuration of a programmable assembler refers to the degrees of freedom of the motion device and the way in which they are implemented. In general, six degrees of freedom are required to position a part in an arbitrary location. However, due to the existence of principal assembly axes on a large number of products this number may be considerably reduced for part assembly on any particular product. In addition, the assembler motion device may actually consist of two motion devices: one to position the product unit and one to assemble the part onto that product unit. The total number of degrees of freedom required may be split between the devices so that each motion device is less complex than if all the degrees of freedom were contained in one device.

The configuration of a programmable assembly system refers to the arrangement of the assemblers and feeding equipment in the system and also the organization of the assembly sequence. The three principal arrangements

(configuration modes) for assemblers in an assembly system are serial, parallel, and overlap.

There are advantages and disadvantages to each mode depending on the specific circumstances involved. One assembly system may use any combination of the modes.

When the designer plans an assembly system, he would like to minimize the cost while still accomplishing the targeted production volume. He therefore needs an estimate of the minimum number of assemblers required to do that. One way to find this is through a priori estimation of the system efficiencies--configuration efficiency and utilization efficiency. The configuration efficiency is a measure of how well the system is balanced; utilization efficiency is a measure of how well the system is matched to the required production volume. Their product is the net station efficiency. By making estimates of these efficiencies, the designer of a system can combine them with other factors he knows--the number of parts in the product, the single part assembly time, and the production volume--to obtain an estimate of the number of assembly stations he will need, and, consequently, the number of parts assembled at each station. This serves as a starting point in the system design process. The designer can then begin to design a system with approximately that number of assemblers in the combination of configuration modes which best fits the particular product assembly sequence.

6. SIMPLE ECONOMIC MODELS OF ALTERNATE ASSEMBLY METHODS

In this chapter simple economic models of alternate assembly methods are developed. The purpose of these models is to gain an understanding of the programmable assembler characteristics that play a major role in the economics so that more effective assemblers can be designed. It is also a goal of this modeling to determine some criteria for indicating the circumstances in which programmable assembly is most applicable.

In the first section of this chapter very simple models of the major alternate assembly methods-- manual, transfer, and programmable--will be developed. While these models are much too simple to provide an accurate estimate of the cost of assembly in any specific situation, the form of the equations does provide some insight into the circumstances under which each of the alternate methods is best used and also suggests a criterion for the design of individual programmable assembler stations. It is important to note that it is the cost to the user of the programmable system that is being modeled.

In the second section two hybrid combinations of the major methods are considered. In one the assembly operations are divided between manual stations and transfer stations and in the other between programmable stations and transfer stations. Again, the form of the equations

leads to some understanding of the circumstances under which the hybrid systems are most applicable.

Finally, in the third section, the simple models previously developed are improved somewhat in their accuracy at the cost of increased complexity of the equations. Labor costs are added to the models of transfer machine and programmable system assembly, and equipment costs are added to the model for manual assembly. An example is used to compare these more complex equations to the equations of the simple model to see if there are any significant differences. Certain differences will appear, but the basic results will still hold.

6.1 Simple Alternate Economic Models

6.1.1 Modeling Manual Assembly Costs

The manual assembly cost per unit will be modeled as follows:

$$\text{MCPU} = \text{MATP} * \text{LABCST} * \text{NPART} \quad (6.1)$$

where MCPU = manual assembly cost per unit, \$/unit
 MATP = manual assembly time per part, sec
 LABCST = cost rate of labor, \$/sec

The concept is that the manual assembly time, and therefore cost per unit, is proportional to the number of parts. Furthermore, the manual assembly cost per unit is independent of the annual volume. To increase his production volume, the manufacturer pays for more worker time. The manual assembly time per part MATP refers to the average time be-

tween the start of the assembly of one part to the start of the assembly of the next. Hence, the manual assembly time per part includes any slack time between part assemblies.

6.1.2 Modeling Transfer Machine Assembly Costs

The system cost for the transfer machine configuration is modeled as proportional to the number of parts it assembles; that is

$$\text{TSCST} = \text{NPART} * \text{TMCPP} \quad (6.2)$$

where TSCST = system cost for transfer machine

TMCPP = transfer machine cost per part

This is reasonable because transfer machines are organized so that a given portion of the equipment is dedicated to the assembly of one part only. The transfer machine cost per part, TMCPP , is dependent on the size of the part and the type of machine, as was discussed in Chapter 2.

We now must translate the original investment cost of the transfer machine into a unit assembly cost. This means that somehow the cost of the machine must be allocated to the units that it produces. We will use an allocation model that can be related to the discounted cash flow (DCF), or return on investment (ROI), method of evaluating capital investments. For descriptions of this and other capital investment evaluation methods see Swalm (20) and Van Horne (21).

We will not derive the DCF method here. Only the important points of the method as they pertain to this modeling will be discussed.

The discounted cash flow method is used to compute a return on investment (ROI) for a specific project involving capital investment. It requires that a projection be made of the cash payments and receipts (the "cash flows") of a project over the life of the project. The ROI itself is the "interest rate" that these cash flows appear to have over the life of the project.

Every firm has a required minimum return on investment for its projects. This minimum return on investment is partially set by company policy and partially set by the ease with which the company can borrow money to finance its projects. When a firm has a selection of potential projects from which to choose, only those projects with ROI's above the minimum return on investment will be considered.

The DCF method is most commonly used to examine replacement projects. For example, if a firm were considering replacing a manual assembly line with a transfer assembly machine, then the cash flow projection upon which the ROI would be calculated would represent the differences of the absolute cash flows of the manual and transfer machine alternatives over the life of the transfer machine. The ROI calculation then depends as much on the absolute cash flows of the manual assembly method as on the cash flows of the transfer machine method. Hence, the

same new assembly method when used to replace different old methods will result in different ROI's.

The use of the ROI does not result in measurement of either the new assembly method or the old assembly method themselves; the value of the ROI only describes the comparison of the two. The evaluation method used in this thesis is first to compute an assembly cost per unit product for each method of assembly and then to compare these costs. The unit assembly cost for one assembly method is not functionally related to the unit assembly cost of another method. This approach simplifies the comparison between alternate assembly methods, especially when more than two alternate methods are involved.

For assembly methods involving capital investment, the cost of assembly per unit product will be based on the minimum required return on investment of the firm. When the unit assembly cost is defined in this way then the requirement that a replacement project ROI be above the minimum ROI is the same as the requirement that the unit assembly cost of the replacement method be less than the unit assembly cost of the old method.

For example, consider the replacement problem in which a firm is contemplating replacing a manual assembly line with a transfer assembly machine. If the manual unit assembly cost is equal to the transfer machine unit assembly cost calculated using the minimum rate of return, then this

is the same as saying that the ROI of the replacement project is equal to the minimum rate of return. The firm would be indifferent to the two assembly methods. But, if the transfer machine assembly cost per unit so defined is less than the manual unit assembly cost, then the replacement ROI is actually greater than the minimum rate of return. Then, the firm will prefer the transfer machine method.

We now seek to derive a unit assembly cost for the transfer machine based on the minimum return on investment of the firm. We will use the "after tax rate of return" approximation to the ROI.

$$R = \frac{CAT}{I} \quad (6.3)$$

where R = after tax rate of return

CAT = net annual cash flow after taxes

I = initial investment

This approximation to the ROI is a commonly used one. For all but the simplest problems, there is no simple expression for the ROI. In almost all practical cases, the value of the ROI is difficult to calculate, and usually a computer is used to obtain a solution. It is important to this analysis that a simple expression for ROI (even though only approximate) be used, and the after tax rate of return suits this purpose. See Appendix 2 for an example illustrating the accuracy of the approximation.

We now assign a unit assembly cost for each unit of product made and will derive an expression for this cost. The cash flow after taxes will be modeled as

$$\text{CAT} = \text{TCPU} * \text{VOL} - \text{TAX} \quad (6.4)$$

where TCPU = unit assembly cost for the transfer
assembly machine

VOL = actual annual production volume

TAX = taxes on income allocated to the transfer
machine

The first term above, $\text{TCPU} * \text{VOL}$, represents the gross annual "wages" of the assembly machine; that is, the cost it must charge for each unit times the total annual production volume.

The taxes, TAX , are computed on the annual income after a depreciation deduction is subtracted. If a straight line depreciation method is assumed, then we may model the tax as

$$\text{TAX} = T * (\text{TCPU} * \text{VOL} - \text{DPTM} * \text{TSCST}) \quad (6.5)$$

where T = tax rate

DPTM = annual depreciation rate for
the transfer machine

TSCST = original investment cost of the transfer
machine.

Substituting equation (6.5) into equation (6.4) gives

$$\text{CAT} = (1-T) * \text{TCPU} * \text{VOL} + T * \text{DPTM} * \text{TSCST} \quad (6.6)$$

Now, by analogy with equation (6.3) using the minimum rate

of return R , we have

$$R = \frac{(1-T)*TCPU*VOL + T*DPTM*TSCST}{TSCST} \quad (6.7)$$

Solving for TCPU gives

$$TCPU = TSCST * \frac{(R-T*DPTM)}{VOL*(1-T)} \quad (6.8)$$

Finally, substituting for the value of the transfer machine from equation (6.2) gives

$$TCPU = TMCPP*NPART * \frac{(R-T*DPTM)}{VOL*(1-T)} \quad (6.9)$$

6.1.3 Modeling Programmable Assembly Costs

A programmable assembly system will be assumed to consist of two types of component equipment: programmable assembly stations and their associated equipment; and parts feeding tooling and its associated equipment. Because they are programmable, the assembler stations can be used for many different kinds of parts. Any given set of parts feeding equipment usually is specially made for a specific product; then, within certain limits, the design of the feeding equipment is relatively unaffected by the number and configuration of the programmable stations. If ten parts must be assembled, then ten sets of parts feeding equipment are required, one for each part, regardless of the number of assemblers in the system. However, the number of assembler stations used in the programmable system may vary depending on the number of parts assembled at each

station.

There may be cases where several identical programmable assembly systems might be used for the assembly of one product. The economics of such duplicate systems are not considered explicitly in this modeling. A simple method of extending the modeling derived here to duplicate systems will be discussed later.

Figure 6.1 illustrates how the configuration of programmable assembly systems may vary. A system for assembling ten parts into a product will need to have ten sets of parts feeding or presentation equipment, each set specific to a particular part, no matter what the assembler configuration. However, the system will have ten stations if one part is assembled at each station, five if two parts are assembled at each station, or two stations if five parts are assembled at each station.

We may model the total cost of a system as follows:

$$PSCST = NSTA * STAP + NPART * TOLPP \quad (6.10)$$

where PSCST = programmable system cost

NSTA = number of assembly stations

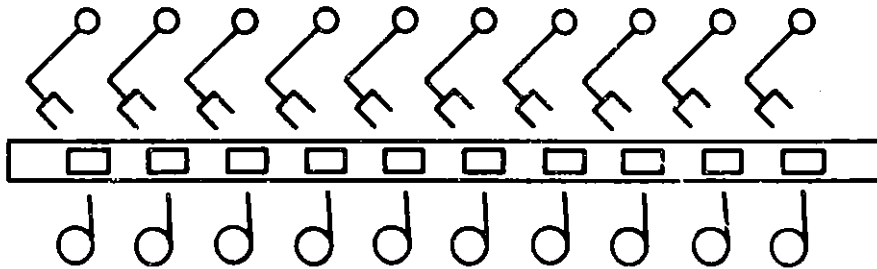
STAP = single station price

TOLPP = price of parts feeding tooling per part.

The important simplifying assumptions behind this model are that all the programmable assembly stations are assumed to have equal cost. Also, the sets of parts tooling and presentation equipment are assumed to have equal cost.

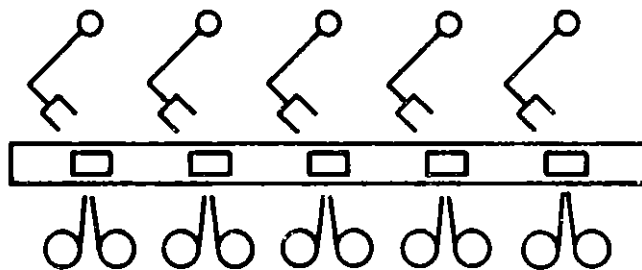
Figure 6.1: Simple Variation of System Configuration for Assembly of One Product

10 Assemblers



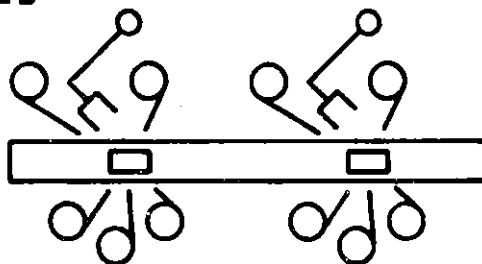
Interval
between
completed
products
= PARTTIME

5 Assemblers



Interval
between
completed
products
= 2 x PARTTIME

2 Assemblers



Interval
between
completed
products
= 5 x PARTTIME

Assumes:

- Product has 10 parts
- All assemblers are identical
- Single part assembly time, PARTTIME, is the same for all parts and all assemblers
- Each assembler assembles the same number of parts

Clearly, in a realistic system this is not the case, but if average numbers are used for the price of a station and for a set of parts feeding tooling, then an average estimate of the cost of the programmable system will result.

The station price per part includes all the costs to the user of the programmable system associated with the particular station. This includes the cost of the programmable assembler itself, all dedicated processors and sensors, and an appropriate portion of the conveying device or index table between stations associated with that station. The station price also includes the engineering cost of integrating that station into the system.

The parts feeding tooling price per part includes the cost of the basic feeding mechanisms--bowl, bowl feeders, hoppers, magazines, or eggcrate table--feed tracks or chutes, and placement or escapement devices that bring the parts to the assembly stations or the conveying mechanism that links them together. The parts feeding tooling considered here may range from relatively sophisticated bowl feeders to a simple table where parts in eggcrates are placed within reach of the assembler. The assembler controller can be given the information describing the eggcrate pattern so that the assembler can pick parts directly from the eggcrate. One possible feeding method would involve the parts presentation equipment "handing off" the part to the assembler directly. Another method might involve placing the

oriented part in some sort of pallet from which the station assembler picks the part. For a special pallet system the pallets should be considered part of the tooling cost but the pallet conveying or index system should be part of the station costs.

By analogy to the method of allocating the capital investment of the transfer machine to the unit assembly cost, equation (6.9), the programmable assembly cost per unit will be modeled as follows:

$$PCPU = \frac{NSTA*STAP*(R-T*DPPA) + NPART*TOLPP*(R-T*DPTL)}{VOL*(1-T)} \quad (6.11)$$

where PCPU = programmable system cost per unit
 DPPA = annual straight line depreciation rate
 for the programmable assembler stations
 DPTL = annual straight line depreciation rate for
 the parts feeding tooling
 T = tax rate.

Here we have assumed separate straight line depreciation rates for the parts feeding tooling and the reusable programmable assemblers.

We now address the problem of specifying the number of assembler stations for the programmable system. We wish to design the minimum cost system that meets the production requirements. Therefore, it is important to use the minimum number of assemblers. (Since we are working under the assumption of a single programmable system to satisfy the

entire production requirements, then we are already using a minimum number of sets of parts feeding equipment.)

In Chapter 5, equation (5.12) was derived to estimate the number of stations required in a system based on the capacity of the stations; that is,

$$NSTA = \frac{VOL * NPART * PARTTIME}{NSPY * CEF * PUEF} \quad (5.12)$$

where CEF = configuration efficiency

PUEF = programmable utilization efficiency

Now, equation (5.12) is substituted into equation (6.11)

for the programmable unit assembly cost to obtain

$$PCPU = \frac{NPART}{(1-T)} * \left[\frac{STAP * PARTTIME * (R-T * DPPA)}{NSPY * CEF * PUEF} + \frac{TOLPP * (R-T * DPTL)}{VOL} \right] \quad (6.12)$$

In this equation the number of stations is no longer fixed but is free to adjust to different volume requirements or assembler capacities. It allows one to estimate the programmable unit assembly cost from a knowledge of the production volume and number of parts in a product, the assembler part assembly time, and assumed values for the configuration and utilization efficiencies. It assumes that a single system is constructed to produce the entire production volume of the product.

6.1.4 A Comparative Example

The simple models of the manual, transfer, and pro-

grammable methods show that the unit assembly cost for each of these methods is proportional to the number of parts in the product. This means that the number of parts does not effect the relative cost of assembly per unit between the three methods. The important product variable is the volume.

An example plot of cost of assembly per unit against annual volume is shown in Figure 6.2. For the purposes of illustration the following values of the parameters have been assumed.

NPART = 10 parts

STAP = \$30,000

PARTTIME = 3 sec

R = .25

DPPA = .125 (8 year life)

TOLPP = \$7500

DPTL = .25 (4 year life)

TMCPP = \$30,000

DPTM = .1 (10 year life)

MATP = 7 sec

LABCST = .0020833 \$/sec (= \$7.50 \$/hr)

NSPY = 1.152×10^7 sec/year

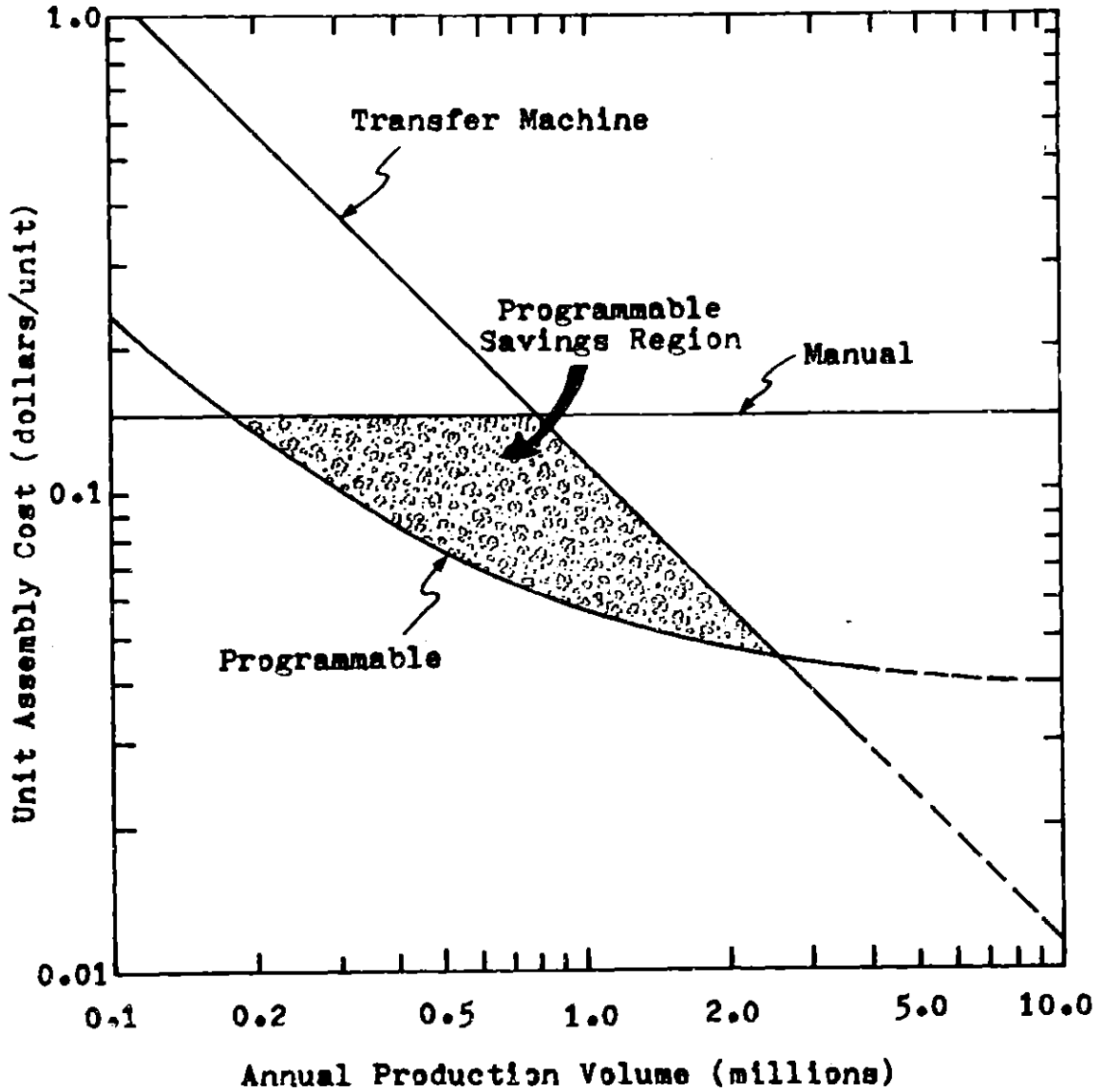
CEF = .8

PUEF = .95

The above are simply round figures that are meant to be plausible, not definitive. Better data could be obtained

Figure 6.2: Comparison of Assembly Costs as a Function of Annual Volume

Assumes hypothetical product with 10 parts



for more specific examples. However, for more accurate answers a very detailed cost model is required. The figures are meant to represent plausible values for an assembly system assembling products limited to 8 inches in size. The station price of \$30,000 and part assembly time of 3 seconds are rough figures meant to represent a small assembler (about one foot reach and lift) with dedicated processor and mounted on a conveyor section. The station price must include the engineering cost of incorporating the station into the system. The transfer machine price per part of \$30,000 is a round figure representative of transfer machine assembly systems for this product size range. The parts feeding tooling price per part of \$7500 for the programmable system represents a rough estimate based on the price of feeding tooling equipment for the corresponding transfer machine (\$2600 to \$5500) plus an additional engineering expense for integrating the tooling to the system.

The configuration efficiency has been set at .8 . Kondoleon (19) has found by a series of simple paper studies on assembly system layouts for real products that configuration efficiencies ranged from about .7 to .9 for a simple layout procedure he developed. An estimate of CEF equal to .8 represents an average value. An estimate of programmable utilization efficiency PUEF of .95 represents a management

decision to have only a small amount of excess capacity in order to bring down the system cost.

The required rate of return of 25 percent after taxes is a common value. Depreciation rates of .1 per year (10 year life) for the transfer machine, .125 per year (8 year life) for the programmable assemblers, and .25 per year (4 year life) for the programmable system parts feeding tooling were assigned. The labor cost rate of \$7.50 per hour is also representative of a range of labor cost rates currently running from \$5 to \$10 per hour (\$10,000 to \$20,000 per year). The assumption of a manual assembly time of 7 seconds per part is a result of observation of certain manual assembly lines where operators assembled roughly two parts in a fifteen second station period. Manual assembly time per part varies considerably in practice. Often the actual operation time for the assembly does not completely fill the station time allowed so that there is some built-in idle time. Nevertheless, the idle time must be included in this model.

The number of working seconds per year NSPY represents two shift operation for 250 days per year with 80 percent uptime fraction.

In Figure 6.2, the vertical axis represents the assembly cost per unit assuming ten parts in the product. Since the assembly cost for all three methods is proportional to the number of parts, the vertical axis can be easily scaled

to any other number of parts in the product.

The intersection of the transfer machine line and the manual line represents the boundary between economic application of manual and transfer machine assembly if programmable assembly is not considered. In this case it occurs at about 800,000 units per year. With the addition of programmable assembly machines, a range of production volumes that would have been handled by manual assembly or transfer machines is now more economically done by programmable systems. The region of cost swings is shaded and extends from annual volume of $1.73 * 10^5$ to $2.60 * 10^6$. This range extends from the boundary between manual and programmable assembly at the low end and programmable and transfer machine assembly at the high end.

This range will depend on the relative values of the costs used in the equations, and as labor rates, capital costs, and equipment costs change, the range will also change. Also, even if accurate average values of the costs were used in the equations, the resulting unit assembly costs are still only average costs. The true unit costs for all three methods would actually form a distribution about the mean lines shown in Figure 6.2. Hence, there will be cases in the manual or transfer ranges where programmable assembly is most economic and

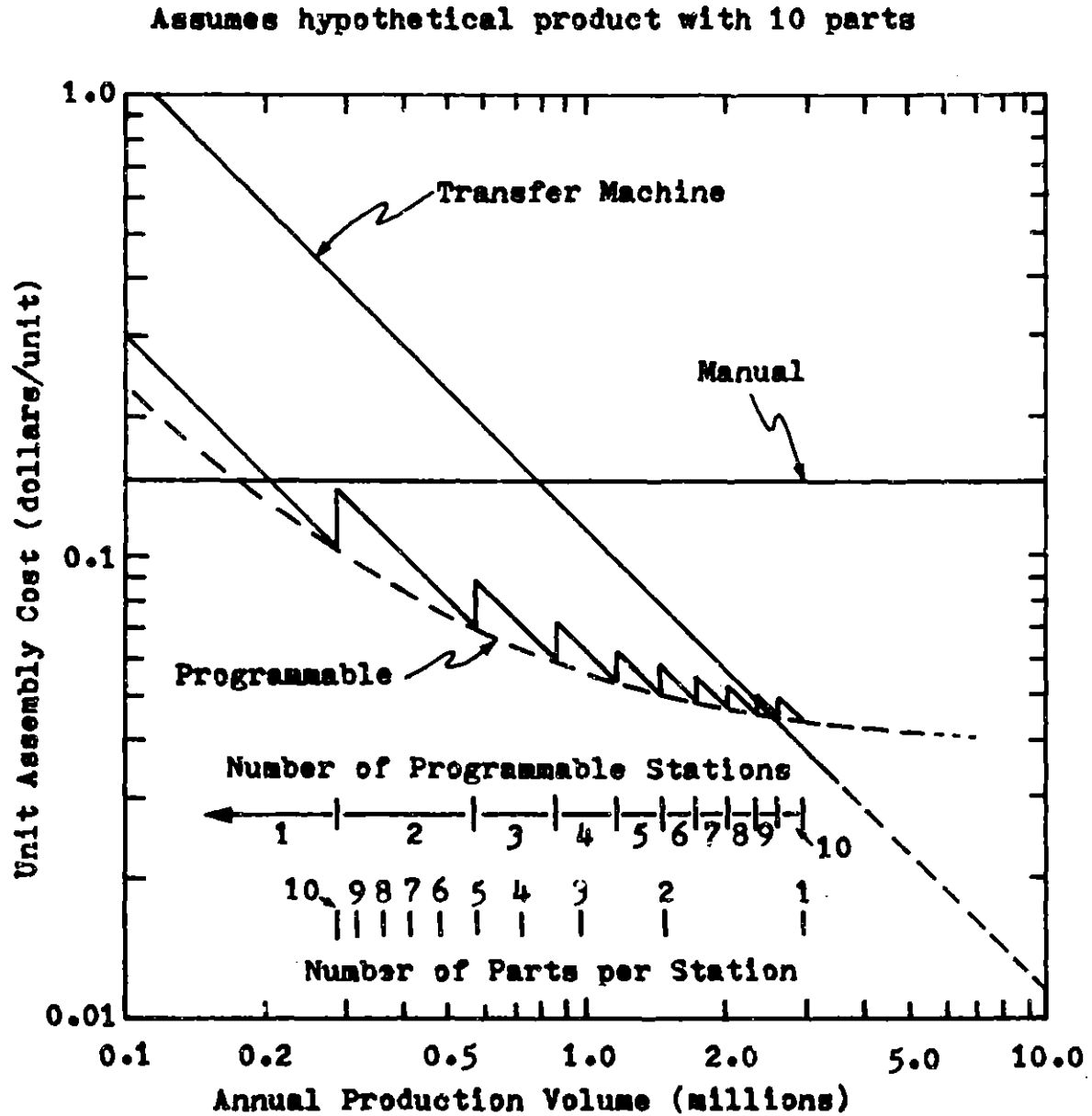
vice versa.

These cases will represent deviations from the average and will therefore be less frequent.

The shape of the programmable unit assembly cost curve approaches a horizontal asymptote at very high volume and a minus 45° asymptote at very low volume. This is because the number of programmable stations will vary along the curve according to the volume requirements. Hence, at low volume, few stations are needed and most of the price of the system is in the fixed cost of the parts feeding tooling equipment. This dominance of the fixed costs makes the cost curve parallel to that of the fixed cost transfer machine. At higher volumes most of the cost is in the programmable assemblers because more of them are needed to meet the production requirements. Their total cost is proportional to the volume and so the unit assembly cost approaches a constant.

Figure 6.3 shows what happens to the unit cost curve if the number of stations is forced to be an integer as of course it must be in practice. Essentially the number of stations used in the system is taken to be the next integral number above the value given by equation 5.12. This does not model all of the quantization problems. For example, this model would still assume that the number of parts assembled per station could be non-integral. For example, if 10 parts were assembled by 7 stations then this model assumes that $1 \frac{3}{7}$ parts are assembled at each station. Rather than attempt to deal with all the quantization effects explicitly, we will describe them with the use of configuration

Figure 6.3: Comparison of Assembly Costs as a Function of Annual Volume with Integral Station Number



efficiencies less than one. Figure 6.3 shows graphically that the number of programmable stations will vary with the production volume and that for the values of the example data the station quantization effect does not drastically alter the unit cost curve.

There is a way in which there may be more assemblers than number of parts; that is, for the number of parts per station to be less than one. This is the case where parallel assemblers are used to assemble the same part. For example, if there were a product with ten parts, then such a system would be one which had two assemblers for each part sharing the parts feeding equipment for that part. Such a system would have twenty assemblers and ten sets of parts feeding equipment and would have twice the production rate of the system with one assembler per part. For the example shown in Figure 6.3, such a system could not compete with a transfer assembler machine. However, later in this chapter in the discussion of hybrid programmable-transfer systems, it will be shown that parallel assemblers for single products may be a part of competitive system designs.

Finally, it has been implicitly assumed that the product has a fairly stable production volume requirement. This is a realistic assumption for some products but not for others. The question of the life cycle of

a product is an important one. Often a product begins with low volume and manual assembly. If the ultimate production volume of a product is expected to rise to the transfer machine range, then it must be decided whether it is wise to build a programmable system when the volume is in the programmable range and climbing.

The answer should depend on the rate of climb. If the production volume is increasing rapidly, then the period of time in the programmable volume range may not be long enough to pay for the feeding equipment and the depreciation on the assemblers. If the climb is slow, then it makes sense to build the programmable system when the volume is sufficient and in several years salvage it and build a transfer system. However, if the anticipated ultimate volume of the product is not high enough to be in the transfer range but is in the programmable range instead, then the programmable system can be built with greater confidence when the volume requirements are met.

6.1.5 Product Volume Analysis

It is possible to solve for the annual volumes representing the boundaries between the regions economically dominated by manual, programmable, and transfer machine assembly. For the programmable-transfer boundary we have

$$VOLPT = \frac{(TMCPP*(R-T*DPTM) - TOLPP*(R-T*DPTL)) * NSPY * CEF * PUEF}{STAP * PARTTIME * (R-T*DPPA)} \quad (6.13)$$

where VOLPT = volume boundary between economic programmable and transfer machine systems.

For the programmable-manual boundary it is

$$VOLPM = \frac{TOLPP*(R-T*DPTL)}{MATP * LABCST * (1-T) - \frac{STAP * PARTTIME * (R-T*DPPA)}{NSPY * CEF * PUEF}} \quad (6.14)$$

where VOLPM = volume boundary between economic manual and programmable systems.

Finally, for the manual-transfer boundary, it is

$$VOLMT = \frac{TMCPP*(R-T*DPTM)}{MATP * LABCST * (1-T)} \quad (6.15)$$

where VOLMT = volume boundary between economic manual and transfer machine systems.

These volumes VOLPT and VOLPM will be called the system volume boundaries because they refer to the limits of the volume range in which a programmable system is economic. Notice that the system volume boundaries are not a function of the number of stations in a system (although the number of stations is a function of the volume) but are a function of the product of the individual station price and the single part assembly time of the stations that make up the system.

Consequently, these volume boundaries apply to products with any number of parts. More parts in the product mean longer transfer machines, more stations in the programmable

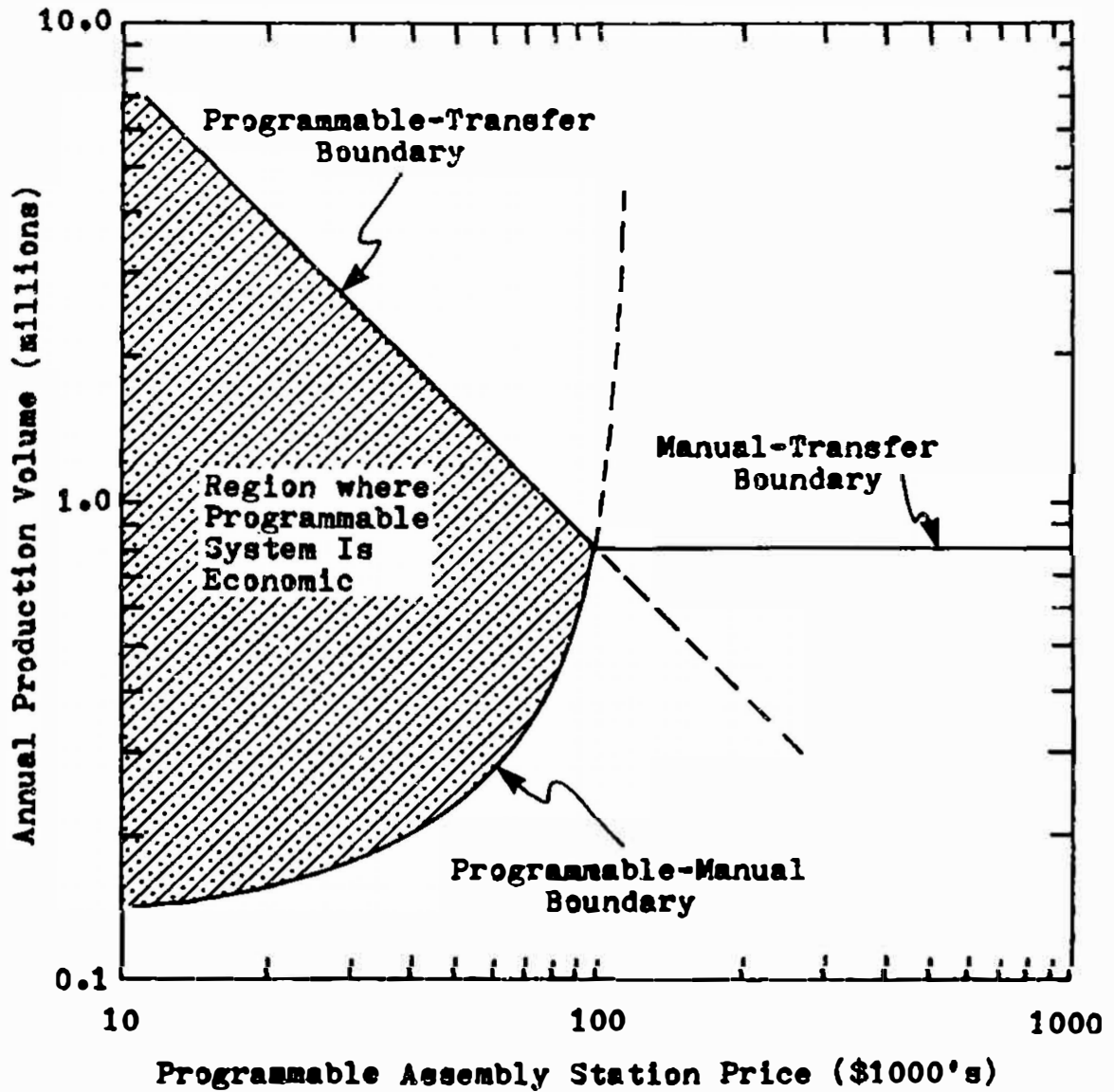
systems, and more workers in the manual lines, but the economic production volume ranges remain the same.

In Figure 6.4 is a plot of system volume boundary versus station price assuming assemblers with single part assembly time PARTTIME equal to 3 sec. (The manual assembly time remains at 7 seconds for this example.) Notice that the lower programmable-manual volume boundary increases with programmable station price while the upper programmable-transfer volume boundary decreases until finally they intersect at a station price of \$98,000. Notice that they intersect at the level of the manual-transfer boundary. The three boundary curves divide the graph into programmable, transfer, and manual regions. For single programmable station prices higher than \$98,000, any programmable system composed of a set of those stations will be uneconomic compared to one of the other two methods. In Figure 6.2 this corresponds to the programmable assembly cost curve being above the corner formed by the manual and transfer machine curves. This condition may be solved for a bound on the product of the single station price and the single station part assembly time. This bound is

$$STAP * PARTTIME < \left[\frac{TMCPP * (R-T * DPTM) - TOLPP * (R-T * DPTL)}{TMCPP * (R-T * DPTM)} \right]$$

$$* \frac{MATP * LABCST * (1-T) * NSPY * CEF * PUEF}{(R-T * DPPA)} \quad (6.16)$$

Figure 6.4: System Volume Boundaries versus Station Price for Assembler Part Assembly Time of 3 Seconds



This is a general solution; the assumptions concerning the values of the parameters have been removed. If this constraint is not satisfied for an individual assembler, then assembly systems made from sets of that assembler will not be economic compared to manual or transfer machine methods, on the average. Furthermore, the lower the station price-time product is below this constraint, the larger the range of economic applicability.

This is an important result because it relates properties of an assembler to the economics of systems composed on that assembler compared to both manual and transfer machine methods. This single result bridges the gap between individual assembler design and assembly systems, it describes the effects of competition with both manual and transfer machine assembly, and it does this for products with different numbers of parts. Later in this thesis STAP*PARTTIME, the "price-time product," will be used as a measure of assembler design. The inequality expressed in equation 6.16 forms a bounding criterion for economically acceptable designs, and the minimization of the price-time product will be used as an assembler design objective.

Using the data of the example we find

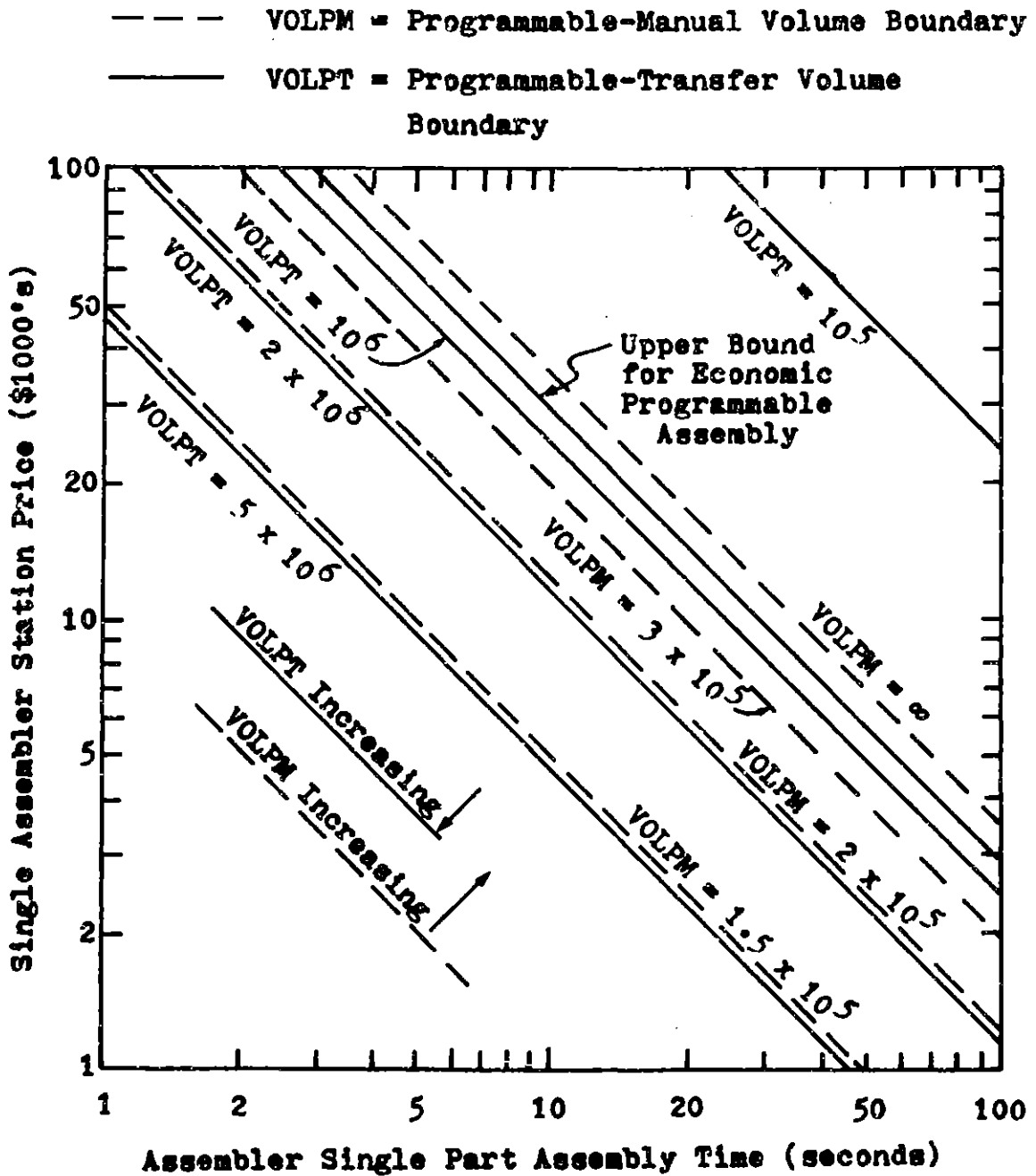
$$\text{STAP*PARTTIME} < 2.93 \cdot 10^5 \text{ \$-sec} \quad (6.17)$$

In other words, if the product of the programmable sta-

tion price and the part time were greater than $2.93 \cdot 10^5$ \$-sec, then the programmable system could not compete with a manual line or a transfer machine or maybe both. If stations cost \$125,000 each then they would have to assemble parts at least at the rate of one every 2.34 sec to be economic compared to manual or transfer machine assembly or both. (Of course, it should be remembered that the numbers used here are only plausible example numbers and, at that, only apply to a product size range of about eight inches. Actual values in specific situations will vary.)

In Figure 6.5 is a plot of constant system volume boundaries for different combinations of individual programmable station price and part assembly time for the example. Individual station price is plotted on the vertical axis and single part assembly time is plotted horizontally. Any combination of station price and part assembly time corresponds to a certain point in the plane. Once the point is plotted, interpolation between the lines of constant boundary volume will give estimates of the upper and lower system boundary volumes. The line corresponding to the constraint on station price - part time product, equation (6.16), is indicated. Points above this line represent uneconomic programmable assembly. This constraint line occurs where the programmable to manual boundary volume is equal to the programmable - transfer boundary volume.

Figure 6.5: Example System Volume Boundary Chart



To illustrate how to use the chart, notice that a programmable assembly system constructed of stations needing 5 sec per part and costing about \$24,000 each would be economic for a range of production from 200,000 to 2,000,000 per year. Also notice that a system having stations with 5 sec assembly time costing \$100,000 each is not economic. Remember that this analysis applies to products with any number of parts. Figure 6.5 contains purely economic analysis, assuming all combinations of station price and part assembly time are possible. Of course, there are engineering constraints and relationships that relate the station price to the part assembly time, the size of the station and its number of degrees of freedom, and so on. There may be lower practical bounds on the part assembly time. A chart like Figure 6.5 can help to assess the economic consequences of these technological relationships.

6.2 Hybrid Alternate Models

In the previous sections we have examined the "pure" alternate methods of assembly. There are two important combinations of these methods that have special interest.

In the hybrid programmable—transfer system, some parts are assembled by programmable technology and others with transfer technology. This is of interest especially

where the transfer assembly technology is almost capable of handling the assembly economically except for certain tasks which require programmability.

Hybrid transfer—manual assembly represents a currently common method, especially in non-synchronous indexing systems. In the design of a transfer-manual system for a product, the assembly of each part is evaluated with respect to manual or transfer machine assembly and then the most economic method is used for that part.

Both of the hybrid approaches will be evaluated from the viewpoint of the simple model to determine conditions of economic applicability.

6.2.1 Modeling Hybrid Transfer-Programmable Assembly

There are three distinct sections of the hybrid transfer-programmable assembly system as modeled here.

1. Programmable assembly stations. Each station may assemble one or more parts to the product.
2. Transfer machine assembly stations. Each of these stations assembles one part to the product and is not programmable.
3. Parts feeding tooling. Each part has a set of parts feeding tooling associated with it. The tooling may be connected to a transfer machine station or a programmable station. A program-

mable station will have tooling for as many parts as it assembles sequentially; a transfer machine station will have the parts feeding tooling only for the one part associated with it.

These sections form the major components of the original cost of the hybrid system. This cost may be modeled as follows:

$$HCST = NSTA*STAP + NPPRT*TOLPP + (NPART-NPPRT)*TMCPP \quad (6.18)$$

where HCST = hybrid system cost
 NSTA = number of programmable stations
 STAP = programmable station price
 NPPRT = number of parts assembled by programmable stations
 TOLPP = parts feeding tooling price per part
 TMCPP = transfer machine cost per part

It will be assumed that the assembly rate will be governed by the programmable stations. This is because the programmable station will probably have a longer single part assembly time than a transfer station. Even a dual programmable station--one in which two single stations are operating in parallel--will probably have a longer effective single part assembly time than a transfer station. The transfer station times are quick because the motions are short and simple and identical. Because the programmable station will have a more complex mechanism and control

function to increase its versatility, it will very likely take longer at any specific task than a transfer machine station specifically designed for it.

If the programmable stations are allowed to pace the entire system, then in some sense the transfer stations are not working at their maximum production rate and the system is not balanced. However, the simple model for the unit assembly cost by transfer machine does not take into account the production rate of the transfer machine except to assume that it is sufficient to meet annual production requirements. The unit assembly cost is obtained by directly charging the cost of the machine to the units actually produced.

As far as determining the unit assembly cost (due to the capital investment) is concerned, the actual production volume is the only volume that matters. To know that certain stations or even the entire system could operate faster does not change their contribution to the unit assembly cost.

The unit assembly cost for a hybrid system may be divided into two parts: One part of the cost comes from the programmable stations and the other part comes from the transfer machine stations. The hybrid system may be regarded as a programmable assembly system interwoven with a transfer machine system. To compute the total unit assembly costs we may add the unit assembly cost from

both parts.

$$\text{HTPCPU} = \text{HPCPU} + \text{HTCPU} \quad (6.19)$$

where HTCPU = hybrid transfer-programmable cost
per unit

HPCPU = unit assembly cost component due to
programmable assembler stations and
associated feeding equipment

HTCPU = unit assembly cost component due to
transfer machine stations.

The unit assembly cost component due to the programmable
stations is

$$\text{HPCPU} = \frac{\text{NPPRT}}{(1-T)} \left[\frac{\text{STAP} * \text{PARTTIME} * (R-T * \text{DPPA})}{\text{NSPY} * \text{CEF} * \text{PUEF}} + \frac{\text{TOLPP} * (R-T * \text{DPTL})}{\text{VOL}} \right] \quad (6.20)$$

where HPCPU = unit assembly cost component due to
programmable assembly subsystem

Here the variables are defined as they were for the purely
programmable system.

The unit assembly cost component due to the transfer
stations is

$$\text{HTCPU} = \text{TMCPP} * (\text{NPART} - \text{NPPRT}) * \frac{(R-T * \text{DPTM})}{\text{VOL} * (1-T)} \quad (6.21)$$

where HTCPU = unit assembly cost component due to
transfer machine stations.

Here, it is assumed that the number of parts assembled by
transfer machine stations is equal to the total number of
parts in the product minus the number of those parts assem-

bled by programmable stations. The rest of the variables are defined as they were for the pure transfer machine assembly system. However, the hybrid unit assembly cost can also be related to the unit cost for a pure programmable system that assembles all the parts and the unit cost for a pure transfer machine system that assembles all the parts by substituting equations (6.20) and (6.21) into (6.19) and then isolating the pure programmable and pure transfer system costs.

$$HCPU = \frac{NPPRT}{NPART} * PCPU + \left(1 - \frac{NPPRT}{NPART}\right) * TCPU \quad (6.22)$$

Notice that the weighting factors $\frac{NPPRT}{NPART}$ and $\left(1 - \frac{NPPRT}{NPART}\right)$ are less than or equal to one and also sum to one.

Equation (6.22) can be reduced somewhat by defining a programmability ratio; that is

$$HCPU = PRATIO * PCPU + (1 - PRATIO) * TCPU \quad (6.23)$$

where $PRATIO = NPPRT/NPART =$ programmability ratio (6.24)

PRATIO is the number of parts assembled at programmable stations divided by the total number of parts. If PRATIO = 1 then the hybrid system corresponds to a purely programmable one. If PRATIO = 0 then the hybrid system is a transfer machine.

An initial examination of equation (6.23) might lead one to conclude that a hybrid system could never be economic because either a purely programmable system or a pure

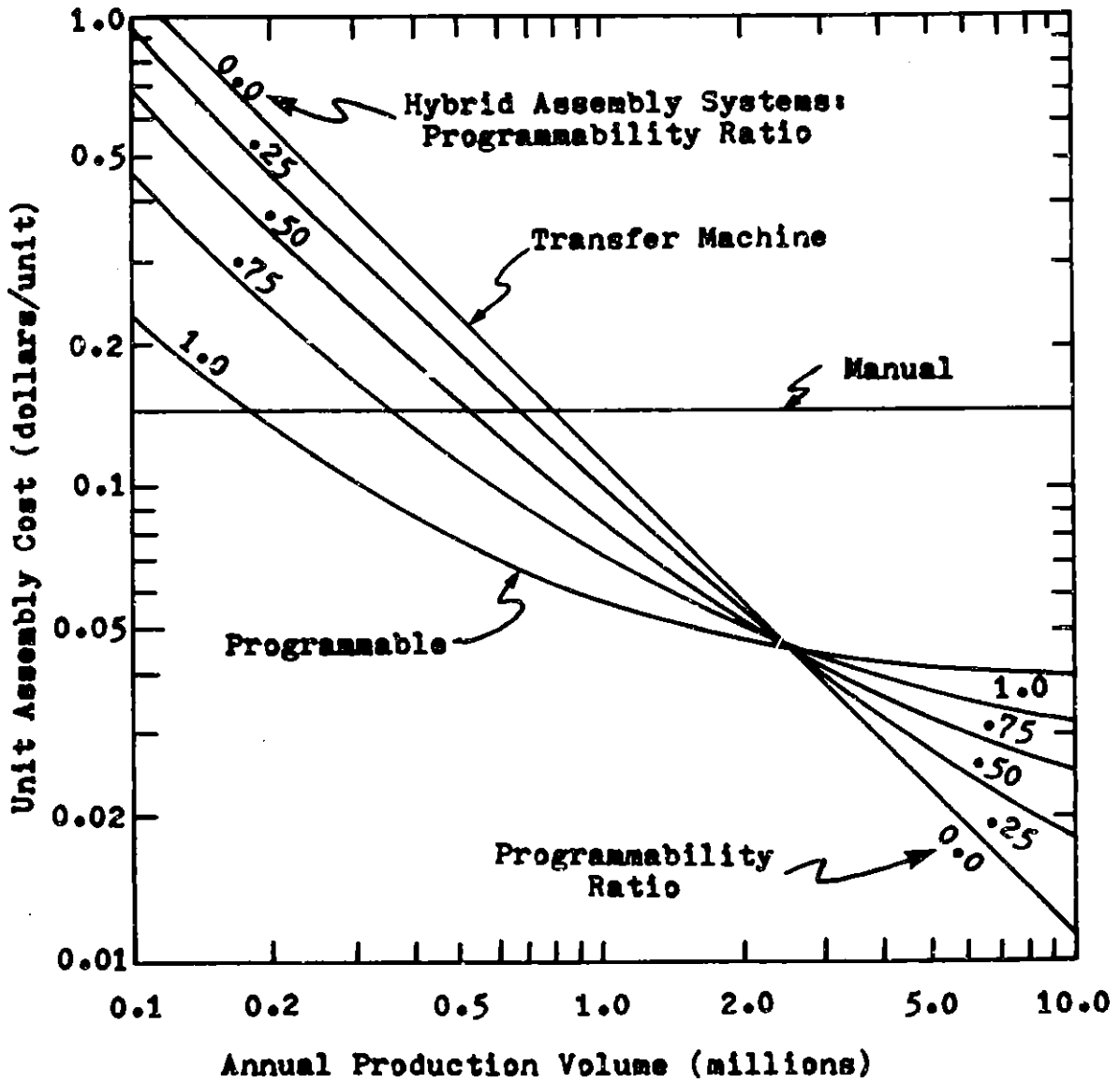
transfer machine system would produce a lower assembly cost. This would be true so long as the production volume VOL in the equations represented a single uniform product.

But if VOL represents a family of products which have some common parts but some different parts, then a single transfer machine may not be technically feasible for the entire product family. Specifically it may not be possible to build the transfer machine to handle the parts that are different from member to member in the product family.

But this part variation between product family members does not affect the application of the purely programmable system. Within the limits of its programmability, it can handle the varying parts. A hybrid system could also handle the entire product family if programmable stations are used to handle the parts that vary between members of the product family. The parts that are the same for all the members of the product family could be assembled by transfer machine stations or programmable ones, whichever is more economical.

A plot of assembly cost per unit versus production volume, VOL, for different methods is shown in Figure 6.6. The numerical values correspond to the example previously developed in section 6.14. It should be remembered that the following values simply represent plausible numbers for illustrative purposes only and are not necessarily accurate estimates of the true mean values.

Figure 6.6: Comparison of Hybrid Transfer-Programmable Assembly Systems



NPART = 10

STAP = \$30,000

TOLPP = \$7500

TMCPP = \$30,000

PARTTIME = 3 sec/part unit

LABCST = \$7.50/hour = 2.0833×10^{-3} \$/sec/worker

MATP = 7 sec/part unit

NSPY = 1.152×10^7 sec/yr (2 shifts, 250 days/yr,
uptime = .8)

DPPA = .125 per yr

DPTL = .25 per yr

DPTM = .10 per yr

T = .48

R = .25 per yr

Cost curves for manual, programmable, hybrid, and transfer machine production are shown. For the hybrid configuration, curves for different values of programmability ratio are shown. It can be seen that a region where manual assembly is best extends up to a certain production volume, 1.73×10^5 . Between this boundary volume and a higher boundary volume at 2.60×10^6 , the purely programmable system is most economical. It is even more economical than a hybrid system. This programmable range is the same one that would exist if the programmable system were competing with only manual and pure transfer machine methods. The reason is that the total

cost of the pure programmable system is less than the transfer machine cost in this range. This is primarily due to the fact that programmable stations are used to assemble more than one part, resulting in fewer total number of stations. If transfer machine stations were used to replace some of the stations of the purely programmable system, the total system cost would increase because more transfer machine stations would have to be added than the number of programmable stations replaced.

Beyond the upper bound of the programmable range any hybrid system (i.e., $0 \leq \text{PRATIO} < 1$) is better than the purely programmable system. This is because the higher volume requirements limit the number of parts that can be assembled at each programmable station, bringing up the programmable system cost per part above the transfer machine cost per part. Systems with low programmability ratio are the most economical because they have fewer of the more expensive programmable stations—they are more like the transfer machine.

The production volumes are high in this region where hybrid systems form the most economic alternative. This means that the programmable stations in a hybrid system will have relatively few parts per station. In fact, in certain circumstances, it may be necessary to use parallel stations for the programmably assembled parts in order to meet the production requirements.

For lower assembly costs, as much of the hybrid system as possible should consist of transfer machine technology in this volume range. In fact, if a transfer machine can be built to handle the product, it will be the most economical alternative. It is the characteristics of the product or product family that will determine whether a transfer machine is technically feasible, or whether programmability is required and how much.

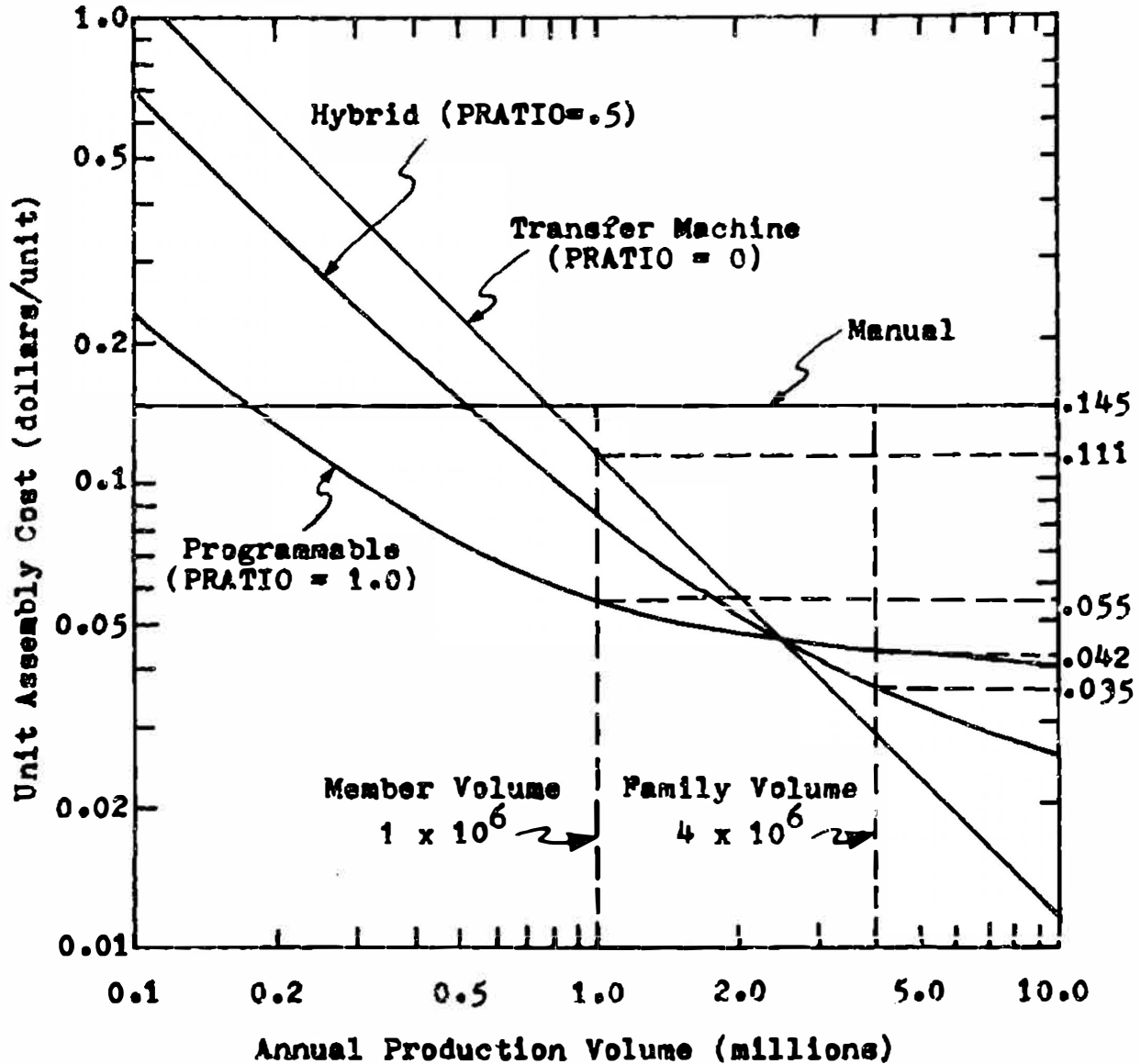
The required degree of programmability of the appropriate hybrid system would depend on the variation between members of the product family. If only a small fraction of the parts actually vary between members then only a small degree of programmability is needed because only certain assembly operations need it.

The potential cost saving resulting from hybrid and purely programmable systems for product families is illustrated by an example shown in Figure 6.7. The system parameters for this example are the same as for Figure 6.6. The example product family has four members, each with annual volume of 1×10^6 . The number of parts in the product is ten, and the programmability ratio of the product family is assumed to be .5, that is, one-half of the parts in the product differ in their assembly operations between the four members.

The dashed lines in Figure 6.7 point out the assembly costs of different assembly methods for this example. These

Figure 6.7: Example of Savings of Hybrid Transfer-Programmable System on Product Family

Assumes hypothetical product with 10 parts



Product family has four members, each with annual volume = 1×10^6 . Programmability ratio assumed equal to 0.5.

costs are:

Manual assembly	.]45 \$/unit
Four pure transfer machines, one for each member	.111 \$/unit
Four pure programmable systems, one for each member	.055 \$/unit
One pure programmable system for all members	.042 \$/unit
One hybrid system, PRATIO = .5, for all members	.035 \$/unit

These costs represent only those due to the capital equipment investment in the assembly machinery or the pure labor rate in manual assembly. In a real system that assembles more than one product in a product family, there will be costs associated with the changeover process when production of one member is halted and another begun. The labor cost of production workers who must tend the machines and are idle during changeover and the labor cost of the workers who effect the changeover are some of the changeover costs. Since the capital equipment does not change with every changeover, and since the annual production volume does not change with the changeover, that component of assembly unit cost due to the capital investment is not affected by the individual changeover process. (Since changeover time is a non-productive time, it might be considered a form of "non-assembly time." Therefore,

its effects on system design may be approximated by reduced configuration efficiency as described in section 5.3.) For all five of the systems tabulated above, there will be changeover costs. Typically the changeover costs should be least for the manual assembly, greatest for the transfer machine assembly, and intermediate for the programmable and hybrid systems. The annual changeover costs will depend heavily on other factors not considered yet such as the number of changeovers per year. To evaluate the effect of changeover costs would require a much more detailed examination and so will not be treated in this simple model.

To estimate the potential savings for hybrid and programmable systems, it is necessary to know or estimate the present assembly cost. In the case of the example, assuming programmability were not available, the obvious choice is four transfer machines since this alternative is cheaper than manual assembly. With programmability, the obvious choice is the hybrid system. The savings of the hybrid over the four transfer machines is .076 \$/unit, or 68 percent. If the product family had been fragmented into more than ten members so that each member had less than $.6 \times 10^6$ annual volume, then manual assembly would have been the obvious non-programmable choice. Then the savings with the hybrid system would be .11 \$/unit, or 76 percent. (This assumes PRATIO = .5 as before.)

Under the assumption of the simple model the source of cost savings for hybrid programmable-transfer systems is different than for pure programmable systems. In the volume range where it is most economic, the hybrid system represents a greater initial investment than a transfer machine, but it obtains unit assembly cost savings by extending the applicability of the assembly system over a larger volume of production than a simple transfer machine would be technologically capable of. The appropriate production volume is the volume of the product family and not of just a uniform product.

6.2.2 Modeling Hybrid Transfer-Manual Assembly

Another important hybrid assembly method is the combination of manual assembly and transfer machine assembly. This combination can be modeled by the same method that was used in the modeling of the hybrid transfer-programmable assembly. The parts of the product are divided into those that are assembled manually and those that are assembled by transfer machine stations. The cost of assembly for each subset is computed and added together to obtain the total cost of assembly per unit.

The cost of the transfer machine stations can be modeled as

$$TSTCST = NPT * TMCPP \quad (6.25)$$

where $TSTCST$ = total cost of the transfer stations
 NPT = number of parts assembled by transfer stations.

The assembly cost per unit for the subset of parts assembled by the transfer machine stations is obtained by analogy with equation (6.9) of section 6.12.

$$TSCPU = \frac{NPT * TMCPP * (R - T * DPTM)}{VOL * (1 - T)} \quad (6.26)$$

where $TSCPU$ = the unit assembly cost for the parts assembled by the transfer stations

The manual cost per unit is simply the manual cost of assembly for the remaining parts in the product.

$$MSCPU = MATP * LABCST * (NPART - NPT) \quad (6.27)$$

where $MSCPU$ = unit assembly cost for the parts assembled manually.

The total unit assembly cost for the hybrid system is the sum of the manual and transfer station costs.

$$HTMCPU = MSCPU + TSTCPU \quad (6.28)$$

where $HTMCPU$ = unit assembly cost for the hybrid transfer-manual system.

We now seek to relate the unit assembly cost of the hybrid transfer-manual system to the unit assembly costs for a pure programmable system and a pure transfer system operating at the same production volume.

First, it is convenient to define a transfer ratio

as the number of parts assembled by the transfer stations divided by the total number of parts in the product.

$$\text{TRATIO} = \frac{\text{NPT}}{\text{NPART}} \quad (6.29)$$

where TRATIO = transfer ratio

We now combine equations for the manual and transfer machine unit costs with the definition of the transfer ratio to obtain an expression for the unit assembly cost for the hybrid transfer-manual system.

$$\text{HTMCPU} = \text{NPART} * (\text{TRATIO} * \text{TCPU} + (1. - \text{TRATIO}) * \text{MCPU}) \quad (6.30)$$

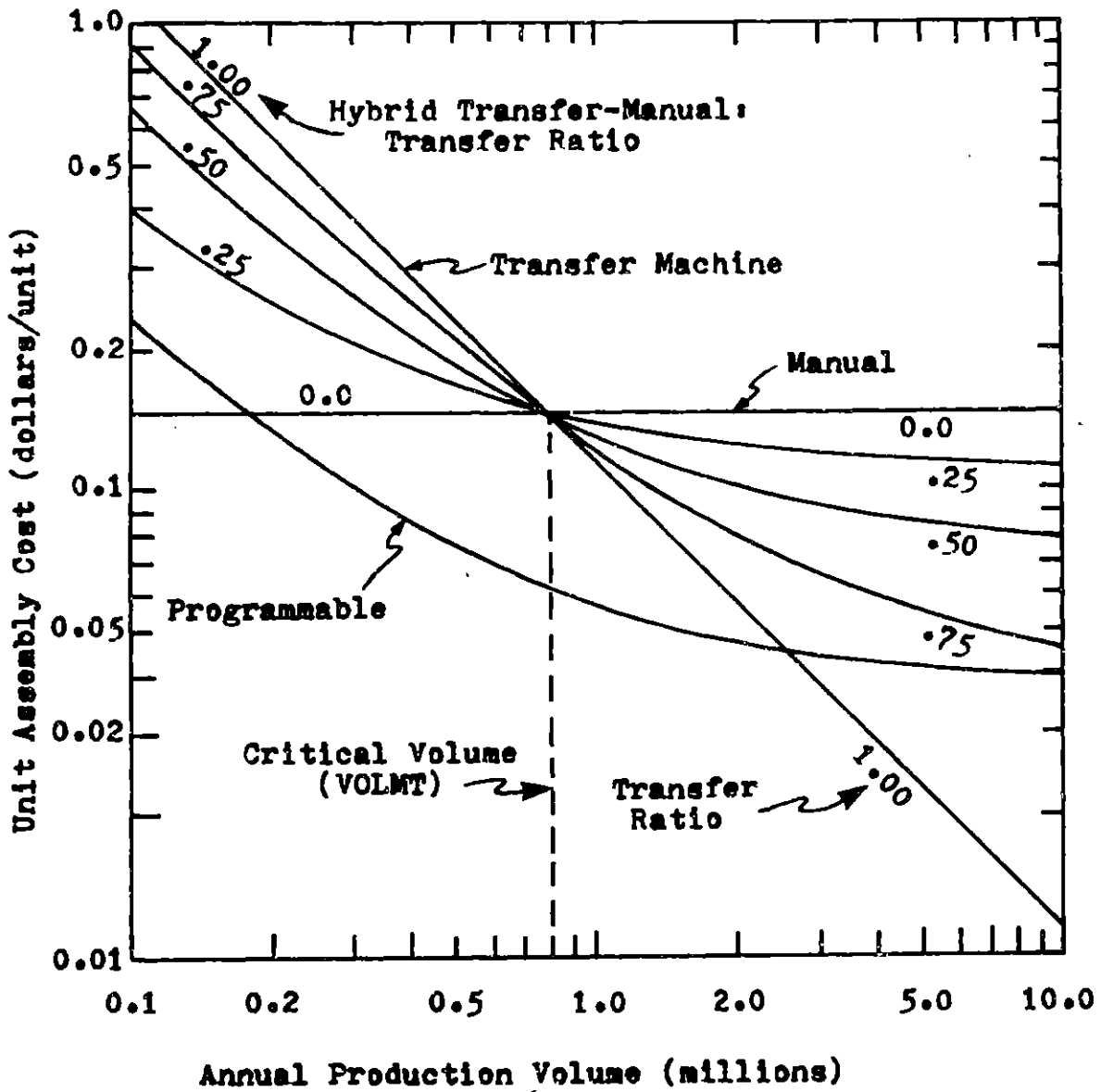
where TCPU = unit assembly cost for a transfer machine operating at the desired production volume

MCPU = unit assembly cost for a manual assembly line operating at the desired production volume.

Figure 6.8 shows an example of curves of unit assembly cost plotted against production volume for the variable values used in the examples of the previous sections. The values are merely plausible estimates of the typical values. The model is not sufficiently detailed to predict costs in individual cases.

The curves indicate that there is a critical value of production volume. For products with volumes below this value, pure manual assembly is the cheapest method,

Figure 6.8 Comparison of Hybrid Transfer-Manual Assembly Systems



even cheaper than the hybrid transfer-manual method. Above this critical value, a pure transfer machine is the most economic alternative. This critical value is the manual-transfer volume boundary derived in section 6.1.5:

$$\text{VOLMT} = \frac{\text{TMCPP} * (\text{R} - \text{T} * \text{DPTM})}{\text{MATP} * \text{LABCST} * (1 - \text{T})} \quad (6.31)$$

where VOLMT = volume boundary between economic manual and transfer machine systems.

For the example values of the parameters,

$$\text{VOLMT} = .799 \times 10^6 \text{ product units/year} \quad (6.32)$$

Since for any production volume under consideration either pure manual assembly or pure transfer machine assembly seems most economic, then it appears that hybrid transfer-manual assembly would never be most economic. But, this conclusion depends on certain assumptions of uniformity that are inherent in this "average" model; for example, that a transfer machine actually can be built to assemble any product, that the manual assembly cost per part is the same for all parts, and that the transfer machine cost per part is also the same for all parts.

However, assembly tasks vary in their susceptibility to transfer machine assembly. Some tasks are either impossible to do by transfer machine methods or would require very expensive equipment. With a knowledge of transfer machine technology and an examination of the product, one could estimate the minimum number of parts

that should be assembled by hand and the corresponding maximum number of parts that could be assembled by the transfer machine stations. This defines a practical upper limit on the transfer ratio $TRATIO$ of the transfer-manual system. If we now examine Figure 6.8 we see that for products with production volumes less than the critical value, manual assembly remains the most economic alternative. This is because manual assembly of any of the parts, including the ones that could be assembled by a transfer machine station, is the cheapest method. For products with production volumes greater than the critical value, the hybrid transfer-manual system with the highest feasible transfer ratio is the most economic alternative. This result is true for classes of products with the same transfer ratio; that is, the model predicts that products with a given transfer ratio, say .5, will, on the average, be assembled most economically by pure manual methods for production volumes less than the critical volume $VOLMT$. For production volumes above the critical value, hybrid systems with transfer ratio equal to .5 are the most economic, on the average.

In practice other factors will influence the design of individual transfer-manual systems. The modeling presented here is intended to describe average costs and to identify general classes of applications. Individual system designs will deviate one way or another from the

average depending on the particular circumstances.

6.3 Improved Simple Economic Models

The simple economic models developed in the preceding sections have been especially useful in that they have led to the identification of the price-time product as a measure of assembler economic performance. Constraints and system economic volume boundaries have been analyzed and expressed in terms of this measure. The concept of the assembler price-time product will be developed more fully in the next chapter.

In the following section certain improvements are made to the simple economic model. Many improvements could have been made, but the ones made here represent what the author feels are the most important additions that sacrifice a minimum of model simplicity. These improved models will be used to repeat quickly the volume and constraint analysis of section 6.1.5 to see if significant changes in the form of the equations will result and to see if significant numerical differences occur in the results of the example model. The improved model will give results which are somewhat less favorable to programmable assembly but which on the whole reinforce the results of the simple model.

6.3.1 Manual Assembly with Equipment Costs

Only rarely will people be used to assemble a product with no tools or support equipment. Consequently, the unit assembly cost formula for manual assembly from the simple model gives an estimate lower than the actual assembly costs. We now add the cost of the manual assembly equipment to the basic manual assembly labor cost.

This improved model of the manual assembly cost per unit is meant only to provide a more accurate estimate of the true unit assembly cost by including the effects of the equipment that is used. It does not refer to improved manual assembly performance because of the addition of better equipment.

It will be assumed that the cost of the manual assembly equipment is roughly proportional on the average to the number of parts in the product. This is plausible because the support equipment is likely to be different for each part and probably can be used as rapidly as the operator can use it. The manual equipment cost is modeled as follows:

$$\text{MECST} = \text{MECPP} * \text{NPART} \quad (6.33)$$

where MECST = total manual equipment cost

MECPP = manual equipment cost per part

To allocate the equipment cost to the production units the same rate of return is used that was applied in the simple model to the programmable and transfer machine

systems.

$$\text{MECPU} = \text{MECPP} * \text{NPART} + \frac{(\text{R}-\text{T} * \text{DPME})}{\text{VOL} * (1-\text{T})} \quad (6.34)$$

where MECPU = manual equipment cost per unit

R = required rate of return

T = tax rate

DPME = annual straight line depreciation rate
for the manual equipment.

Now, the manual equipment cost per unit, equation (6.34), is combined with the manual labor cost per unit, equation (6.1), to obtain the improved estimate of the manual unit assembly cost.

$$\text{MCPUI} = \text{NPART} * \text{MATP} * \text{LABCST} + \frac{\text{MECPP} * (\text{R}-\text{T} * \text{DPME})}{\text{VOL} * (1-\text{T})} \quad (6.35)$$

where MCPUI = manual unit assembly cost, improved model.

Notice that the unit assembly cost is still proportional to the number of parts in the product, but now the manual cost is not independent of volume. A comparative example will be presented in a subsequent section.

6.3.2 Transfer Assembly with Labor Costs

No transfer machine can run entirely by itself. It must be tended, perhaps only occasionally, by one or more workers. In the case of transfer assembly machines,

these workers are responsible for supplying some or all of the parts to the feeding equipment on the machine. They must also clear the jams in the feeding equipment and the actual assembly equipment.

The number of workers assigned to a transfer machine varies widely and does not depend solely on the characteristics of the machine. Sometimes the local work agreements will influence the assignment. The stockman who refills feeding devices may be a different worker from the one that actually performs assembly or operates assembly equipment. Also, there is a tendency to have at least one whole worker assigned to a new type of machine. Hence, one new assembly machine may have one whole worker assigned to it even though it requires only a half or a quarter of a worker's attention (i.e., only one job of a worker who has more than one job). But, if more similar machines are added, that same single worker will tend them all until he reaches a true load limit (or a work rule limit). This may have the effect of using more labor than necessary at small assembly system installations. For the purposes of this model it will be assumed that the number of workers required is proportional on the average to the number of parts in the product.

$$\text{NWRKR} = \text{NPART} * \text{NWPP} \quad (6.36)$$

where NWRKR = number of workers assigned

NWPP = number of workers assigned per part

The total annual labor cost depends on the number of hours that the system transfer machine must be run in order to meet the required annual production volume. This time must take into account the effect of downtime. The first step is to model the total annual operational time.

$$TOPT = \frac{TTIME * VOL}{UT} \quad (6.37)$$

where TOPT = total annual transfer machine operational time, sec

TTIME = average time between the production of single product units, sec

UT = uptime ratio of the transfer machine

Here, TTIME represents the average time between the assembly of single product units on a transfer machine, and so it corresponds to the INDEXTIME variable used in section 5.3.2 to describe the time between product units on the programmable system.

For the purposes of this model, the same uptime ratio will be assumed for the programmable and transfer machine systems. (This assumption is a matter of convenience. The programmable system should have greater uptime than the transfer machine as discussed in section 4.2.3).

The annual labor cost is obtained by multiplying the total operational time by the number of workers and the labor cost rate per worker per second, LABCSST.

$$ATLCST = \frac{NPART * NWPP * TTIME * VOL * LABCSST}{UT} \quad (6.33)$$

where $ATLCST$ = annual labor cost for transfer machine operation.

This annual cost must be allocated over the annual production volume of the product.

$$TLCPU = \frac{ATLCST}{VOL} \quad (6.39)$$

where $TLCPU$ = transfer machine labor cost per unit. Equation (6.39) may be combined with equation (6.38) to obtain

$$TLCPU = \frac{NPART * NWPP * TTIME * LABCSST}{UT} \quad (6.40)$$

Finally, the improved estimate of the transfer machine cost per unit is obtained by adding the unit cost due to the equipment investment from the simple model, equation (6.9), to the labor cost per unit, equation (6.40) above.

$$TCPUI = NPART * \left[\frac{TMCPP * (R - T * DPTM)}{VOL * (1 - T)} + \frac{NWPP * TTIME * LABCSST}{UT} \right] \quad (6.41)$$

where $TCPUI$ = improved estimate of the unit assembly cost for the transfer machine.

This improved estimate of the transfer machine unit assembly cost is still proportional to the number of parts in the product. An illustrative example will be presented in a subsequent section.

6.3.3 Programmable Assembly with Labor Costs

Just as in the case of the transfer assembly machine, no programmable assembly system will be able to operate without human intervention. The workers that tend the programmable system will be performing many of the same functions as the workers that tend the transfer machine system. They will be clearing jams in the parts feeding equipment and also will be supplying some or all of the parts to the parts feeding equipment. Because of the programmability, the assemblers should have the ability to sense certain jams at the assembly site before significant damage is done and take appropriate clearing action on their own in many cases. This will act to reduce the total downtime.

In order to model the labor cost in operating a programmable assembly system, it will be assumed that the attending workers will be paid during both uptime and downtime just as in the case of the transfer machine system. Recall from Chapter 5 that the programmable utilization efficiency PUEF is the amount of time (including downtime) that a system requires to meet the production volume divided by the total amount of time that the system has available in the year. The programmable utilization efficiency can be used to model the total annual operational time for the programmable system.

$$\text{POPT} = \text{DY} * \text{HD} * 3600 * \text{PUEF} \quad (6.22)$$

where POPT = total yearly operational time for the
programmable system

DY = number of working days in the year

HD = number of working hours in the day

PUEF = programmable utilization efficiency

This equation may be simplified by using the variable NSPY representing the effective number of working seconds in the year. It was defined in equation(5.2) in the simple configuration modeling of Chapter 5.

$$NSPY = UT * DY * HD * 3600 \quad (5.2)$$

where NSPY = the effective number of working seconds
per year.

Using equation(5.2) in equation (6.42) above results in a simplified equation for the total annual operating time.

$$POPT = \frac{NSPY * PUEF}{UT} \quad (6.43)$$

Following the example of the labor analysis of the transfer machine, the number of workers assigned will be modeled as proportional to the number of parts in the product.

$$NWRKR = NWPP * NPART \quad (6.44)$$

where NWRKR = number of workers assigned

NWPF = number of workers assigned per part.

This is reasonable since these workers would be performing many of the same tasks that the workers who tend transfer machine systems would do--restocking the feeding equipment and clearing any jams of parts that may occur.

The total annual labor cost for the system is the product of the number of workers, the total work time, and the labor cost rate per second.

$$APLCST = \frac{NPART * NWPP * NSPY * LAB CST * PUEF}{UT} \quad (6.45)$$

where $APLCST$ = the annual labor cost for a programmable system

The labor cost attributed to each product unit is the annual labor cost divided by the annual volume.

$$PLCPU = \frac{NPART * NWPP * NSPY * LAB CST * PUEF}{UT * VOL} \quad (6.46)$$

where $PLCPU$ = the programmable system labor cost per unit of product.

Finally, we may combine the labor cost per unit of the programmable system, equation (6.46), with the programmable equipment cost per unit, equation (6.12), to obtain an improved estimate of the unit assembly cost of the programmable system.

$$PCPUI = NPART * \left[\frac{\frac{STAP * PARTTIME * (R - T * DPPA)}{NSPY * CEF * PUEF} + \frac{TOLPP * (R - T * DPTL)}{VOL}}{(1 - T)} + \frac{NWPP * NPY * PUEF * LAB CST}{UT * VOL} \right] \quad (6.47)$$

where $PCPUI$ = programmable cost of assembly per unit product for the improved model.

Notice in this formulation that the unit assembly cost is still proportional to the number of parts in the product. An example illustrating this equation follows in the next

section.

6.3.4 A Comparative Example Using the Improved Models

An example plot of unit cost of assembly against production volume for the three improved models of the production methods is shown in Figure 6.9. The values used for the variables in this example are illustrative only. They are meant to be plausible values but not necessarily accurate estimates of the true average values of the variables.

The assumed values of the variables are

NPART = 10 parts

STAP = 30,000 \$/station

PARTTIME = 3 sec/part unit/station

NSPY = 1.152×10^7 sec/year

PUEF = .95

CEF = .8

TOLPP = 7,500 \$/part

NWPP = .1 worker/part

UT = .8

LABCST = .0020833 \$/sec (= 7.50 \$/hour)

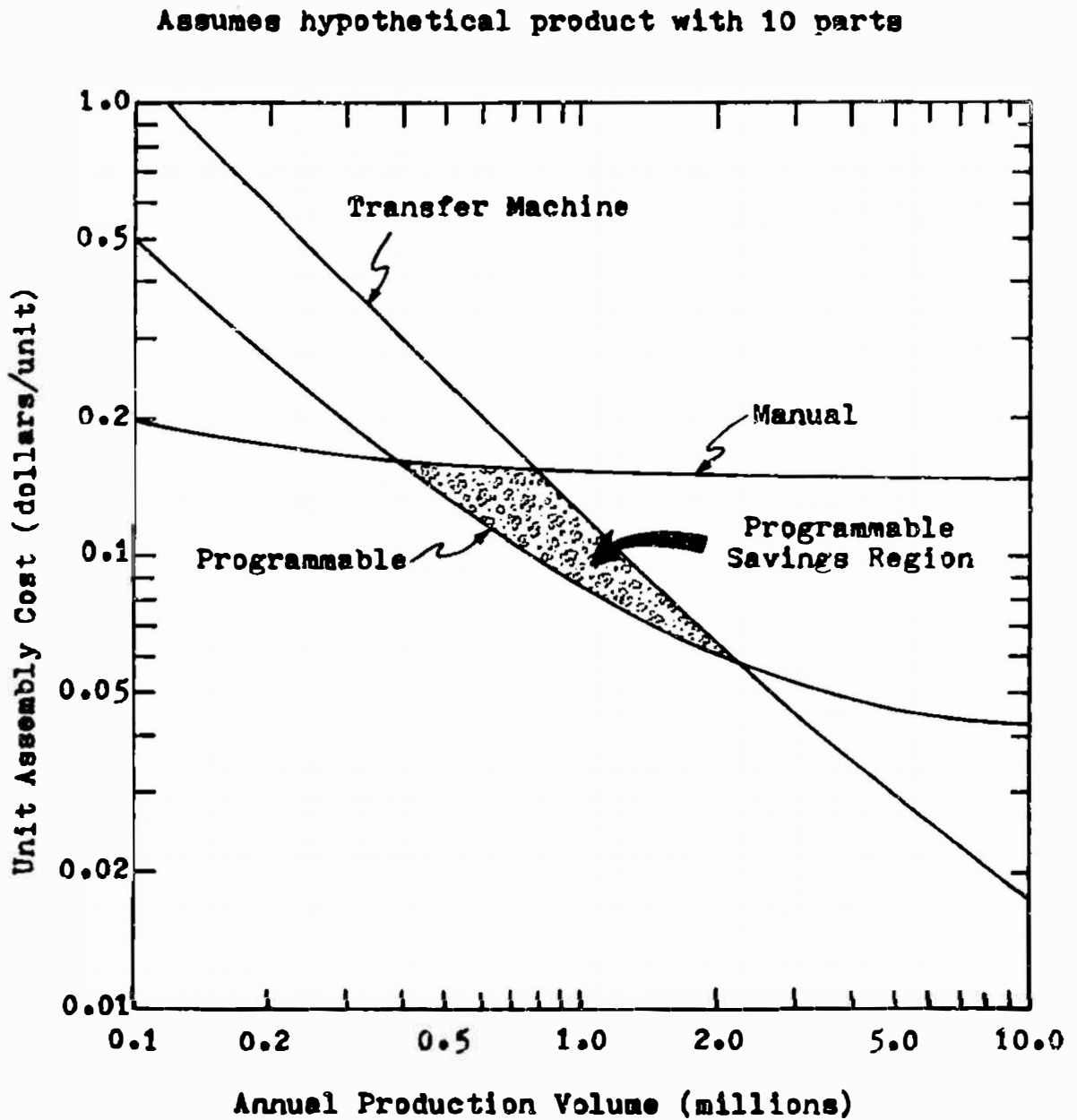
TMCPP = 30,000 \$/part

MATP = 7 sec/part unit/worker

MECPP = 2000. \$/part

TTIME = 2 sec/part unit

Figure 6.9: Comparison of Unit Assembly Costs using Improved Model



DPTM = .1 per year

DPPA = .125 per year

DPME = .25 per year

DPTL = .25 per year

T = .48

R = .25 per year

The variables presented above are essentially the same as the example variables discussed in section 6.1.4 with the exception of certain new variables introduced in the improved model.

The assignment of one worker for every ten parts being assembled both in the programmable and transfer systems is a guess; the actual numbers may vary widely depending on the work rules and the number of programmable systems installed in the factory. A transfer machine index time T_{TIME} of 2 seconds is typical, although many transfer systems can operate at twice this speed. Finally, a manual assembly equipment cost per part of \$2000 represents only a rough estimate of the cost of hand and power tools, work area, conveyer segment, and installation costs.

Notice that the general shape of the curves in Figure 6.9 is the same as those in Figure 6.2 for the simple model, except that the region in which programmable assembly is most economic is somewhat smaller. This comparison will be made more quantitative below with volume boundary analysis using the improved model.

When the improved model is used, the expressions for the volume boundaries and price-time product criterion are more complex, harder to handle, and harder to grasp intuitively. Consequently, only a compact set of volume boundary equations is presented here.

The improved model for the programmable, manual, and transfer cost per unit may be expressed in the following compact form:

$$PCPUI = NPART * \left[AP + \frac{BP}{VOL} \right] \quad (6.48)$$

$$MCPUI = NPART * \left[AM + \frac{BM}{VOL} \right] \quad (6.49)$$

$$TCPUI = NPART * \left[AT + \frac{BT}{VOL} \right] \quad (6.50)$$

where the constants are defined as follows:

$$AP = \frac{STAP * PARTTIME * (R - T * DPPA)}{NSPY * CEF * PUEF * (1 - T)} \quad (6.51)$$

$$BP = \frac{TOLPP * (R - T * DPTL)}{(1 - T)} + \frac{NWPP * NSPY * PUEF * LAB CST}{UT} \quad (6.52)$$

$$AM = MATP * LAB CST \quad (6.53)$$

$$BM = \frac{MECPP * (R - T * DPME)}{(1 - T)} \quad (6.54)$$

$$AT = \frac{NWPP * TTIME * LAB CST}{UT} \quad (6.55)$$

$$BT = \frac{TM CPP * (R - T * DPTM)}{(1 - T)} \quad (6.56)$$

The volume boundaries that divide the ranges of economic assembly as defined in section 6.1.5 for the simple model can now be expressed in terms of these constants here in the improved model.

$$\text{VOLMTI} = \frac{\text{BT}-\text{BM}}{\text{AM}-\text{AT}} \quad (6.57)$$

$$\text{VOLPMI} = \frac{\text{BP}-\text{BM}}{\text{AM}-\text{AP}} \quad (6.58)$$

$$\text{VOLPTI} = \frac{\text{BT}-\text{BP}}{\text{AP}-\text{AT}} \quad (6.59)$$

where VOLMTI = volume boundary between economic manual and transfer machine assembly, improved model

VOLPMI = volume boundary between economic programmable and manual assembly, improved model

VOLPTI = volume boundary between economic programmable and transfer machine assembly, improved model.

Finally, the constraint on the price-time product for an assembler can be determined in the case of the improved model. If an assembler has a price-time product above this value, then it cannot be used to create programmable systems that are economic compared to manual or transfer machine assembly, on the average. This was expressed in the simple model in equation (6.16). Following the same reasoning with the improved model, the constraint is

$$\text{STAP} * \text{PARTTIME} < \frac{\text{NSPY} * \text{CEF} * \text{PUEF} * (1-\text{T})}{(\text{R}-\text{T} * \text{DPPA})} * \left(\frac{\text{AT} * (\text{BP}-\text{BM}) + \text{AM} * (\text{BT}-\text{BP})}{\text{BT}-\text{BM}} \right) \quad (6.60)$$

Using the example values for illustration, the system volume boundaries and the price-time product constraint

have the following values in both the simple and improved models:

<u>Quantity</u>	<u>Improved Model</u>	<u>Simple Model</u>
Manual-transfer volume boundary	$.793 \times 10^6$ units/yr	$.799 \times 10^6$ units/yr
Programmable-manual volume boundary	$.390 \times 10^6$ units/yr	$.173 \times 10^6$ units/yr
Programmable-transfer volume boundary	2.14×10^6 units/yr	2.60×10^6 units/yr
Price-time product upper bound	2.23×10^5 \$-sec	2.93×10^5 \$-sec

At least for the example values, the effect of the improved model is to tighten the constraint on programmable assembly by slightly reducing the range in which programmable assembly is on the average most economic, and to lower the upper bound on the assembler price-time product. In general, however, the results are very similar to those of the simple model.

6.4 Summary

The economic modeling provides a framework which permits a number of results based on a consistent set of assumptions. Hence, not only does it model the three principal methods of assembly, but also it allows a comparison among them to understand how the applicability of programmable assembly depends on the economics of the other two methods

as well as its own. The model also provides a means of examining hybrid methods of assembly--combinations of the principal methods. The model identifies distinct volume ranges where the various alternate methods are each most economic and provides a way of examining the sensitivity of the economic production volume range of programmable assembly to general economic parameters, such as wage scales or the required rate of return.

The principal result of the economic modeling has been to identify the assembler price-time product as an important measure of assembler performance. The price-time product directly affects the unit assembly cost of programmable systems. The price-time product was also shown to affect directly the range of production volume for which programmable systems composed of a given assembler would be applicable. The economic analysis also provided a way of estimating bounds on the price-time product for economic assembler designs--designs which could compete with manual and transfer machine assembly. An example showed how this might be calculated for a specific case; other cases could be easily examined. The nature of the price-time product as a measure of assembler design will be examined more closely in the next chapter.

7. CONSEQUENCES OF THE ECONOMIC MODELS

Both the simple and improved models of the preceding chapter were developed to gain an understanding of how the general characteristics of assemblers influence the economics and application of programmable assembly systems.

The modeling framework provides a way of investigating the sensitivity of the economic applicability of programmable assembly to various economic parameters as well as the properties of an assembler. In the first section of this chapter we will examine how alternate values for the labor wage rate, the required rate of return, and the assembler price-time product affect the applicability of programmable assembly.

The chief measure of economic performance of an assembler to emerge from these models is the assembler price-time product. Having used the simple model to identify the price-time product as a measure of assembler economic performance under the severe simplifications of the simple model, we now examine the price-time product as a measure under less restrictive assumptions to see under what conditions it remains valid.

Finally, the relationship of the configuration efficiency to assembly system design will be examined.

7.1 Variation of Parameters of the Comparative Example

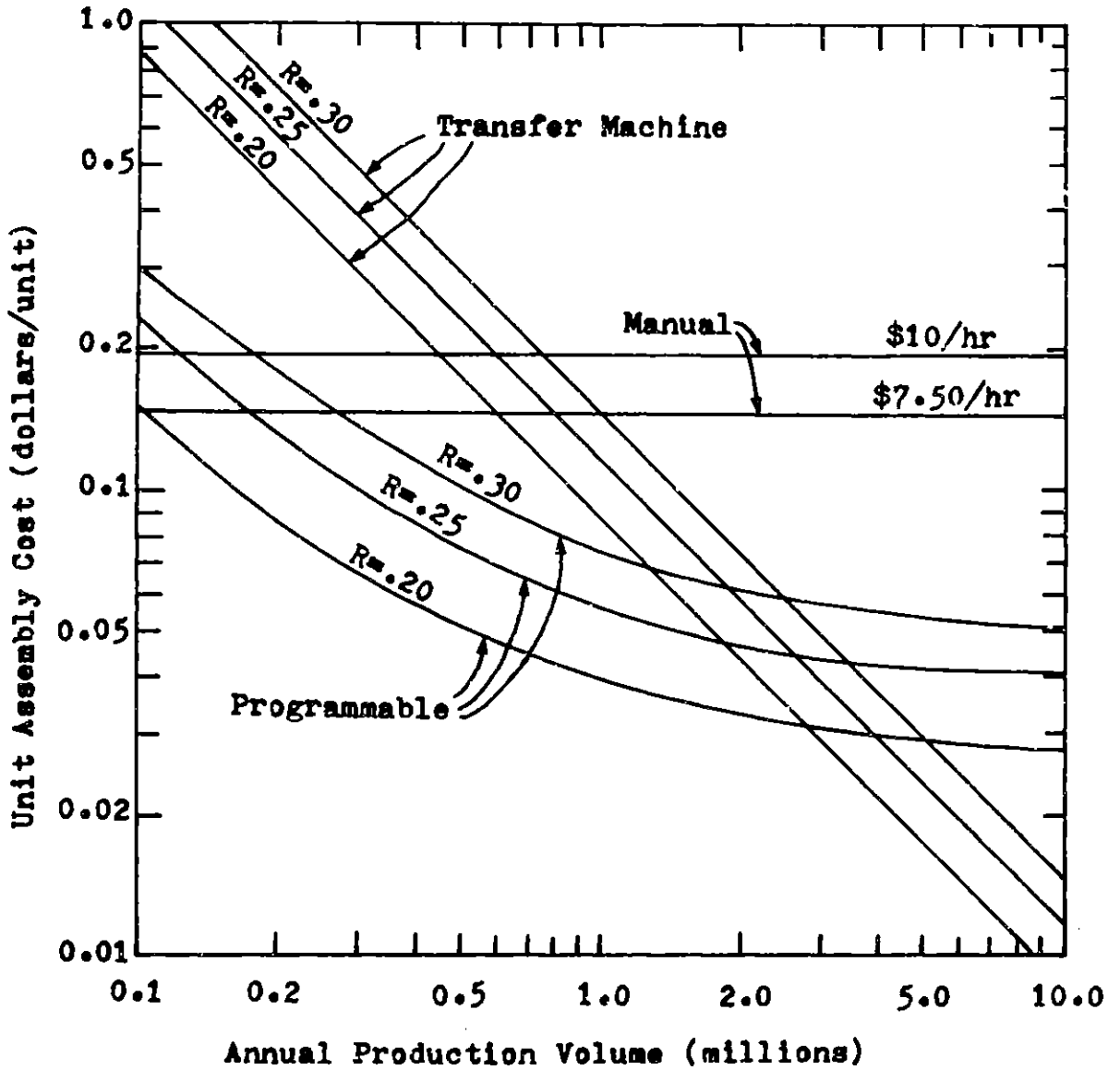
One use for the modeling framework developed in the previous chapter is to examine how the relative economics of the alternate assembly methods change with changes in important parameters. We now take a brief look at how changes caused by variations in the required annual rate of return, the labor rate, and the price-time product will appear in the context of the simple example developed in the previous chapter.

All values for the variables used in this example are the same as in the example developed in the previous chapter. However, the required minimum annual rate of return is allowed to have the values of .3 and .2 in addition to the value of .25 used before; the labor rate is allowed to have the value of \$10 per hour in addition to the value of \$7.50 per hour used before; and the price-time product is given the values of 50,000 \$-sec and 200,000 \$-sec in addition to the value of 90,000 \$-sec used in the example.

The results of the comparison are shown in Figures 7.1, 7.2, and 7.3. In Figure 7.1 are shown results for different rates of return and wage rates for assemblers with price-time product equal to \$90,000 \$-sec. As can be seen,

Figure 7.1: Comparison of Unit Assembly Costs with Price-Time Product Equal to 90,000 \$-sec

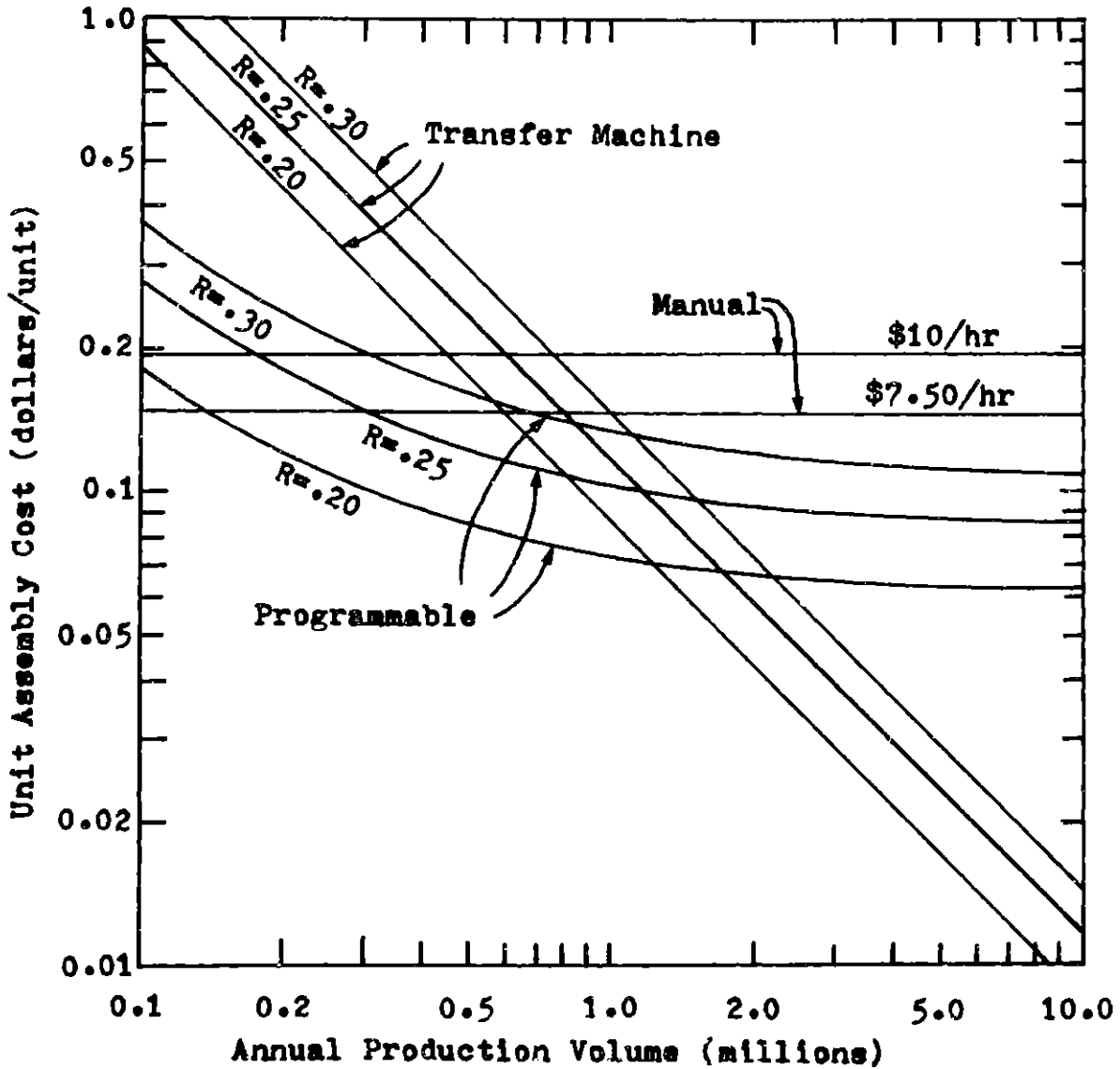
Assumes hypothetical product with 10 parts



R = required annual rate of return

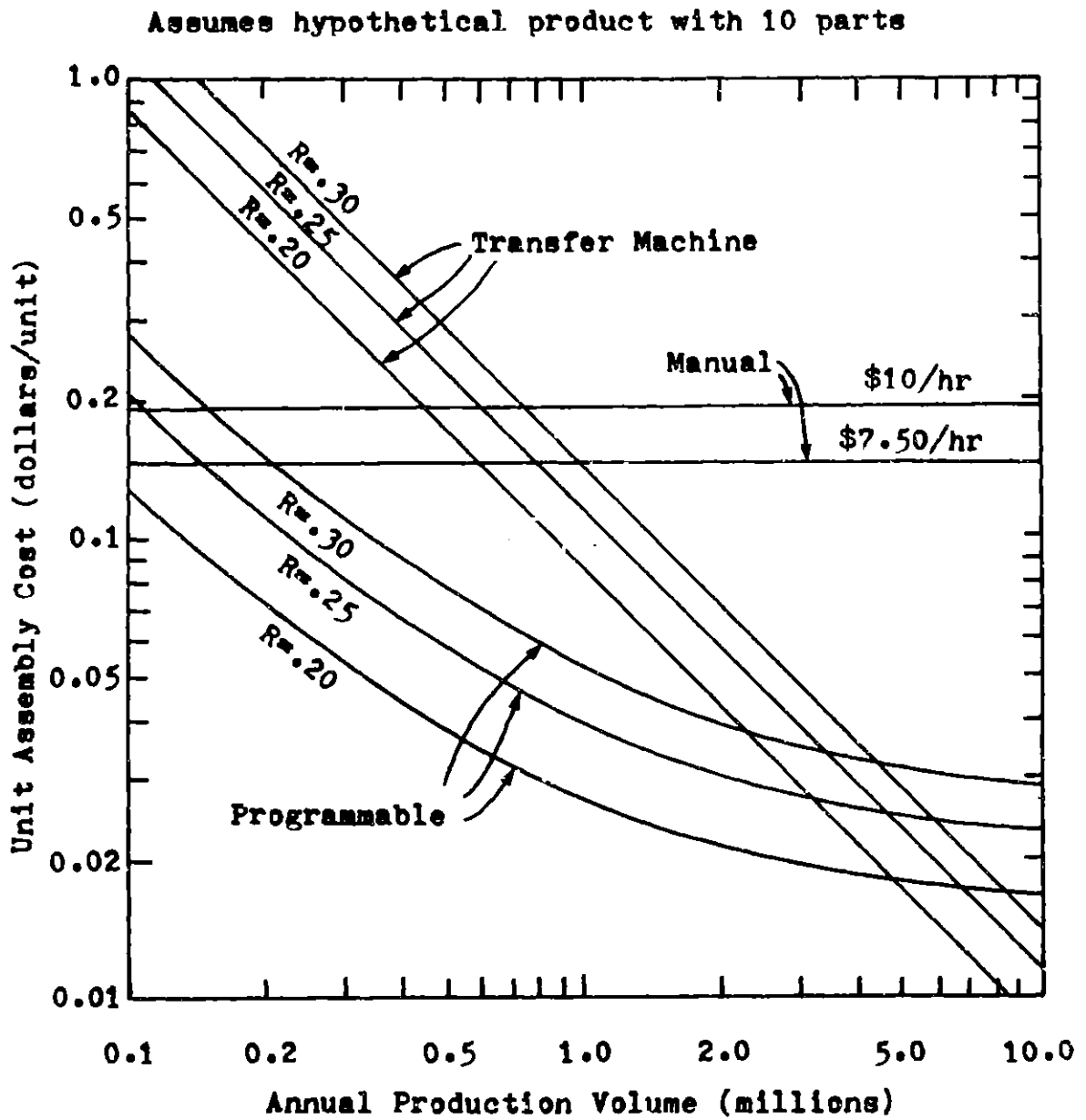
Figure 7.2: Comparison of Unit Assembly Costs with Price-Time Product Equal to 200,000 \$-sec

Assumes hypothetical product with 10 parts



R = required annual rate of return

Figure 7.3: Comparison of Unit Assembly Costs with Price-Time Product Equal to 50,000 \$-sec



R = required annual rate of return

the required annual rate of return and the labor rate can drastically affect the range of applicability of the programmable assembly systems. For a manual rate of \$7.50 per hour and a required annual return of .3, the range of applicability of programmable assembly is only between production volumes of 270,000 to 2.4 million per year. On the other hand, if the labor rate were \$10 per hour and the required annual return were .2, then the applicable production volumes range from about 75,000 to about 2.8 million. The upper end of the volume range does not change much because it is the boundary between two automated methods subject to the same required annual rate of return: labor rates are not involved. The lower end of the volume range is drastically affected because it is a boundary between a labor method and a capital method; changes in labor rate or required return will affect one and not the other.

The same type of results for assemblers with price-time product equal to 200,000 \$-sec, a slower and/or more expensive assembler, are shown in Figure 7.2. Such assemblers are only marginally competitive if the required annual rate of return is .30 and the labor rate is \$7.50 per hour. Then the production volume is only from about 650,000 to about 1.1 million. At the other extreme, if the labor rate were \$10 per hour and the required annual rate of return were .20, then this assembler would have a production volume range from about 90,000 to about 1.2 million.

Finally, these same results are shown in Figure 7.3 for assemblers with price-time product equal to 50,000 \$-sec. This corresponds to a cheap and/or fast assembler. Such an assembler product produces competitive systems for volumes from 210,000 to 4.4 million if the manual labor rate were \$7.50 per hour and the required minimum return were .30 . On the other hand, if the labor rate were \$10 per hour and the required annual return were .20, then the competitive volume range would be from about 70,000 to 4.9 million.

The results of these comparisons show that price-time product, labor rate, and required annual return are significant influences on the competitive relation between programmable assembly and manual or transfer machine assembly. The labor rate and the required annual rate of return will change over time, largely due to national economic conditions, but the model provides a framework to take these changes into account. The price-time product of the programmable assembler is a measure of the state of the technology. It is a variable whose value can be reduced by further research and development. Reducing the price-time product will improve the competitive range of programmable assembly for any set of economic conditions represented by labor rate and required annual return. Accordingly, we now examine the price-time product as a measure of assembler design to see how it may be used.

7.2 Significance of the Price-Time Product

In the simple economic model, the equation for programmable assembly cost per unit is a function of the product of the price and part assembly time of the programmable station, not price or time individually. This equation is

$$PCPU = \frac{NPART}{(1-T)} \left[\frac{STAP * PARTTIME * (R-T * DPPA)}{NSPY * CEF * PUEF} + \frac{TOLPP * (R-T * DPTL)}{VOL} \right] \quad (6.12)$$

where PCPU = programmable assembly cost per unit

STAP = price of the programmable station

PARTTIME = part assembly time for one part, sec

This functional dependence on the price-time product has the following implications:

1. Assuming the other parameters, such as parts feeding tooling costs, are held constant, design of assembly stations for minimum assembly cost per unit is achieved by minimizing the product of the station price and the part assembly time, not price or time individually.
2. Programmable assembler designs with different prices and assembly times but the same price-time product will result in systems having the same assembly cost per unit, on the average.
3. The sensitivities of the cost of assembly to fractional changes in price and part assembly time are

equal in the following sense: reducing the price of the programmable station by a certain fraction will result in the same cost savings as reducing the part assembly time by the same fraction.

These implications make sense intuitively. By reducing the price of the programmable stations the unit assembly cost can be reduced. By reducing the assembly time per part, fewer programmable stations are needed to meet the required annual production volume of the product. (We are assuming that the amount of parts feeding tooling remains the same.) This means lower system price and consequently lower assembly cost per unit if the station price is constant. A station design that is twice as fast as another but has twice the price gains no advantage. It will replace two of the slower stations in performance but for exactly the same price.

The equivalent relative sensitivities of assembly cost to station price and part assembly time can be seen from equation (6.12). A reduction of ten percent in the price of a programmable assembler station will produce the same ultimate reduction in assembly cost per unit as a ten percent reduction in average part assembly time. The reduction in assembly cost per unit will decline by less than ten percent because the cost of parts feeding tooling has remained the same.

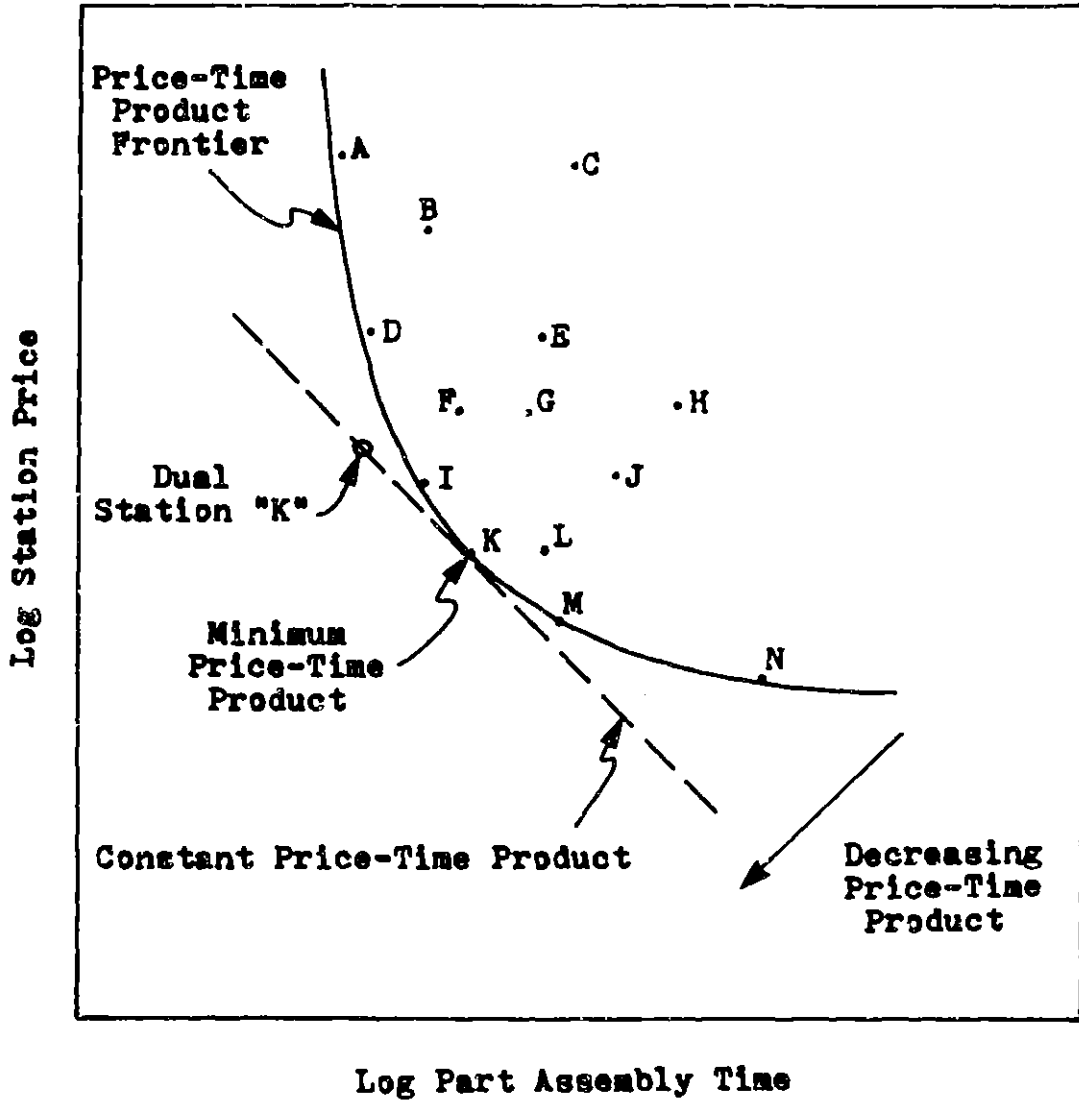
7.3 Programmable Assembler Station Design

7.3.1 Choosing Between Alternate Assembler Designs

To develop the concept of the minimization of the price-time product in the choice of an assembler for a system or in the design of an assembler, it is helpful to take the position of a designer of a particular programmable system. Because of the nature of the product for which the system is to be designed, the designer has certain constraints on his choice of programmable assemblers from which to build his system. The size and weight of the parts will place a lower bound on the size and force capabilities of the assemblers that he can consider. The groupings of the parts, the nature of the assembly directions and axes, and the production volume will influence the choice of number and kind of degrees of freedom needed. Given these basic constraints, the designer can now collect price and time data on all of the acceptable assemblers. In theory, he could display this data on a price-time chart such as Figure 7.4 where points for several hypothetical assemblers are plotted.

In Figure 7.4 the curved line represents the price-time frontier for all assemblers that meet the designer's constraints for his particular application. The dotted line is a line of constant price-time product for the assembler

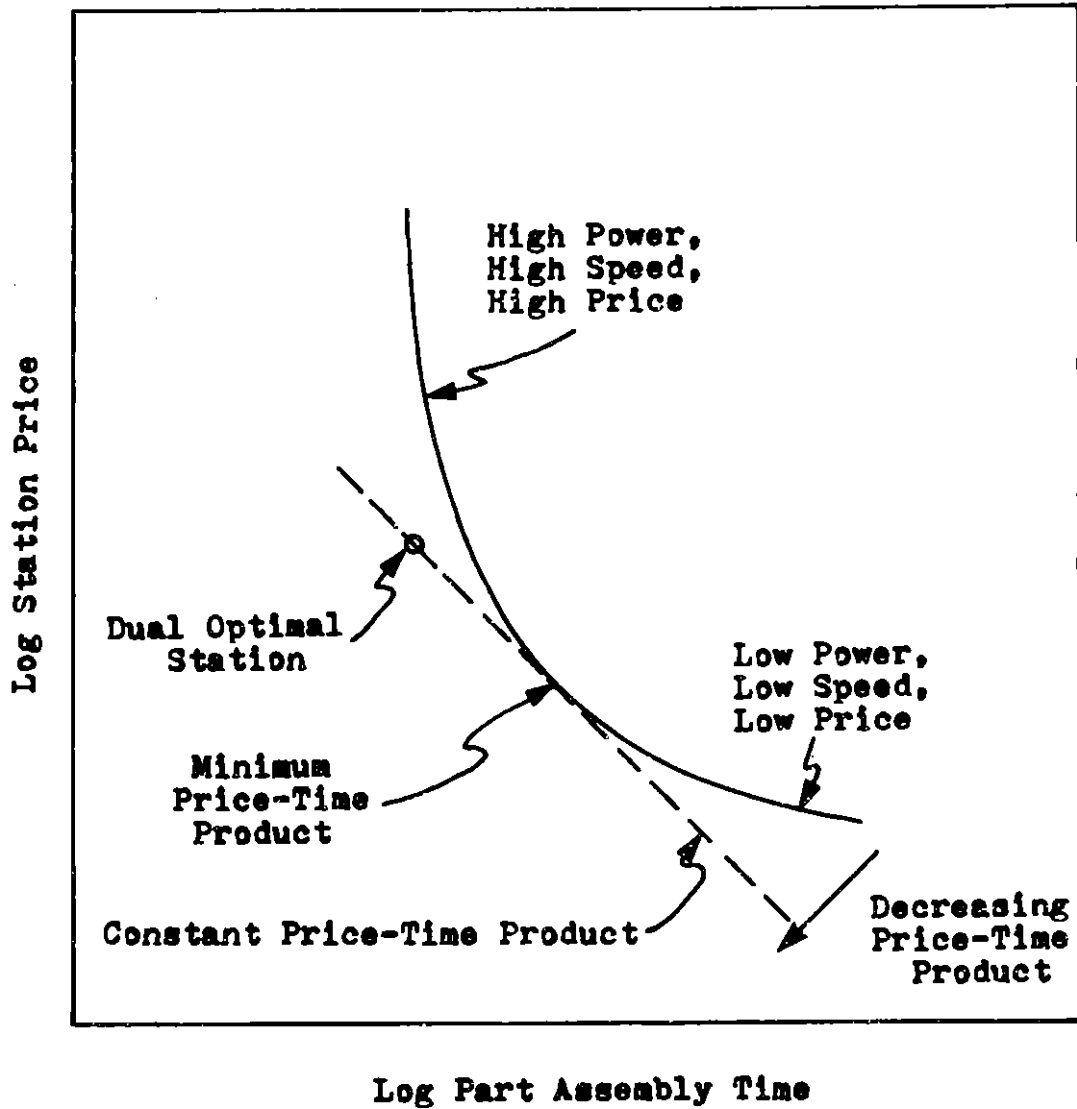
Figure 7.4: Price-Time Product Data for Hypothetical Set of Assemblers



with the minimum price-time product. The points plotted in Figure 7.4 represent many different assembler technologies (electric, hydraulic, or pneumatic) and degrees of freedom (so long as the right degrees of freedom are included for the designer's needs). The price-time product criterion enables the designer to choose among the assemblers of widely varying technologies, costs, and single part assembly times. By choosing the assembler or assemblers with the lowest price-time product, he can then proceed to design a minimum cost system for the production constraints.

The price-time product criterion can also help to optimize a tradeoff in the design for a particular kind of assembler. Suppose that for other reasons an assembler design is almost fixed with respect to its size, force, capacity, and number and arrangement of degrees of freedom. Yet to be determined are the part assembly time for this design and the corresponding actuator power requirements necessary to move the assembler fast enough to meet this part assembly time. Increasing the speed of the assembler requires increased power in the actuators which leads to an increased price for the assembler. Figure 7.5 illustrates the range of prices and speeds for this particular assembler design as the actuator power is varied. The price-time product minimization criterion can be used to

Figure 7.5: Example Assembler Design Problem to Minimize Price-Time Product



pick the best choice of power and part assembly time to give the most economic assembler performance.

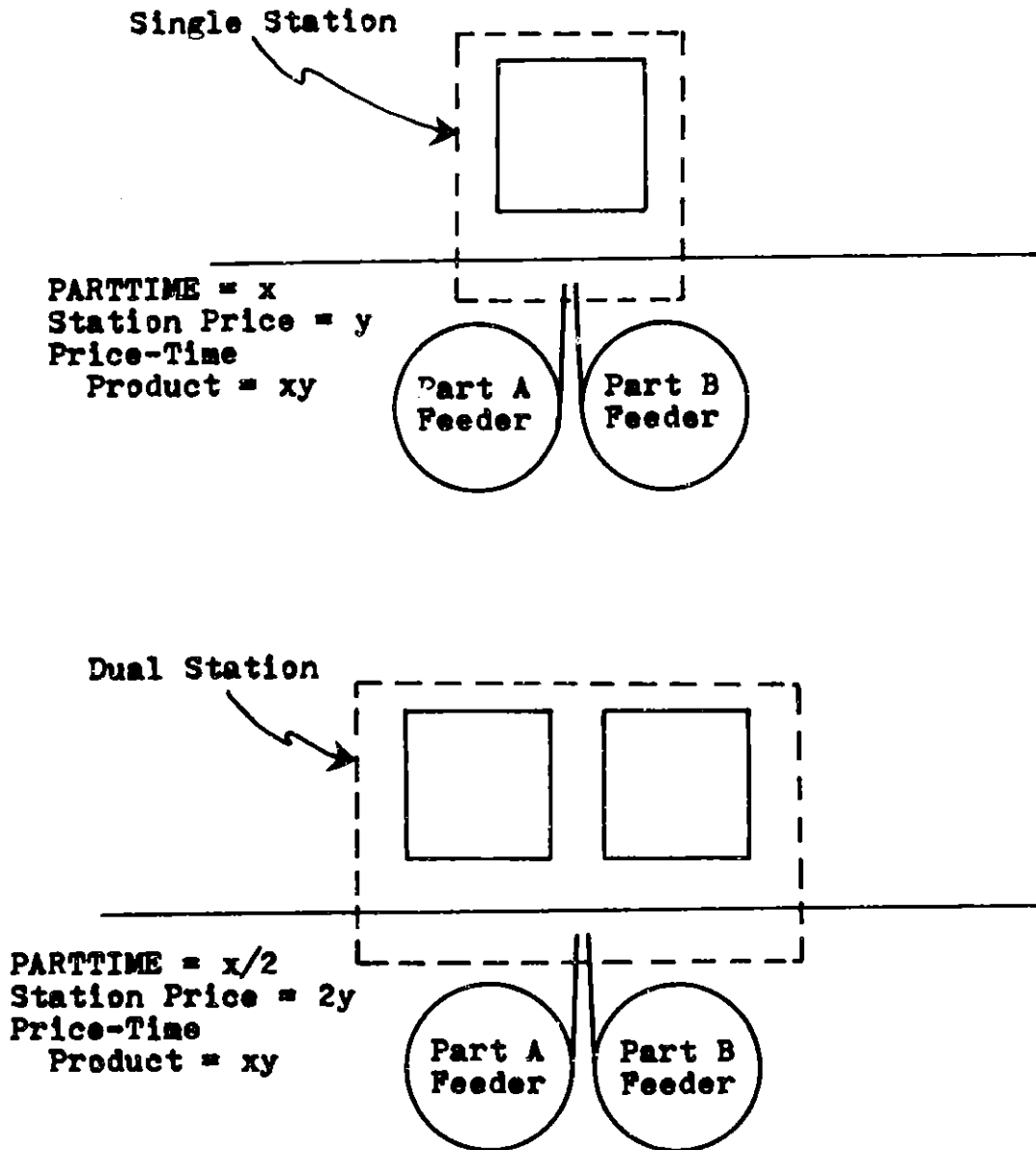
7.3.2 Parallelism and the Price-Time Product

If assemblers that are optimal in the price-time sense are too slow for a given application, then the price-time advantages of the optimal design can be had at twice the speed by using dual parallel station assemblers.

It can be shown that a given programmable station, when used in a parallel manner, will result in a dual station with exactly the same price-time product. If, for a given application, the assembly rate of a station is too low, a higher assembly rate can be obtained by operating two such stations in parallel sharing the same parts feeding equipment. The arrangement is illustrated in Figure 7.6. The pair of stations can be regarded as a dual station with twice the price but half the time. Hence, the price-time product for the dual station is exactly the same as the individual station. A system configured from these dual stations for a given maximum production volume would have half as many dual stations as individual ones in the conventional arrangement. The cost of assembly per unit would remain the same because the total cost of the system has not changed.

As was noted in section 5.2.2, there may be practical upper limits to the number of assemblers that can share the

Figure 7.6: Parallelism of Programmable Assembly Stations



Each Individual Station Handles Every Other Assembly

same part feeder. However, to have several assemblers sharing one feeder would likely correspond to a high volume production--circumstances under which transfer assembly tends to have an economic advantage. Hence, there may be relatively few situations in which one would want to have several assemblers share one part feeder.

When used to create a dual station, a slower assembler station design can compete with a faster one if it is cheap enough. It need not be restricted to lower production volumes because of its longer part assembly time. Figures 7.4 and 7.5 show where the price-time point for a dual optimal station is located relative to the other assembler designs.

7.3.3 Minimization of the Price-Time Product with Integral Station Number

The concept of minimizing the price-time product was developed from the simple model for a restrictive set of assumptions, but it now can be shown to be a valid and useful criterion under a much less restrictive set of assumptions.

To develop the general concept, it is helpful to take again the point of view of a designer of individual programmable systems. This designer uses programmable assemblers to create assembly systems for specific products or product

families. He is given a product with a certain production volume requirement and a specific number of parts. Suppose for the moment that there is a three axis assembler on the market that he could use in the construction of his particular system.

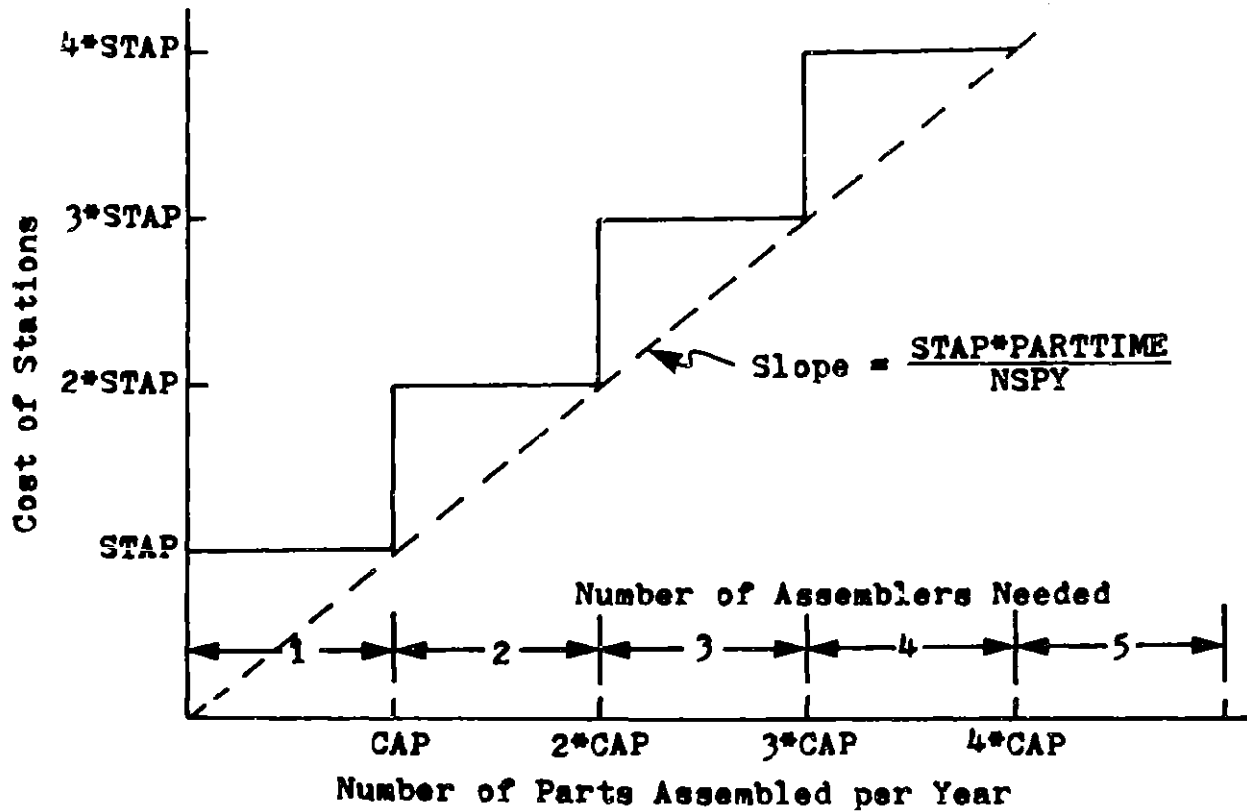
To continue the example, suppose that his product has two distinct directions of assembly and that one direction has more parts to be assembled than the other. Our designer considers the problem and decides that he wishes to use one or more three axis assemblers aligned with one of the directions of assembly and also one or more three axis assemblers aligned with the other direction of assembly. He now must choose the number of assemblers needed for each direction to meet the production volume requirements. He should consider a chart such as Figure 7.7.

In Figure 7.7 is a plot of the price and capacity of a given assembler design used by itself and in parallel. The capacity is the number of parts that could be assembled per year. Assume that the basic assembler unit has a given price STAP and a given capacity CAP. Then CAP can be expressed as follows (as in equation (5.1))

$$CAP = \frac{NSPY}{PARTTIME} \quad (7.1)$$

For any situation in which the number of parts that must be assembled by a single station is less than CAP, one station is required with a corresponding cost equal to STAP. When

Figure 7.7: Price-Capacity Chart



STAP = programmable station price

CAP = capacity of station, parts per year

PARTTIME = part assembly time

NSPY = number of seconds per year

the number of parts that must be assembled per year is between CAP and $2 * CAP$, then two stations are required with a corresponding price of $2 * STAP$. Because integral numbers of stations are used, the chart has a stairstep appearance.

Next our designer must determine the annual capacity that is required for each principal direction of assembly of his product. The required capacity for each direction is the number of parts assembled in that direction times the required production volume of the product. This gives the number of parts units per year that the assembler (or assemblers) aligned in that direction must assemble per year. By examining Figure 7.7, the designer can determine how many assemblers will be needed for each direction and how much they will cost.

Only rarely will any assembler on the market be used to its maximum capacity. This full capacity utilization will occur only when the required number of parts per year in a particular application happens to be an exact multiple of the capacity of one assembler and no extra capacity is purchased. The busiest assembler—the one with the most parts to assemble—will be the one which paces the entire system, but even it may not be working at its maximum capacity.

If the number of parts that must be assembled by the system in one direction is, say, only half of the capacity of the available assembler on the market, our designer may

well wish that another assembler were available with less capacity but at a cheaper price. This would allow him to reduce the cost of the system that he is designing and consequently reduce the unit assembly cost of the product. In fact, our designer may wish that there were a range of assemblers available so that he could buy just the capacity that he needs and no more if future flexibility were not important to him.

In this simple model, the optimal assembler design is defined as the one which minimizes the price-time product. It can be shown that the slope of the staircase in Figure 7.7 is proportional to the price-time product. The slope is the ratio of the individual station price STAP to the annual capacity of the individual station:

$$\text{SLOPE} = \frac{\text{STAP}}{\text{CAP}} \quad (7.2)$$

where SLOPE = the slope of the staircase.

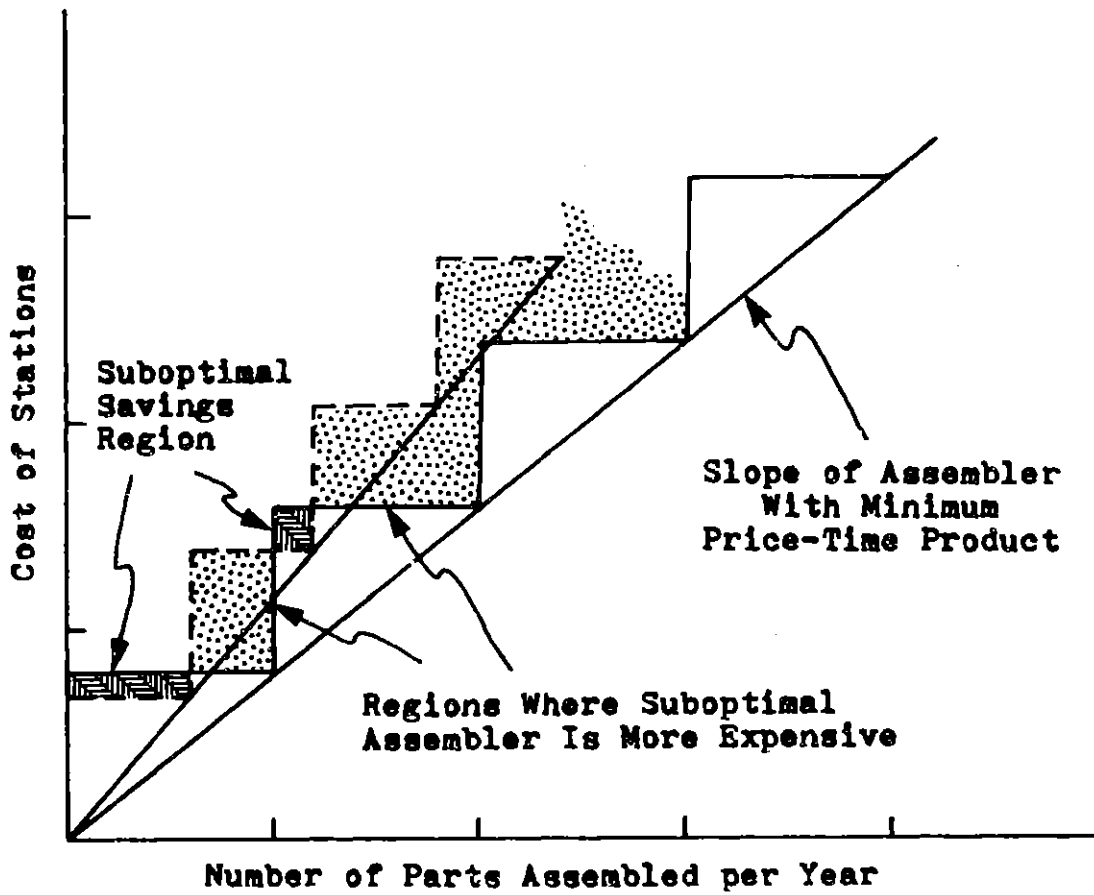
Substituting from equation (7.1), we obtain

$$\text{SLOPE} = \frac{\text{STAP} * \text{PARTTIME}}{\text{NSPY}} \quad (7.3)$$

The assembler which minimizes the price-time product also has the lowest slope. See Figure 7.8.

A non-minimum design in which both the capacity and the price were less would create the second stairstep pattern in Figure 7.8. Notice that the steps of the stairs are smaller but the slope of the stairs is larger. (Another kind of non-

Figure 7.8: Price-Capacity Comparison for Optimal versus Suboptimal Assembler Designs



minimum design would have higher price and higher capacity with larger stairsteps and also larger slope.) Regions where the non-minimum design represents a savings in assembler price compared to the minimum design are shown shaded.

It can be seen that the non-minimum design does lead to a savings in price of over the minimum design in some ranges of required capacity. However, it is more costly where its reduced capacity means that more of them have to be used than would be necessary of the optimal design.

If it is assumed that the distribution of the number of potential applications for such an assembler in industry over the range of required capacities is uniform, then the industry wide savings for the non-minimum assembler is proportional to the area of the shaded boxes in Figure 7.8. This savings is more than offset by a much larger area representing the additional expense of the non-minimum assembler in this example. If only the non-minimum assembler were on the market, then the average programmable cost of assembly would be higher than it needs to be.

If only one design is to be built and marketed, it should be a minimum price-time product design. But, whether only one design should be built or more depends on other factors not yet considered. One of the important factors is the shape of the price-time function. If there is a well-defined point at which the minimization of the price-time product occurs, then only the minimum design would

probably be justified. This is because for a well-defined minimum there must be a sharp bend in the price-capacity curve. or, equivalently, the price-time curve. For capacities below the minimum point, relatively little additional price reduction is possible; for capacities above the minimum point, significantly greater prices are necessary.

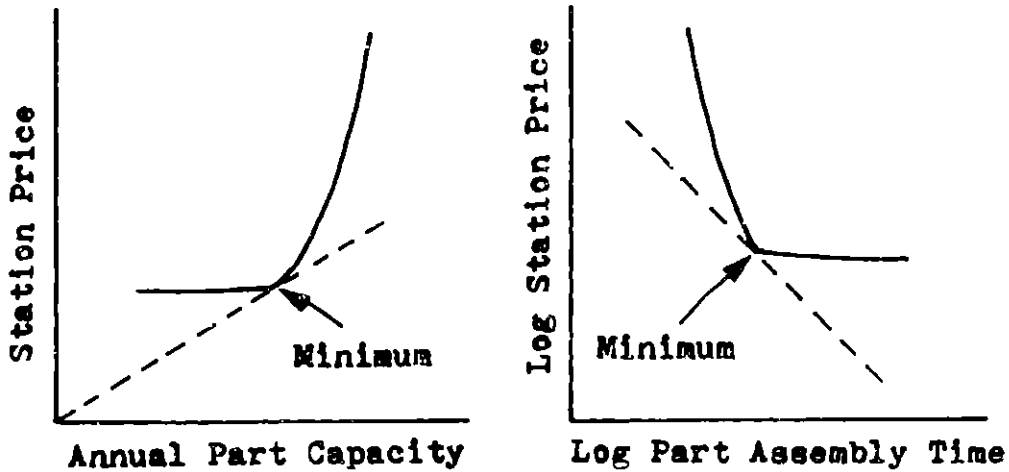
If, on the other hand, the location of the minimum is not well-defined, then significant reductions in capacity will result in almost as great a fractional reduction in the price. Greater prices will result in almost as great an increase in capacity. In either case, the price-time product is nearly the same over a wide range of designs, which means that very little price penalty is paid for the suboptimal assemblers. Figure 7.9 illustrates the well-defined and the ill-defined cases. If the minimum is ill-defined then a range of assembler capacities and prices would make sense because it would allow significantly lower average programmable system costs.

7.3.4 Ways of Reducing Price-Time Product

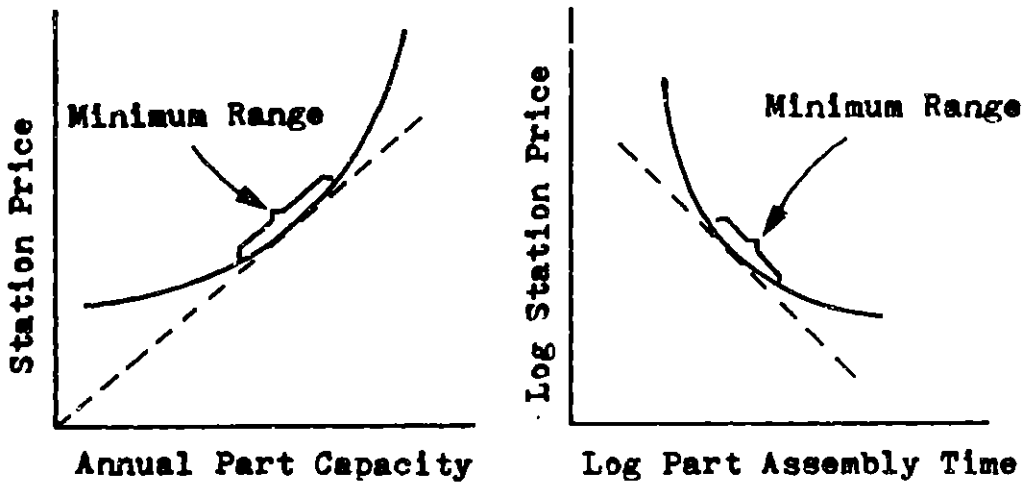
There are two primary ways of reducing the price-time product: First, reducing the number of degrees of freedom; and, second, reducing the overall physical size. Both have the effect of reducing the number and size of the parts in the assembler equipment and the power required to move

Figure 7.9: Comparison of Assembler Price-Capacity Curves for Individual Assembler Design Problems

Well-Defined Minimum Price-Time Product:



Ill-Defined Minimum Price-Time Product:



Each curve represents a range of design alternatives assuming certain parameters, such as size and number of degrees of freedom, are held constant. Curves are assumed monotonic, i.e., greater capacity costs more.

that equipment through its motions for any given part assembly time.

Reducing the number of degrees of freedom is particularly effective. Each additional degree of freedom in an assembler design requires an additional actuator, position sensor, control circuit, and perhaps tachometer. For hydraulic systems, additional hydraulic capacity is required as well as another control valve. For electric actuators an additional driving amplifier is required. When another degree of freedom is added, the control strategies for the entire assembler must be expanded in capability to deal with the extra dimension. For the same part assembly time, a six axis assembler will certainly cost significantly more than a three or four axis one.

When the number of degrees of freedom increases, not only is more hardware needed for the extra degrees of freedom, but also some of the degrees of freedom will have to increase in size, power, and expense. The reason is that the degrees of freedom located relatively nearer the base will have to be stronger and more powerful to carry the additional degrees of freedom distributed out along the assembler if the part assembly time is to remain the same as that for the reduced degree of freedom device.

Of course, a six axis assembler is more versatile than a three axis one. It may be argued that this versatility combined with economies of scale would allow the six axis

assembler price to be reduced significantly. The six axis assembler could certainly handle all the jobs the three axis assembler could do and more. The argument is that this versatility leads to a larger production volume of six axis assemblers which by the economies of scale leads to a reduction in price and then more demand and so on.

However, the fact is that a significant fraction of assembly can be done by a three or four axis device. As has already been discussed in Section 5.1.2, Kondoleon (19) has found for a small set of products that roughly two thirds of the parts are assembled in one principal direction and over 80 percent are assembled in only two principal directions. A three or four axis device aligned with a principal direction could do almost all of these tasks. Kondoleon has also found that many products have only one or two principal directions of assembly so that three or four axis devices generally aligned with these directions would be adequate.

Since the three axis assembler is cheaper than a six axis one of equivalent speed, the three axis assembler should be preferred when it can do the required tasks. If the number of assemblers required by production volume of the product is equal to or greater than the number of principal assembly directions anyway, then a system configuration using three axis devices aligned with the principal assembly directions would be more economic than using an equivalent number of six axis assemblers of equivalent speed.

Since system configurations based on three axis assemblers could handle a large fraction of all the programmable assembly applications, and do it cheaper than the six axis devices, the demand for three axis assemblers would be such that at least the same economies of scale would apply to them as apply to the six axis type. Consequently, the three axis assembler will always be cheaper than the six axis, and should be the economic choice whenever it can do the required tasks.

The six axis assembler will find use where its extra versatility is required -- jobs which assemblers with fewer degrees of freedom cannot do. In particular, the six axis assembler might be most useful where the following conditions exist:

1. Complexity of assembly motions
2. Large number of parts assembled in different directions at one station, perhaps associated with products with low production volume where relatively few stations are needed to satisfy productions requirements.
3. Large uncertainty of future assembly tasks, perhaps due to volatile product design or job shop operation.

The price of versatility is the premium paid for the extra degrees of freedom.

7.4 Maximization of Configuration Efficiency

The configuration efficiency indicates how well balanced the work is among the assemblers in the system.

If one assembler must wait idly for another assembler to complete its work, or if an assembler is not performing assembly tasks and instead is transferring parts or something else, the configuration efficiency is reduced.

The configuration efficiency enters in the first term in the expression for the programmable unit assembly cost, equation 6.12.

$$PCPU = \frac{NPART}{(1-T)} \left[\frac{STAP * PARTTIME * (R-T * DPPA)}{NSPY * CEF * PUEF} + \frac{TOLPP * (R-T * DPTL)}{VOL} \right]$$

Since the configuration efficiency appears in the denominator of the term, reductions in configuration efficiency lead to increases in unit assembly cost. The reason is that reduced configuration efficiency means that more assemblers will be required to build a system to achieve the required production volume. Also, since the configuration efficiency appears in the denominator of the term related to total assembler investment in the system, the portion of the unit assembly cost that comes from the cost of the assemblers is inversely proportional to the configuration efficiency.

Configuration efficiency should be maximized to achieve lower unit assembly costs. Maximization of configuration efficiency in the design of an assembly system is accomplished by two methods. First, the assembly work should be balanced among the assemblers so that no station is slower to complete its cycle of tasks than the others thereby forcing the others to wait for it. Secondly, stations should

devote as much of their time as possible to assembly operations, and pacing stations especially should avoid doing non-assembly tasks (such as part transport, part loading and unloading). Such functions should be performed by other devices, such as conveyors or the pallet indexing system.

7.5 Summary

This chapter dealt with three consequences of the simple economic model. First, the economic model can be used to examine the sensitivity of the economic applicability of programmable assembly to important parameters such as labor wage rate, required annual return, and assembler price-time product. Each of these factors can have a significant influence on the economic applicability of programmable assembly, but the assembler price-time product is a variable representing the state of programmable assembly technology, and may be improved by further research and development.

The second, and primary, implication concerned individual assemblers: minimization of the price-time product as a means of selecting among competing assemblers and as a means of resolving tradeoff issues in the design of assemblers. The third implication, concerned with assembly systems, was the maximization of the configuration efficiency

as a means of reducing the number of assemblers required and thereby reducing the unit assembly cost.

As a means of choosing between competing assembler designs, minimization of the price-time product is useful to the user of programmable assemblers as well as the designer of assemblers. The user of course must select between competitive brands; the assembler designer must resolve design tradeoff issues in a way that produces an economic and competitive product.

In the design of an assembler, the tradeoff issues will produce a range of design options that may have a sharp, well-defined price-time product minimum or a shallow, ill-defined minimum. In the case of the well-defined minimum, one design is significantly more economic than the others. In the case of the ill-defined minimum, a range of designs are "nearly" best. Then, other considerations will be necessary to resolve the assembler design tradeoff. Alternatively, the builder of assemblers may decide to offer a range of assembler designs of near-minimum price-time product to the user so that he may choose the design that best fits his system needs.

The price-time product criterion, having been obtained from the simple economic model in which continuous station numbers were permitted, can be shown to be valid for integral station numbers when examined from the point of view of the assembly system designer.

Configuration efficiency as a measure of assembly system design was examined. Configuration efficiency should be as high as possible because this leads to a requirement for fewer assemblers in the assembly system, which will ultimately reduce system cost. Configuration efficiency may be improved by balancing the assembly tasks so that there is as little waiting time as possible for any assembly assembler and by reducing the number of nonassembly tasks that are performed by the assemblers.

8. EXAMPLE DESIGN PROCESS FOR A THREE AXIS PROGRAMMABLE ASSEMBLER

8.1 Introduction

It has been shown in the previous chapter that the minimization of the price-time product provides a means to choose between assemblers of very different configuration and technology with respect to application in specific assembly systems. The minimization of the price-time product is also helpful in the design of a specific type of assembler. An example of such a design process will be given in this chapter. It will be concerned with only one important design tradeoff.

The designer of an assembly system has specific requirements for the assemblers he uses in his system in

addition to the need for them to be economic. Because of the product and its assembly sequence, the system designer may require a certain payload capacity, a certain number and arrangement of degrees of freedom, and/or a minimum range of motion. Assemblers with less payload capacity, fewer degrees of freedom, and/or smaller size will almost certainly have lower price-time products, but will just as certainly be inadequate for the system designer's specific application.

This chapter concerns the design of a particular three axis assembler in which the arrangement of the axes is fixed. The problem is formulated so that the size of the assembler can be fixed at any value within a size range. Once the size of the assembler is fixed, the torque capacity of the actuators remains to be chosen.

Suppose that we have selected a nominal choice of actuator torque capacity. If actuators with greater torque are chosen, then the assembler may have a shorter part assembly time. However, these stronger actuators will certainly cost more, and so the station price will increase. The price-time product will probably change, but because the factors move in opposite senses, it is not clear whether their product will increase or decrease. Minimization of the price-time product can be used as a way to choose the actuators to achieve an economical design. In this chapter it will be shown that, as actuator power is varied, there is

a region of actuator power where the price-time product is a minimum.

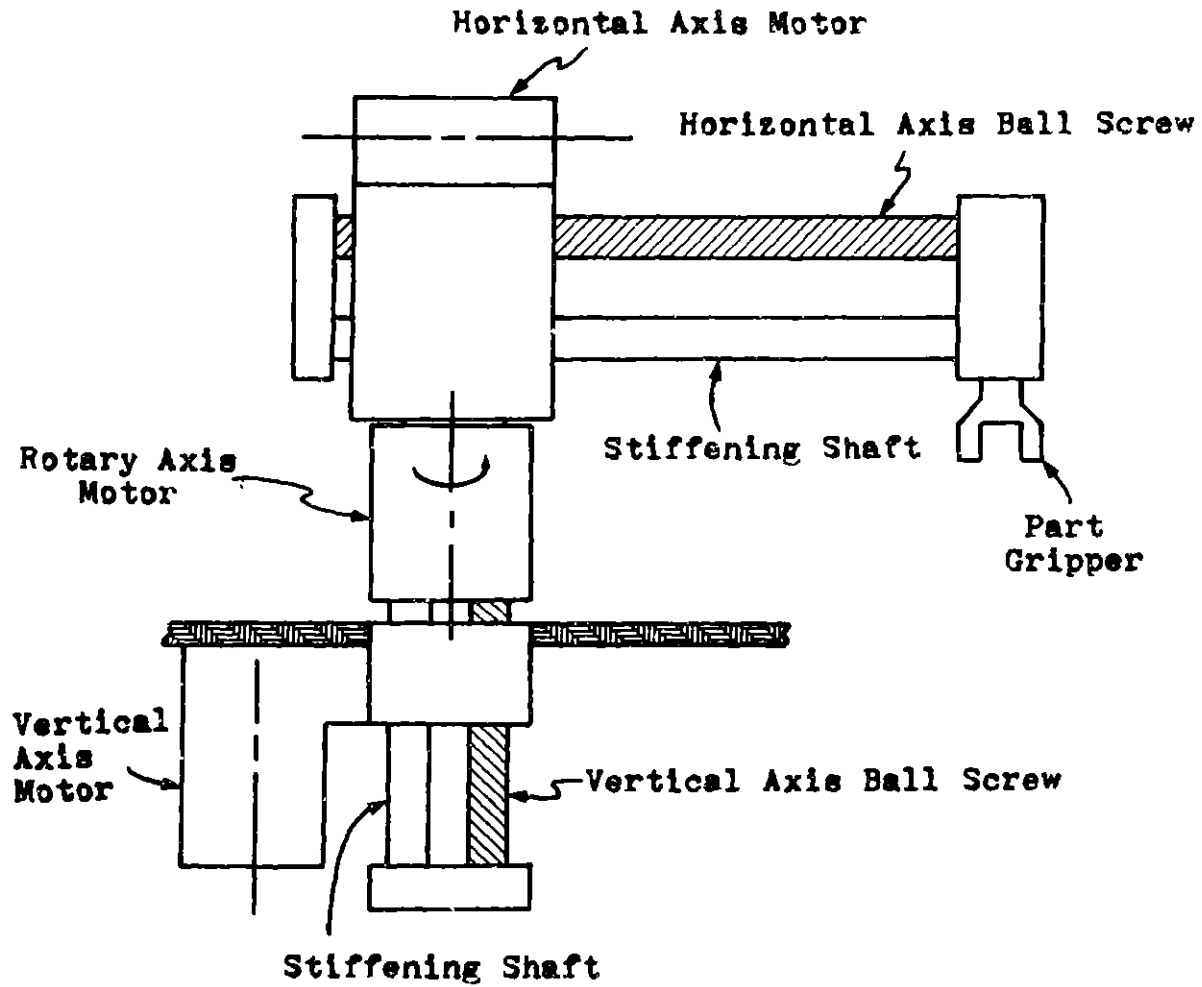
The design process described in this chapter requires the ability to model the actuator power needed for a certain single part assembly time and the assembler station price as a function of the actuator power as well as the other components. These two functions will allow us to plot curves on the price-time chart showing how price and time vary as actuator power is varied while assembler size is held constant.

The remainder of the chapter includes a description of the assembler and the design process for the actuators, the development of the assembler station pricing model, sample results of the design process, and an analysis of these sample results with respect to consequences for research and development of programmable assembly.

8.2 Physical Description

The device is illustrated in Figure 8.1. It is a three axis assembler with cylindrical symmetry. A part gripper is carried at the end of a horizontally moving degree of freedom. This horizontal degree of freedom is rotated about a vertical axis by a rotary actuator. Finally, both the horizontal and rotary degrees of freedom are raised and lowered by a vertical degree of freedom.

Figure 8.1: Sketch of Example Three Axis Assembler



This arrangement of actuators was chosen because of the simplicity of construction it offers. Another arrangement would have been to switch the positions of the rotary and vertical axes, so that the rotary axis carries the other two. The actuators for all three axes are electric. Motion for the vertical and horizontal axes is accomplished by means of ball screws. Certain limitations on ball screw design, such as maximum critical speed, are not considered here. It is assumed that the ball nut is preloaded to eliminate backlash. The moving frame carrying the part gripper is assumed to be made of aluminum, and its mass is estimated from its size.

Resolvers are assumed for measuring the axes' positions. One resolver converter will be multiplexed to read all three resolvers. Each axis is also assumed to have a tachometer to provide velocity information to the servo electronics for that axis. A processor will be dedicated to each assembler and will be responsible for issuing position and/or velocity commands to each axis servo system. The processor will also contain the programming necessary for the assembler to execute its specific assembly task sequence.

The assembler is mounted on a segment of an index table or conveying device. This device carries subassemblies to and from the assembler itself. Together the assembler and the segment of conveying device upon which it is mounted form the assembly station.

8.3 Actuator Selection Process

8.3.1 Selection Process Outline

In the actuator selection process the single part assembly time is regarded as a fixed value. Once this part assembly time is given, the design procedure will choose a consistent set of actuators for the three axes.

It will be assumed that the requirements of the gross motion will largely determine the motor requirements and that the time the assembler spends in gross motion will be a certain fraction of the total part assembly time. With these assumptions a given part assembly time implies a given gross motion time which will in turn be used to estimate the actuator power requirements. Specifically, the power requirements are determined for a certain nominal gross motion trajectory completed within the given gross motion time.

The sequence for determining the actuator power is as follows:

1. Estimate the power required for the horizontal axis. This is the axis farthest from the base.
2. Estimate the corresponding mass for the horizontal actuator.

3. Estimate the required actuator power for the rotational axis including the mass of the horizontal motor.
4. Estimate the mass of the rotary axis actuator.
5. Estimate the required actuator power for the vertical axis including all of the moving hardware mass including the horizontal and rotary actuators.

Hence, each actuator is automatically chosen to move its axis and any attached load.

A procedure will be developed to estimate the power and torque required to move a single axis if its load mass and required gross motion time is known. This procedure will then be used to estimate the power and torque requirements for each of the three axes in the design sequence described above.

8.3.2 Motion Cycle of the Single Part Assembly Time

The microeconomic analysis of the previous chapters treated the single part assembly time as a basic parameter, but actually it is made up of a series of individual operations. For the purpose of this analysis the following sequence of operations will be assumed to occur during one part assembly cycle:

1. Assembler moves to part presentation site (gross motion).

2. Assembler grasps part from part presentation device (fine motion).
3. Assembler carries part in gross motion to assembly site (gross motion).
4. Assembler fits parts together (fine motion).
5. Assembler releases part (fine motion).

Notice that there are no tool changes involved. It is assumed that one part gripper will be satisfactory for all parts handled by any one assembler, which means that it is not necessary to consider any time devoted to changing tools or the part gripper. This is a favorable assumption since it tends to increase the production rate of the assembler station. This same analysis could also be done assuming that the assembler must change tools or grippers for every part and so would represent the other extreme.

The total part assembly time is composed of two gross motions and three fine motions. Accordingly, we may model the single part assembly time as follows.

$$\text{PARTTIME} = 2 * \text{TGM} + \text{FMT} \quad (8.1)$$

where PARTTIME = average single part assembly time

TGM = average time for one gross motion

FMT = total time for all fine motions during
the single part assembly cycle.

We now make the additional assumption that the total fine motion time FMT is proportional to the time for one gross

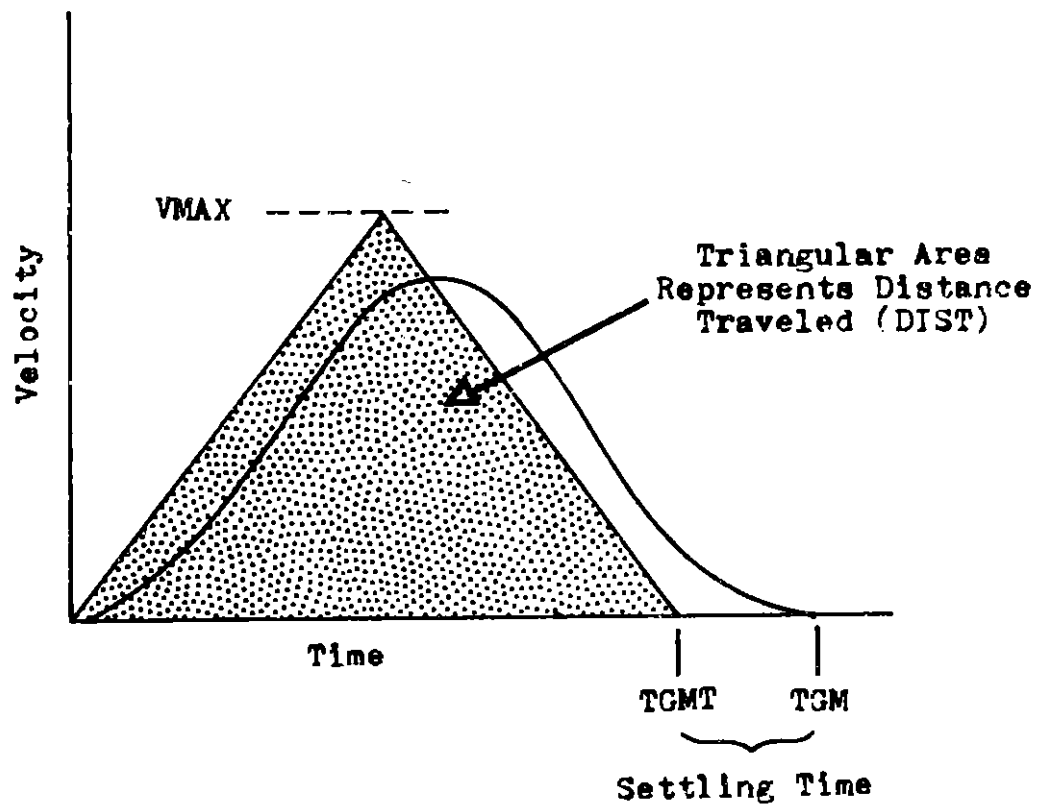
motion TGM. We make this assumption by reasoning that an assembler with fast gross motion capability will also be able to execute the small fine motions quickly. This assumed proportionality will be expressed by defining the ratio of the total gross motion time in a part assembly cycle to the total part assembly time as follows:

$$\text{GRATIO} = \frac{2 * \text{TGM}}{\text{PARTTIME}} \quad (8.2)$$

where GRATIO = fraction of part assembly time in gross motion

8.3.3 Torque Requirements for a Single Degree of Freedom

A gross motion is a large displacement of one or more assembler axes, perhaps from one extreme of its travel range to the other. This motion should be made in minimum time. We will make the assumption that principal limitation of the actuator that drives an axis is with respect to its torque. To obtain minimum time, gross motion trajectories will be generated by applying maximum torque in the forward direction for the first half of the motion, then maximum reverse torque for the second half. A roughly triangular velocity profile would result for a single gross motion, as shown in Figure 8.2.

Figure 8.2: Modeling Gross Motion

Notice that two forms of the motion are shown in Figure 8.2: First, a triangular shape with sharp corners representing the ideal motion, and, second, a smoother shape with rounded corners and longer duration representing the way the axis will actually move under servo control. The duration of the theoretical motion will be designated TGMT, and the longer duration of the servo motion will be designated TGM. Similarly, the duration of the theoretical single part assembly time will be called PARTTIMET; the actual single part assembly time, PARTTIME. The analysis will proceed using the theoretical motions as the bases for the modeling. Later, a correction factor will be applied to estimate the lengthening effects of the settling time of the motions.

It will be assumed that the actual motions are longer than the theoretical ones by a fixed fraction.

$$\text{SETLF} = \frac{\text{TGM} - \text{TGMT}}{\text{TGMT}} \quad (8.3)$$

where SETLF = fractional duration of the actual gross motion time beyond the theoretical time, i.e., the settling time fraction

TGMT = theoretical gross motion time.

We will assume that the same correction factor applies to fine motion time. Hence, by extension, the factor applies to the entire single part assembly time.

$$\text{SETLF} = \frac{\text{PARTTIME} - \text{PARTTIMET}}{\text{PARTTIMET}} \quad (8.4)$$

where PARTTIMET = theoretical single part assembly time
 Finally, it can be shown that the gross motion ratio can also be expressed in terms of the theoretical times defined above.

$$\text{GRATIO} = \frac{2 * \text{TGMT}}{\text{PARTTIMET}} \quad (8.5)$$

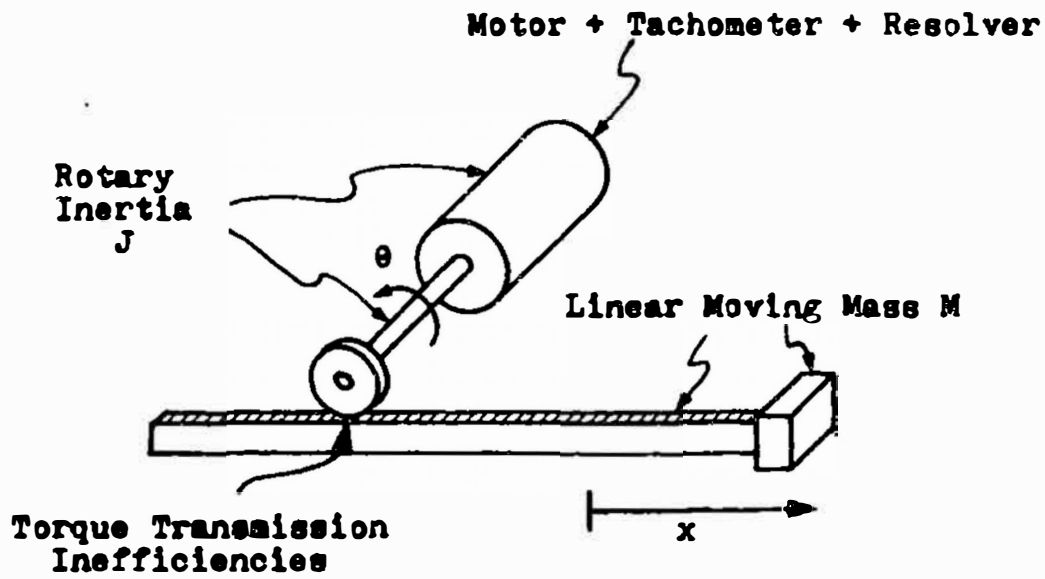
We now seek to derive a simple model for the torque requirements for a single assembler axis assuming that a desired gross motion time and a desired gross motion displacement are given. Later this relation will be combined with a model of electric motor thermal limitation and the previously developed model relating single part assembly time to gross motion time. The result will be a model estimating the electric motor capacity needed for a given assembler axis.

The physical model of one degree of freedom is shown in Figure 8.3. A mass M , consisting of supporting beam, part gripper, and part, moves along dimension x . This is driven through ball screw or rack and pinion gearing by a motor or rotary actuator. The rotary parts have combined inertia J in the rotary displacement direction θ . The relationship between x and θ is

$$\Delta x = C \Delta \theta \quad (8.6)$$

where Δx = small change in x
 $\Delta \theta$ = small change in θ

Figure 8.3: Model of Single Assembler Axis



Rotary-Linear Conversion Relation:

$$\Delta x = C \Delta \theta$$

C = conversion constant

The ideal relationship between torque about axis θ and force F in direction x is

$$\text{TORQ} = C * F \quad (8.7)$$

where TORQ = torque about axis θ

F = force in x direction

This relationship ignores torque transmission inefficiencies, which will be dealt with later.

For a given gross motion, the maximum velocity is a function of the length and the time of the gross motion.

$$\text{VMAX} = \frac{2 * \text{DIST}}{\text{TGMT}} \quad (8.8)$$

where VMAX = peak velocity in x direction

DIST = distance of gross motion

TGMT = time of gross motion, theoretical

The magnitude of the equal and opposite initial and final accelerations is a function of the motion time and maximum velocity.

$$\text{ACC} = \frac{\text{VMAX}}{(\text{TGMT}/2)} \quad (8.9)$$

where ACC = magnitude of required acceleration

The required acceleration as a function of distance and motion is given by combining equations 8.8 and 8.9.

$$\text{ACC} = \frac{4 * \text{DIST}}{\text{TGMT}^2} \quad (8.10)$$

The inertia that must be accelerated is a combination

of the linear moving mass (supporting beam, part, part gripper, and other axes) and the rotary inertia (motor rotor, gear, and shaft). This effective mass is modeled here.

$$EM = M + \frac{J}{C^2} \quad (8.11)$$

where EM = effective mass to be moved in x direction
M = linear moving mass
J = rotary inertia

The mass M will vary in practice for two reasons. First, the payload of the assembler will vary as different parts are assembled. As parts change and the load varies, the mass that must be moved by every axis will vary. Secondly, certain axes may interact in such a way that the position of one axis will affect the load or inertia on another axis. For example, the extension of the horizontal axis will affect the rotary inertia seen by the rotary axis motor: If the horizontal axis is fully extended, the rotary inertia on the rotary axis is large. If the horizontal axis is retracted, the rotary inertia is less.

We now have both effective mass and required acceleration in the x direction. Using Newton's law we may express the required force as

$$FR = \left(M + \frac{J}{C^2} \right) * \frac{4 * DIST}{TGMT^2} \quad (8.12)$$

where FR = required force in x direction

The corresponding torque required from the motor is obtained by combining equation 8.12 with equation 8.7.

$$T_R = C * \left(M + \frac{J}{C^2} \right) * \frac{4 * DIST}{TGMT^2} \quad (8.13)$$

where T_R = torque required on load

The derivation so far has assumed that there are no losses in the system. It is now assumed that there are losses that result in a torque transmission efficiency less than one. The torque at the motor must be greater than the required torque to account for this.

$$T_R = TEF * TORQ \quad (8.14)$$

where $TORQ$ = torque that motor must deliver

TEF = torque transmission efficiency (less than one)

Here the torque transmission efficiency is used to describe the losses that occur in the mechanism of the axis. Frequently motion transmission and conversion devices such as gearboxes and ball screws are described with efficiencies defined in terms of power. For example, ball screws are described as about 90 percent efficient, meaning that 10 percent of the input power is lost. A constant torque transmission efficiency corresponds to a constant power efficiency and has the same value. The actual loss processes are usually functions (often nonlinear) of the velocity of the device, and the true power efficiency varies

accordingly. However, in keeping with the level of modeling established for this analysis, we will assume the torque transmission efficiency to be a constant and will choose a representative value.

Combining equations 8.14 and 8.13 we have

$$\text{TORQ} = \frac{4 * \text{DIST} * \text{C}}{\text{TEF} * \text{TGMT}^2} * \left(\text{M} + \frac{\text{J}}{\text{C}^2} \right) \quad (8.15)$$

Solving for time of gross motion gives

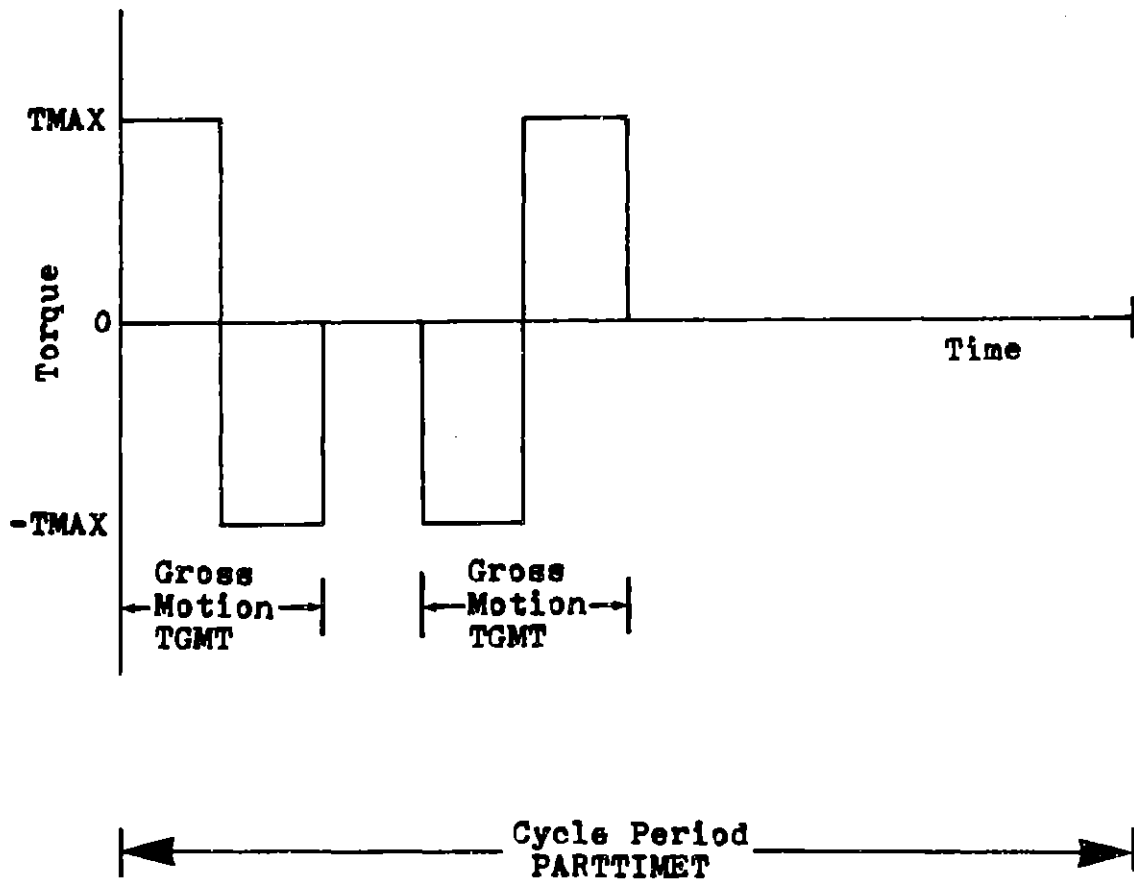
$$\text{TGMT} = 2 * \frac{\text{DIST} * \text{C}}{\text{TEF} * \text{TORQ}} * \left(\text{M} + \frac{\text{J}}{\text{C}^2} \right) \quad (8.15)$$

8.3.4 Torque Limitation of Electric Actuators

We have developed models for the single part assembly cycle and the torque requirements of a single gross motion. A model must now be developed for the torque an electric motor can deliver for the gross motions in a single part assembly cycle.

The torque requirements of a single part assembly cycle (assuming constant load mass) are illustrated in Figure 8.4. During the gross motions the torque history has a square wave character because the axis is undergoing maximum acceleration and deceleration. During the rest of the part assembly cycle it will be assumed that the torque will be at comparatively low levels, or essentially zero when compared to the maximum values. During these fine

Figure 8.4: Torque Requirements for Single Part Assembly Cycle



motion times only very small movements are taking place. (The effect of a constant gravitational loading will be discussed later).

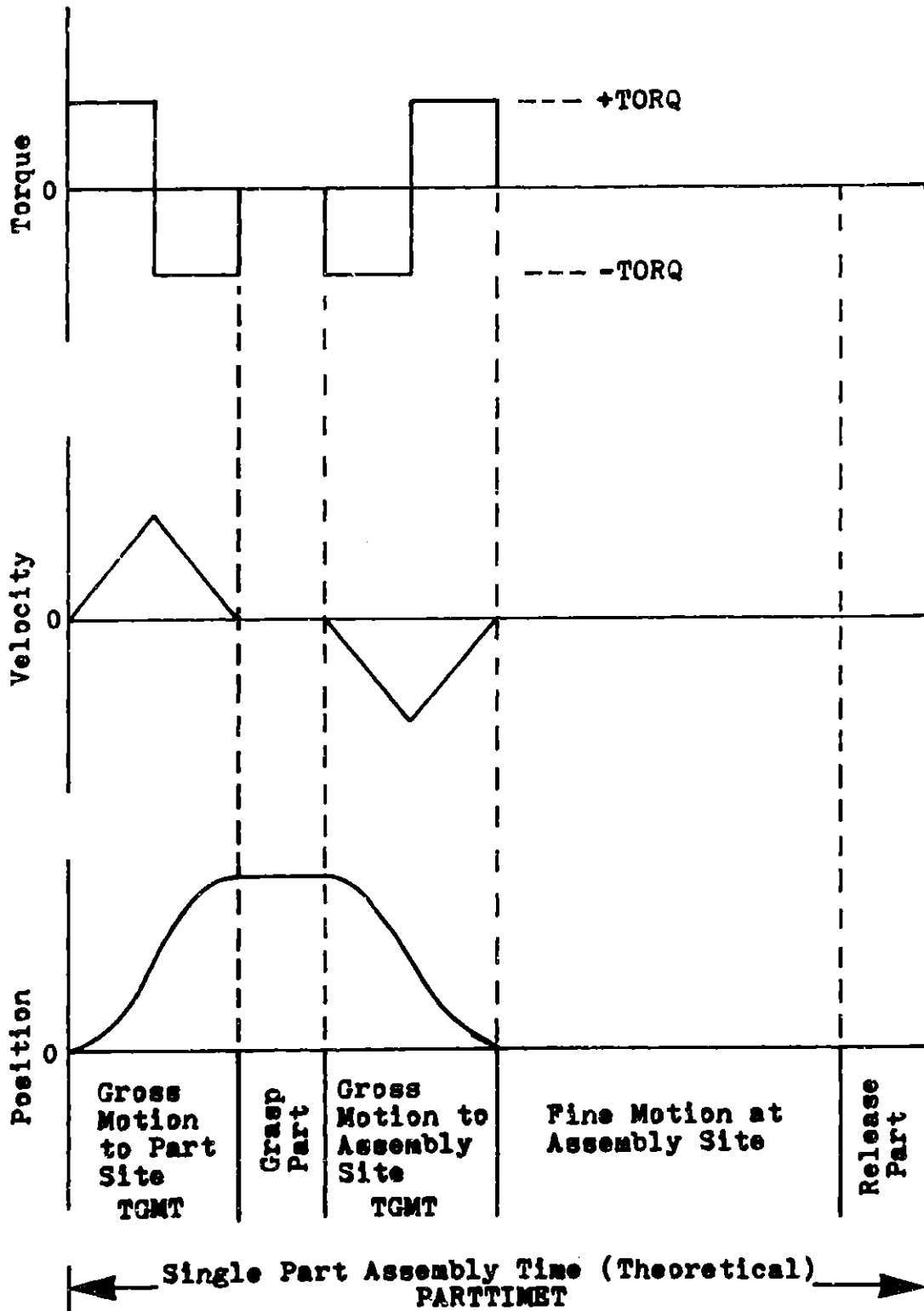
The common limitation on electric motors is electrical resistance heating of the windings. At any moment the power dissipated as heat is proportional to the square of the current through the device. Since the torque of a DC motor is proportional to the current through the winding, then the instantaneous power lost as heat is proportional to the square of the instantaneous torque. This proportionality also applies to the time averages; that is, the average power lost as heat is proportional to the average of the square of the torque.

For mechanical systems such as this one where the periodic motions are much faster than the thermal time constant of the motor (about half an hour), temperature deviations about the mean values due to the part assembly cycling are small. Therefore, the following analysis will be concerned only with average thermal effects.

One of the parameters with which electric motors are rated is their maximum continuous torque. This essentially represents the thermal limit of the motor. The square of the maximum continuous torque is proportional to the maximum average power that the motor can safely dissipate as heat.

We now model the average of the square of the torque for the single part assembly cycle illustrated in Figure 8.5.

Figure 8.5: Gross Motion in Part Assembly Cycle



This is easy to do because of the square wave character of the torque history.

$$AVTSQ = \left(\frac{2 * TGMT}{PARTTIMET} \right) * TORQ^2 \quad (8.17)$$

where AVTSQ = average value of square of torque

TORQ = magnitude of torque during gross motion

If we wish to operate the electric motor at its maximum capacity, then the average value of the square of the torque AVTSQ should equal the square of the continuous torque rating of the motor.

$$AVTSQ = CONTRQ^2 \quad (8.18)$$

where CONTRQ = maximum continuous torque rating of the
the motor

Equation 8.17 and equation 8.18 may be combined to produce an expression for the gross motion maximum torque.

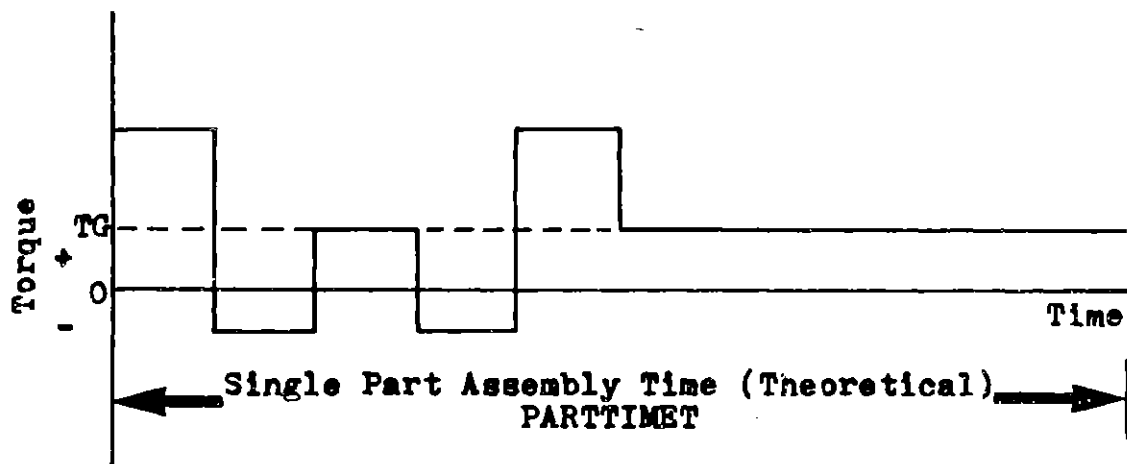
$$TORQ = \left(\frac{PARTTIMET}{2 * TGMT} \right)^{-\frac{1}{2}} * CONTRQ \quad (8.19)$$

Finally, the definition of the gross motion ratio GRATIO, equation 8.5, can be used to simplify this last expression.

$$TORQ = GRATIO^{-\frac{1}{2}} * CONTRQ \quad (8.20)$$

The case when there is a constant gravitational load on the electric motor is illustrated in Figure 8.6. In this case there are two components of the torque history -- the inertial component as before and a constant gravitational component. The average square of the torque can be

Figure 8.6: Torque History with Gravitational Component



TG = gravitational torque component

expressed as

$$AVTSQ = \frac{1}{PARTTIMET} \int^{PARTTIMET} (TG + TI)^2 dt \quad (8.21)$$

where TG = constant gravitational torque

TI = "square wave" inertial torque

t = time

This integral may be expressed as follows:

$$\begin{aligned} AVTSQ = & \frac{TG^2}{PARTTIMET} \int^{PARTTIMET} dt \\ & + \frac{2*TG}{PARTTIMET} \int^{PARTTIMET} TI dt \\ & + \frac{1}{PARTTIMET} \int^{PARTTIMET} TI^2 dt \end{aligned} \quad (8.22)$$

The first integral in the sum above reduces to TG^2 . The second integral is equal to zero because the average value of the inertial torque is zero. The third integral corresponds to the average value of the square of the torque without gravity, equation 8.17. This results in the following expression for the average squared torque:

$$AVTSQ = TG^2 + GRATIO * TORQ^2 \quad (8.23)$$

Here TORQ still represents the amplitude of the square wave of the inertial torque without the gravitational torque.

In order to operate the motor at its maximum capacity, we specify that the average squared torque should equal the square of the maximum continuous torque rating of the motor.

$$CONTRQ^2 = TG^2 + GRATIO * TORQ^2 \quad (8.24)$$

The amplitude of the inertial torque becomes

$$\text{TORQ} = (\text{CONTRQ}^2 - \text{TG}^2)^{\frac{1}{2}} * \text{GRATIO}^{-\frac{1}{2}} \quad (8.25)$$

8.3.5 Model for Single Part Assembly Time

Now the models developed in the previous sections can be combined to develop a model for the motor requirements for a single assembler axis. The single part assembly time can be expressed as a function of the theoretical gross motion time from equation 8.5.

$$\text{PARTTIME} = (1 + \text{SETLF}) * \frac{2 * \text{TGMT}}{\text{GRATIO}} \quad (8.26)$$

This expression may be combined with equation 8.20, an expression for the time for a single gross motion.

$$\text{PARTTIME} = \frac{4 * (1 + \text{SETLF})}{\text{GRATIO}} * \left(\frac{\text{DIST} * \text{C}}{\text{TEF} * \text{TORQ}} * \left(\text{M} + \frac{\text{J}}{\text{C}^2} \right) \right)^{\frac{1}{2}} \quad (8.27)$$

Finally, the expression for the torque that the electric motor can deliver, equation 8.25, can be substituted above.

$$\text{PARTTIME} = 4 * (1 + \text{SETLF}) * \left(\left(\frac{\text{DIST} * \text{C}}{\text{TEF} * (\text{CONTRQ}^2 - \text{TG}^2)} \right) * \left(\text{M} + \frac{\text{J}}{\text{C}^2} \right) \right)^{\frac{1}{2}} * \text{GRATIO}^{-3/4} \quad (8.28)$$

There are still some functional relationships to be determined. For example, the distance of the gross motion DIST and the mass M of the assembler axis may be related to the size of the unit. The motor rotational inertia will be related to the motor power. The torque transmission efficiency TEF will be related to the type of gearing used.

These relationships are dependent upon the specifics of the design and upon empirical relationships, such as those relating power to rotor inertia. The empirical and design relations have been kept separate in this analysis so that in future work different relations could be substituted and examined.

The equation for the single part assembly time (8.28) is used three times in the design process for the three axis assembler--once for each axis--according to the outline given in section 8.3.1. The values for moving mass M and effective gravitational torque TG will vary depending upon which axis is being considered. For example, in the configuration of the example, there is no gravitational torque on the horizontal or rotary axis actuator, but there is such a torque on the vertical axis actuator. This vertical axis torque will depend on the weight of the other axes including their actuators. In order to estimate the inertial load of the rotary axis, the horizontal axis was considered to be extended to one half of its length.

The linear/rotary conversion constant C for each axis will depend on the lead length of the ball screws used. (For the rotary axis no conversion is necessary.) In this analysis the ball screw lead length is chosen as a fixed fraction of the ball screw diameter. The ball screw diameter is chosen to provide a certain deflection of the horizontal axis endpoint under the assembler payload. The deflection

is computed by assuming that the structural members of the horizontal and vertical axes consist of the ball screw and a stiffening shaft of the same diameter (see Figure 8.1), and that the direction of the applied force is perpendicular to the plane formed by the ball screw and the stiffening shaft. Therefore, the axis is twice as stiff as the ball screw alone. Finally, the required payload is estimated from a power law based on the size of the assembler. The design sequence is shown in Table 8.1.

Table 8.1 Three Axis Assembler Design Sequence

1. Choose assembler size and desired single part assembly time.
2. Specify payload corresponding to assembler size.
3. Choose ball screw diameter for acceptable deflection of horizontal axis.
4. Estimate horizontal axis moving mass and ball screw lead.
5. Estimate necessary horizontal actuator torque rating.
6. Estimate horizontal actuator mass, power, and size.
7. Estimate rotary inertial load for rotary axis actuator.
8. Estimate necessary rotary axis actuator torque rating.
9. Estimate rotary axis actuator mass, power, and size.
10. Estimate mass load of vertical axis.
11. Estimate necessary vertical actuator torque rating.
12. Estimate vertical actuator power.

It is important to the economic analysis to estimate an average single part assembly time. To do this a test motion for each axis was chosen to be two thirds of the range of motion of that actuator. This will result in a single part assembly time that is average under the assumption that a gross motion of any given length is just as likely as any other length. The factor two thirds is a result of the fact that gross motion time is a function of the square root of the motion distance.

8.3.6 Empirical and Assumed Relationships

Several empirical relationships are needed to complete the modeling of the dynamics of the example three axis assembler design. Among them are relationships between motor power and motor mass, rotor inertia, continuous torque capacity, and motor length. (Motor length of the horizontal axis motor was used to compute a rotational inertia seen by the rotary axis motor.) Data for the empirical relationships for the motors was obtained from catalogs for DC torque motors. Additional assumed relationships were developed relating ball screw lead length to ball screw diameter, ball screw diameter to axis deflection, and payload to assembler size. These relationships will be treated briefly below:

- 1) Continuous torque vs. actuator motor power. This relationship is shown in Figure 8.7. The manually

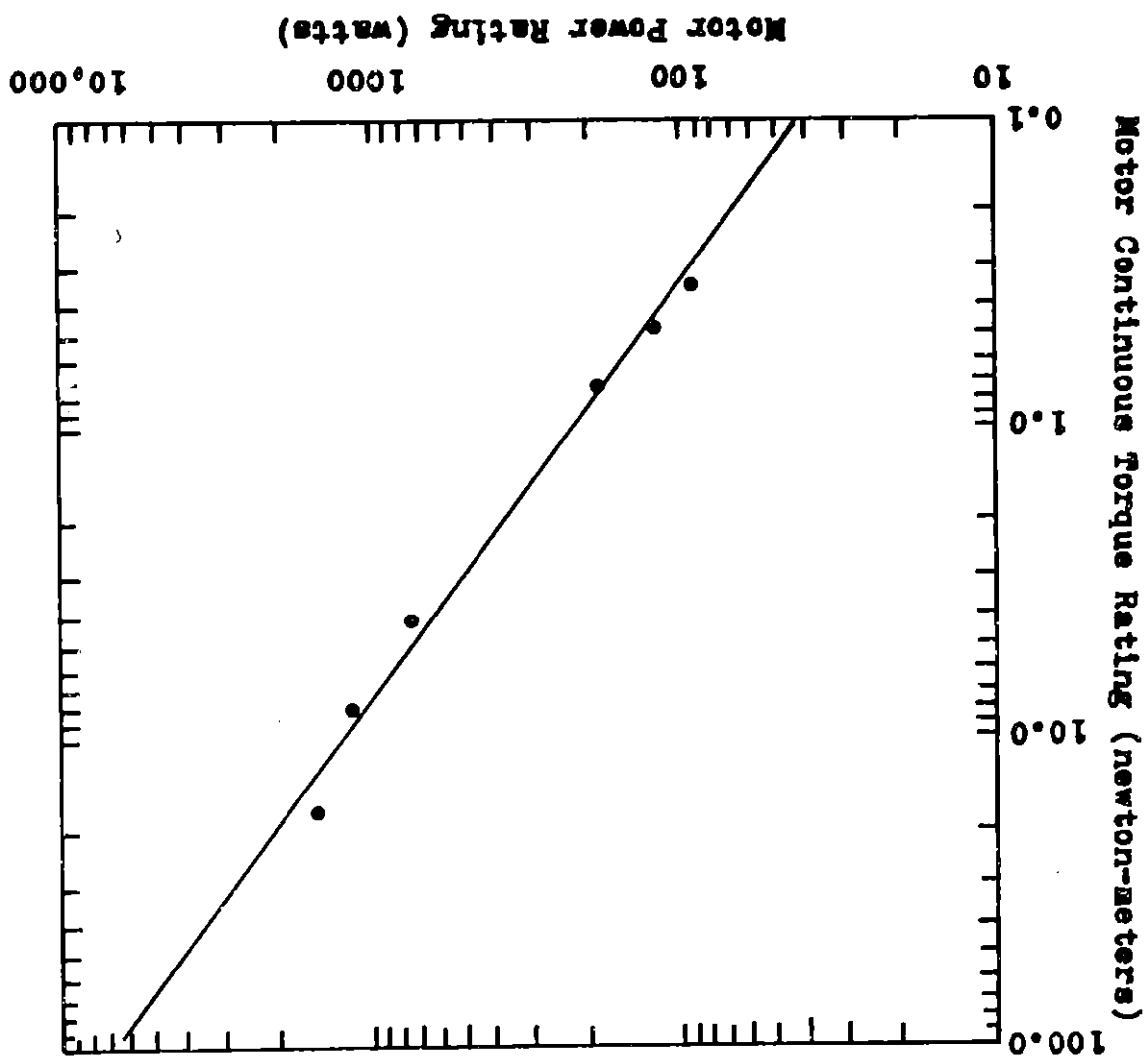


Figure 8.7: Motor Torque versus Motor Power

fitted curve used to represent the relationship is

$$\text{CONTRQ} = 6.372 \cdot 10^{-4} * P^{1.357} \quad (8.29)$$

where CONTRQ = continuous torque rating, newton-meters

P = motor power rating, watts

- 2) Motor mass vs. motor power. This relationship is shown in Figure 8.8. Here, the manually fitted curve is

$$\text{MM} = 6.76 \cdot 10^{-2} * P^{.875} \quad (8.30)$$

where MM = motor mass, kg

P = motor power rating, w

- 3) Motor length vs. motor power. The data and the following manually fitted relationship are shown in Figure 8.9.

$$\text{ML} = 2.34 * 10^{-2} * P^{-4} \quad (8.31)$$

where ML = motor length, m

P = motor power rating, watts

- 4) Motor rotor inertia vs, motor power. The following relationship was fitted to the data shown in Figure 8.10.

$$\text{JM} = 3.2 * 10^{-6} * P \quad (8.32)$$

where JM = motor rotor inertia, nt-m-sec²

P = motor power rating, watts.

- 5) Ball screw lead length vs. diameter. Ball screw lead length (that is, the distance the ball nut travels down

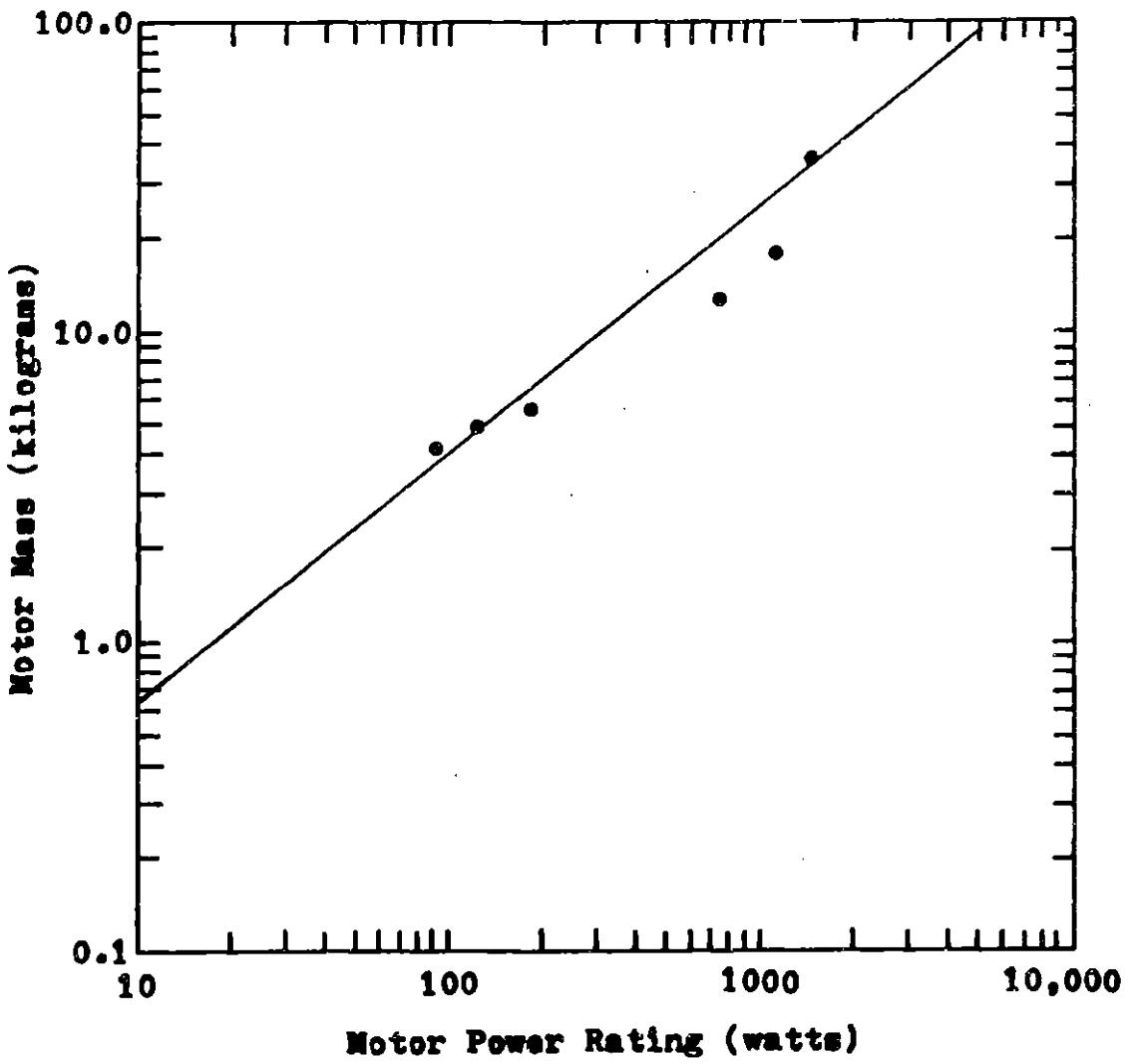
Figure 8.8: Motor Mass versus Motor Power

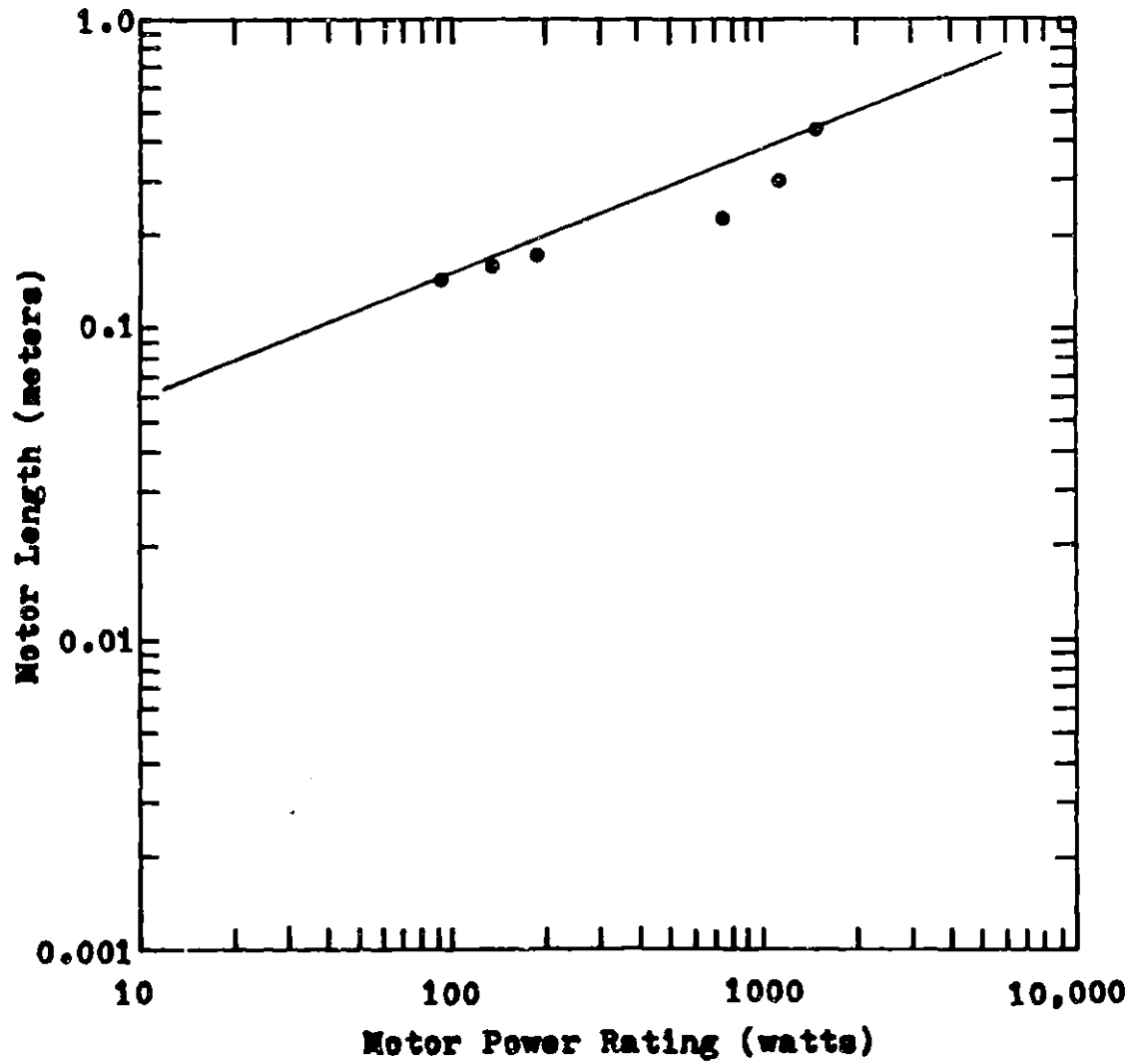
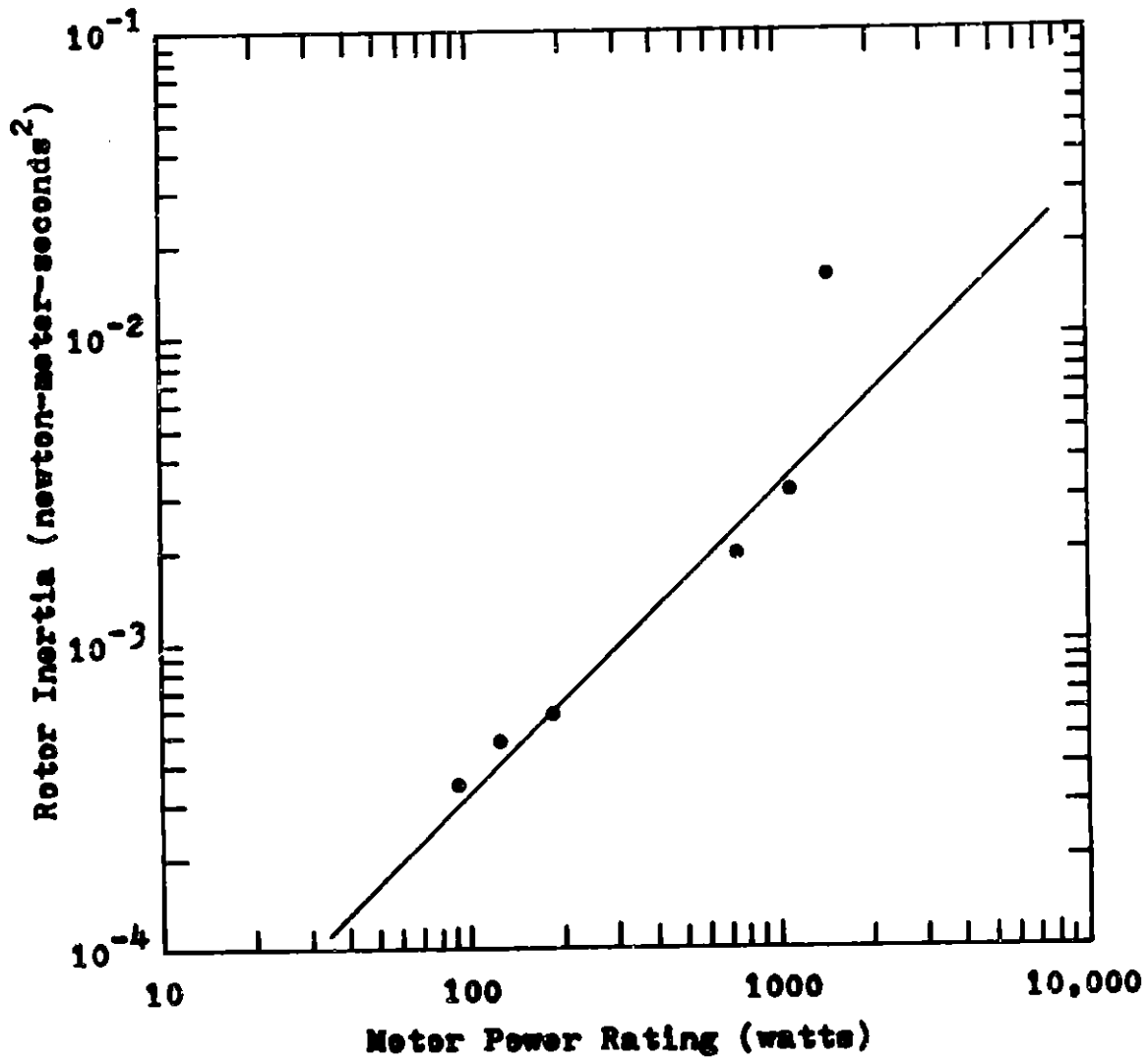
Figure 8.9: Motor Length versus Motor Power

Figure 8.10: Motor Rotor Inertia versus Motor Power

the long axis of the screw during one screw rotation) may be modeled as proportional to the diameter of the ball screw. However, the proportionality constant may vary through a range from .1 to 1.0 .

- 6) Ball screw diameter and axis stiffness. The diameter of the ball screw was specified so that the vertical deflection of the horizontal axis (ball screw and stiffener) was less than a certain maximum amount when carrying the payload. This deflection was set at $5 * 10^{-3}$ inch. The diameter of the vertical axis ball screw was specified so that the vertical axis (ball screw and stiffener) would meet the same deflection criterion if the assembler were rotated so that the vertical axis was horizontal.
- 7) Payload scaling law. A power law was used to specify payloads for the different sizes of assemblers. This power law was

$$PL = 10 * DH^{1.301}$$

where PL = payload, kg

DH = length of horizontal axis, m

The effect of this law is to specify a 10 kg payload for an assembler with a reach of 1 m, and a 0.5 kg payload for an assembler with a reach of .1 m. This scaling law was used as a specification rule, and was not meant to describe current industrial manipulator

design. Furthermore this scaling law is not meant to describe absolute maximum payloads, but rather payloads for the purpose of computing power requirements for gross motions.

- 8) Gross motion ratio. A gross motion ratio GRATIO of .4 has been assumed. This is really an estimate based on several different estimates of the time breakdown in a part assembly cycle. One such breakdown is given below. It was generated by examining performance data for an industrial robot currently under development.

a) Gross motion to pick up part	--	1.0. sec
b) Grasp part	--	.5 sec
c) Gross motion to assembly site	--	1.0 sec
d) Assembly fine motion	--	2.0 sec
e) Release part	--	.5 sec
Total	--	5.0 sec

The total average assembly cycle time is about 5 sec for this device, and, since a single gross motion time is roughly 1 sec, the gross motion ratio for the cycle is about .4.

- 9) Settling time fraction. A settling time fraction SETLF of .2 was assumed. This number was obtained from observations of the motion of certain currently available industrial robots.

8.4 Modeling Station Price

Until now we have concentrated on describing the performance of a degree of freedom in terms of the physical parameters of the hardware and the characteristics of the motor. We now turn to estimating the costs associated with the assembly station.

8.4.1 The Basic Model

A basic assumption of the microeconomic modeling work was that the station price should include all costs associated with the station. Therefore, the station price must include

- 1) The cost of the assembler itself.
- 2) The cost of all system equipment directly related to the assembler, such as the cost of the portion of the conveying or indexing device on which the assembler is mounted.
- 3) Cost of engineering, building, and debugging the station.

These costs must all be measured from the point of view of the user of the programmable assembly system.

For the purpose of modeling station price, all station costs can be divided into variable and constant costs.

Variable costs are functions of the parameters that are allowed to vary in a particular design study; constant costs are not. In the present analysis of the three axis assembler, motor power and the size of the assembler are the principal parameters that are allowed to vary and are determined by the part assembly time specification. Costs that are not a function of motor power or assembler size will be assumed constant. In this station price model the variable costs will be developed as functions of motor power and assembler size.

The assumed model for the station price is as follows:

$$\text{STAP} = \text{ASMPRC} + \text{IDXCST} + \text{INTCST} \quad (8.33)$$

where STAP = total station price

ASMPRC = purchase price of assembler

IDXCST = cost of portion of index or conveying device dedicated to the assembler (assumed constant)

INTCST = cost of engineering, building, and debugging station (assumed constant)

Of the terms composing the station price, only the assembler price will be assumed variable.

The assembler purchase price ASMPRC is not the same as the manufacturing cost of the assembler. The firm that makes the assembler must charge a price higher than its direct costs to cover the indirect costs of doing business and to make a profit. Therefore, we assume

$$\text{ASMPRC} = \text{PFCTR} * \text{ASMCST} \quad (8.34)$$

where PFCTR = price factor

ASMCST = direct manufacturing costs of the assembler

In the industrial robot and manipulator industry, the most common value of the price factor is two, and this is the value we will use in this example.

We now turn to the modeling of the direct manufacturing cost of the assembler, ASMCST. Some component costs will be considered constant and some will be considered as functions of motor power or assembler size; that is,

$$\text{ASMCST} = \sum \text{VARIABLE COSTS} + \sum \text{CONSTANT COSTS} \quad (8.35)$$

The items which will contribute to the variable costs are listed in Table 3.2.

Power laws were used to model the parameters of the physical model of assembler performance, but linear models will be used to model the cost relationships. The reason is that the cost data is fitted better by linear relationships, at least in the area of interest. In particular, the cost function of an assembler component is often the sum of a constant, fixed cost and a variable cost that is linear with respect to the cost function. When plotted on log-log scales, the constant cost component produces a horizontal asymptote at the low end of the curve resulting in a curved plot.

Table 8.2 Variable Component Costs for Example
 Three Axis Assembler Design

Horizontal Axis Motor

Horizontal Axis Amplifier

Horizontal Axis Hardware (includes ball screw)

Rotary Axis Motor

Rotary Axis Amplifier

Vertical Axis Motor

Vertical Axis Amplifier

Vertical Axis Hardware (includes ball screw)

Table 8.3 lists the components whose costs will be considered constant for this analysis. Notice that a direct labor cost for assembling the components is included.

Table 8.3: Components with Assumed Constant Cost

Horizontal Axis Tachometer

Horizontal Axis Resolver

Rotary Axis Tachometer

Rotary Axis Resolver

Rotary Axis Hardware

Vertical Axis Tachometer

Vertical Axis Resolver

Assembler Base

Gripper

Resolver Converter

Processor

Miscellaneous Components

Direct Labor

Index Device Segment

System Integration Cost

8.4.2 Empirical Price Relationships

Empirical price relationships have been developed for DC motors and their driving amplifiers as a function of the motor power. Also, an approximate price relationship has been assumed for the ball screw axes as a function of their length. Nominal values have been assumed for the remaining constant costs and will be presented here.

- 1) Motor price vs. motor power. The data and the fitted empirical relationship are shown in Figure 8.11.

The relationship is

$$\text{MOTCST} = 580. + .446 * (P-1118.55) \quad (8.36)$$

where MOTCST = motor cost, dollars

P = motor power rating, watts

This relationship gives a reasonable estimate for motors up to about 2000 watts.

- 2) Amplifier cost vs. motor power. The data and the manually fitted relationship are shown in Figure 8.12.

The relationship is

$$\text{APCST} = 180. + .2667 * (P-500) \quad (8.37)$$

where APCST = driving amplifier cost, dollars

P = motor power, watts

The amplifier power capacity is usually higher than that of the motor with which it is matched. The pricing function for the driving amplifiers must take this into account.

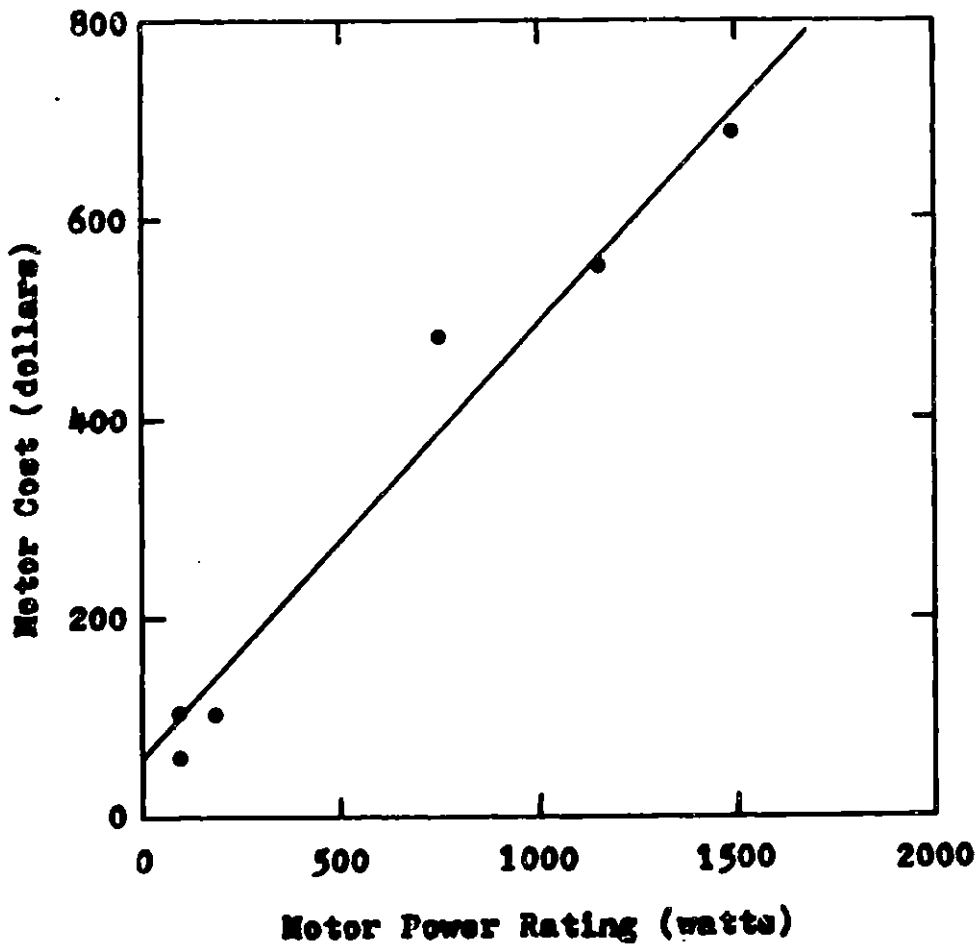
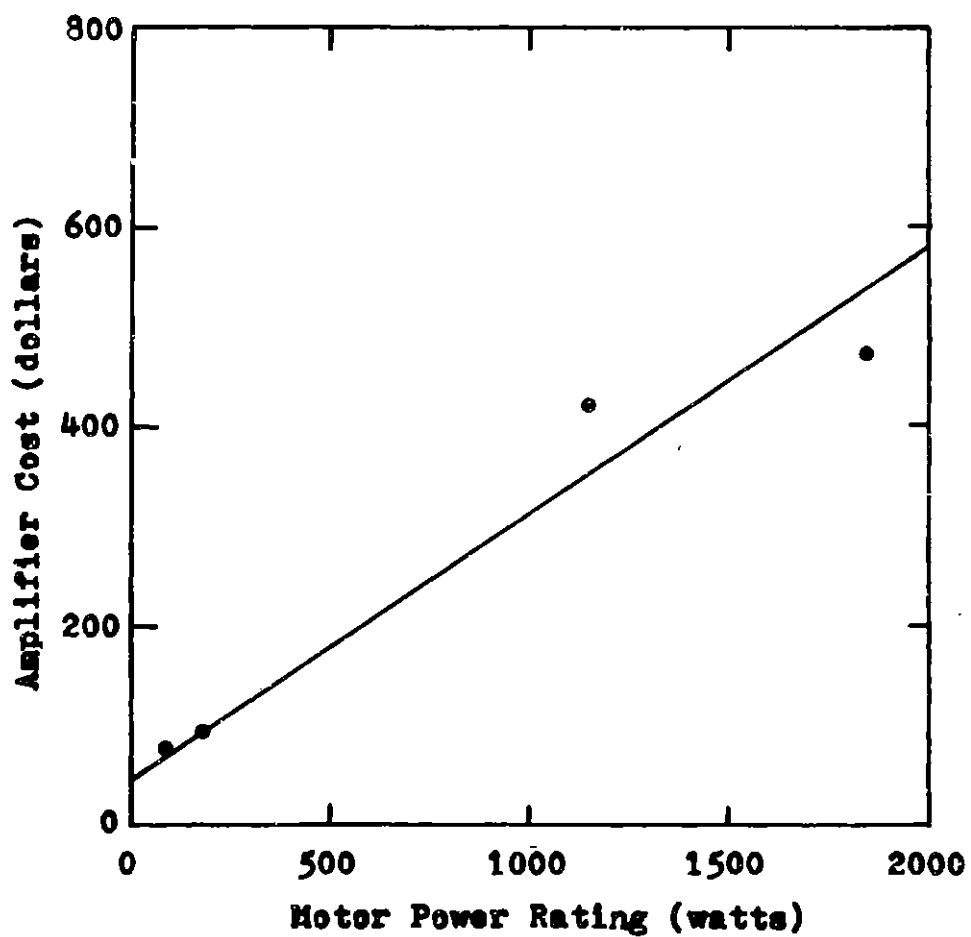
Figure 8.11: Motor Cost versus Motor Power

Figure 8.12: Amplifier Cost versus Motor Power

- 3) Ball screw cost vs. ball screw length. The data and empirical relationship for the cost of the ball screws is shown in Figure 8.13. This relationship is approximately

$$\text{BSCST} = 24 * D \quad (8.38)$$

where BSCST = ball screw cost, dollars

D = length of ball screw, m

Given the variation among ball screw prices, this relation can only be a rough approximation at best. Fortunately, the cost of the ball screw is not a large fraction of the total assembler cost.

- 4) Constant costs. A list of constant costs is given in Table 8.4. These costs do not vary as the actuator power or size is varied.

The assumptions leading to one of the constant costs--the system integration cost--are important and should be discussed. The system integration cost is the engineering, debugging, and machine shop labor that is devoted to the integration of the programmable assembler into a station of the programmable system. It does not include similar labor devoted to the implementation of parts feeding equipment surrounding the station. It is assumed that both the assembler and the conveying or indexing chassis are purchased complete from suppliers. The assembly station integration task consists of mounting the assembler on the

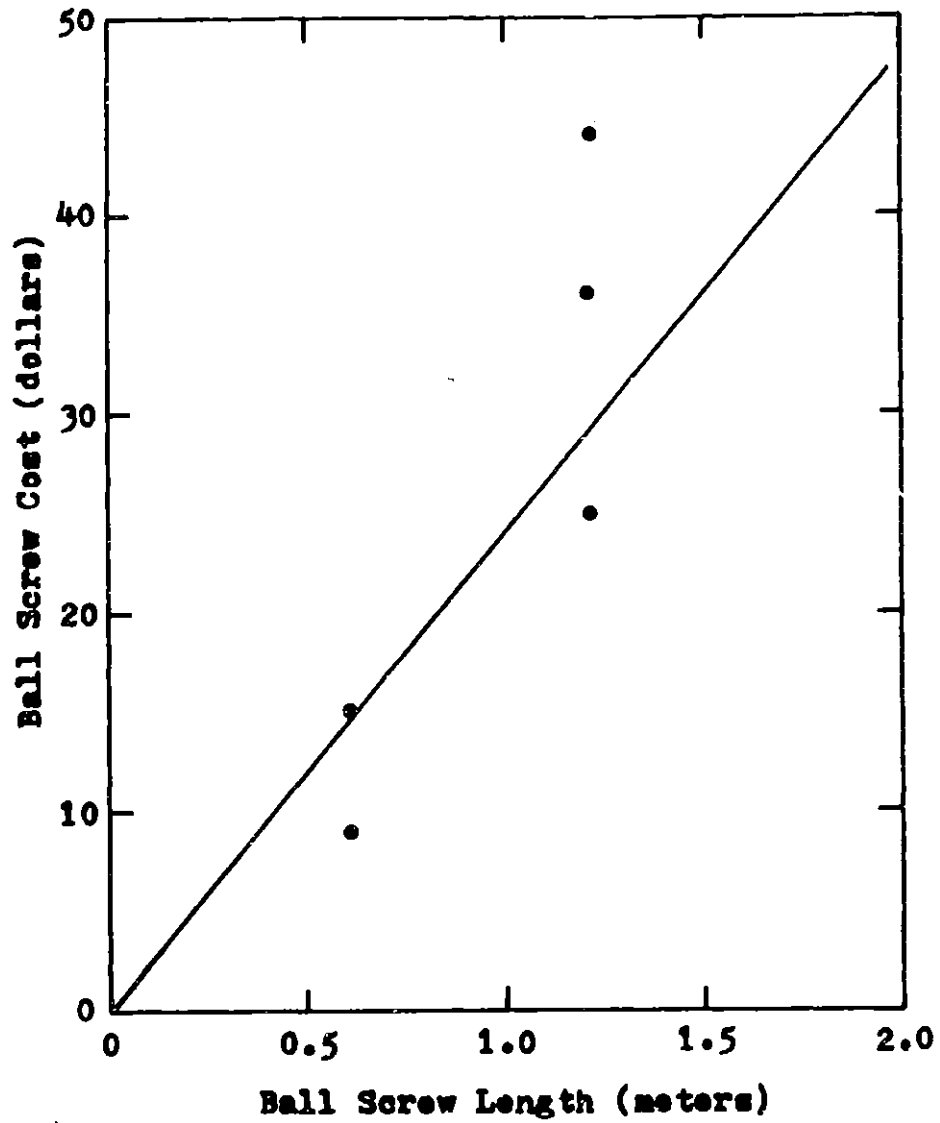
Figure 8.13: Ball Screw Price versus Length

Table 8.4: Values for Constant Prices for Example
Three Axis Assembler Design

Tachometer	\$150
Resolver	\$50
Rotary Axis Hardware	\$50
Assembler Base	\$100
Gripper	\$200
Resolver Converter	\$600
Processor	\$4000
Miscellaneous Components	\$1000
Direct Labor	\$500
Index Device Segment	\$2000
System Integration Cost	\$4000

conveying device in a location so that it is positioned properly with respect to the product and the part presentation devices. The programmability of the assembler means that its location need not be specified particularly accurately although angular alignment accuracy for a three axis device may be important.

After the assembler and the parts feeding tooling are mounted on the chassis, the assembler must be programmed (using stock routines) to execute its assembly task sequence. This programming process may go through a few cycles before a satisfactory program is developed. The system integration cost estimate of \$4000 per station is roughly one man-month of an engineer's time plus supporting technician labor.

Both the variable and constant costs presented in this section should be considered as examples only. They should be viewed as merely estimates of unit costs for quantity purchases of the components. They are certainly not meant to represent the best available prices.

8.5 Sample Results

8.5.1 Sample Price-Time Curves

The design process described in the previous sections has been used to develop a set of price-time curves shown

in Figure 8.14. Each curve represents a different assembler size.

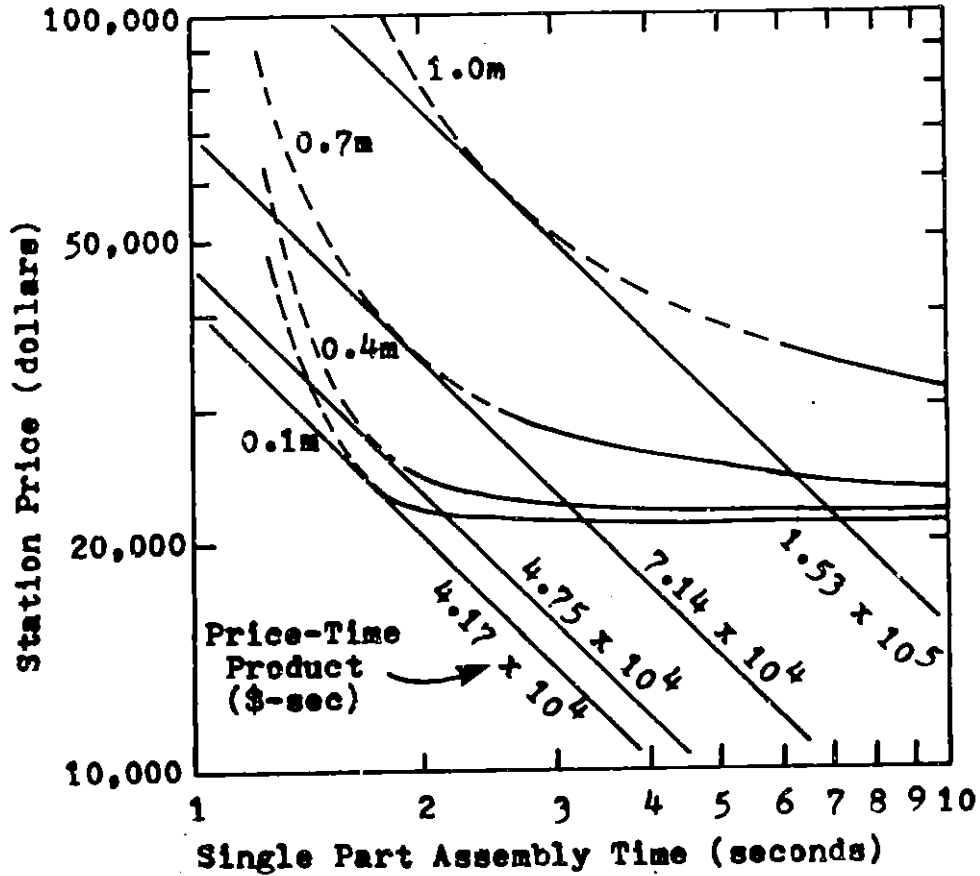
The assembler size is defined by the length of the horizontal axis. The vertical axis is assumed to have the same length as the horizontal one. The rotary axis is assumed to have nearly 360 degrees of motion range, but most of the motions made by the rotary axis are assumed to be less than 90 degrees.

The curves in Figure 8.14 show how the station price for an assembler increases with requirements for shorter single part assembly time. The curves are plotted using dashed lines where an individual actuator power was specified in excess of 3000 watts to show how power requirements increase with assembler size. The actuators become very heavy and bulky for large power, and so then the practicality of the design becomes questionable. In cases for the larger assemblers, the price-time product minimum occurs in the region where an individual actuator power exceeds 3000 watts.

The constant cost components begin to dominate for the longer part assembly times where the price-time curves become very flat. Station assembler designs in this region have nearly the same price but widely varying speeds and, therefore, widely varying price-time products.

The spacing of the price-time curves shows that, for this three axis configuration, the effect of assembler

Figure 8.14: Price-Time Curves for Example
Three Axis Design



Price-time curves for example three axis designs in which horizontal and vertical axes are both .1 m, .4 m, .7 m, and 1.0 m respectively. Dashed lines indicate that at least one actuator is over 3000 watts.

size on price-time product is less for the smaller assemblers (less than .4 m). Considering the set of minimum price-time product designs, the increase in price-time product from the .1 m assembler to the .4 m assembler is relatively small compared to the increase from the .4 m to the .7 m assembler, or from the .7 m to the 1.0 m assembler. Hence, for the assembler design represented by this model, the size of the assembler is a more important influence on the price-time product if the assembler is large than if it is small.

The design of an assembler is a complicated process involving many kinds of constraints. The price-time curves of Figure 8.14 represent the results of a very simple model of assembler cost and performance for one type of assembler. Their use in this thesis is to examine general trends and to obtain some estimate of what price and performance may be possible for a three axis assembler of this particular type. In the following section, the "sensitivity" of this design to various important parameters will be defined and discussed as an aid to identifying areas of further research work in assembler design.

However, if the price-time curves of Figure 8.14 are used as part of a design process for a specific assembler, then it is important that the curves be refined at succeeding stages of the design process. These

initial curves should be used only to narrow the range of possible designs under consideration rather than to pinpoint an exact one. Once such a range is defined, then the various design relations and assumptions should be reevaluated to be more accurate in the narrower range. The designs should be more thoroughly checked to see if there are constraints not accounted for in the simple formulation that would affect the design in the local range.

For example, the physical size of a 3000 watt motor would make it impractical to use with a small assembler (say .1 m assembler as defined above). The size of the motor was not considered for all the axes in the simple formulation. This is not a problem for the larger assemblers but it is a problem for the smaller ones. Hence, for small assemblers of this type, one of the new design constraints that should be added for specific designs is motor size.

Similar reformulation may have to be repeated several times as the design becomes more specific.

8.5.2 Sensitivities of Price-Time Product to Component Variation

We now examine a particular design point selected from the price-time curves of the previous section corresponding to horizontal and vertical axis length of .4 m and part

assembly time of 1.8 sec. The important physical design statistics are given in Table 8.5. The price breakdown of the assembler station is given in Table 8.6. This is nearly a minimum price-time product design.

By examining the price breakdown we can see that there are certain large components of the station cost; such as the system integration cost, the processor cost, and the cost of the index device. The average hardware cost of each axis is about \$1000, but, because of the price factor of two, the cost per axis to the system user is about \$2000. These large price components are primary targets for further work to develop economic programmable assembly stations.

In order to develop a procedure for assessing the importance of further work in economic assembler design, we define a price-time product sensitivity as follows:

$$PTS_j = \frac{\frac{\Delta(STAP * PARTTIME)}{(STAP * PARTTIME)}}{\frac{\Delta P_j}{P_j}} \quad (8.39)$$

where PTS_j = price-time product sensitivity of parameter j

$STAP * PARTTIME$ = price-time product

P_j = parameter j

$\Delta(STAP * PARTTIME)$ = small change in price-time product

ΔP_j = small change in parameter j

Essentially, the price-time product sensitivity is

Table 8.5 Example Design State for Three Axis
Assembler Design -- Physical Data

DESIGN STATE							
AXES	MASS	LENGTH	DIAM	PITCH	POWER	CONTINUOUS	ROTOR
	KG	M,RAD	M	M/RAD	WATT	TORQUE	INERTIA
						NT-M	KG-M**2
HORIZONTAL:							
MOTOR-	22.2	0.336			750.0	5.08	0.002400
SHAFT-	3.3	0.400	0.026	.0041			
HARDWARE-	1.0						
ROTATE:							
MOTOR-	41.8	0.449			1550.0	13.60	0.004960
ROTATION-	0.0	1.571					
HARDWARE-							
VERTICAL:							
MOTOR-	38.7	0.434			1417.7	9.61	0.003840
SHAFT-	12.5	0.400	0.050	.0079			
HARDWARE-	3.0						

Table 8.6: Example Design State for Three Axis
Assembler Design -- Price Breakdown

AXES		
HORIZONTAL:		
MOTOR-	415.63	
AMPLIFIER -	246.67	
TACH-	150.00	
RESOLVER-	50.00	
HARDWARE-	59.60	
TOTAL-		921.90
ROTATE:		
MOTOR-	772.43	
AMPLIFIER-	460.03	
TACH-	150.00	
RESOLVER-	50.00	
HARDWARE-	50.00	
TOTAL-		1482.46
VERTICAL:		
MOTOR-	713.41	
AMPLIFIER-	424.75	
TACH-	150.00	
RESOLVER-	50.00	
HARDWARE-	59.60	
TOTAL-		1397.76
BASE-		100.00
GRIPPER-		200.00
RESOLVER CONVERTER-		600.00
PROCESSOR-		4000.00
OTHER COMPONENTS-		1000.00
DIRECT LABOR-		<u>500.00</u>
TOTAL ASSEMBLER DIRECT COST		10202.12
INDIRECT BUSINESS COSTS-		<u>10202.12</u>
ASSEMBLER PRICE-		20404.24
INDEX DEVICE SEGMENT-		2000.00
SYSTEM INTEGRATION COST-		<u>4000.00</u>
TOTAL STATION PRICE-		26404.24

the fractional change of the product divided by the corresponding fractional change of the parameter that caused the product change. All other parameters are held constant. For example, in this analysis, the price-time product sensitivity to processor hardware cost is about one third. Therefore, fractional changes in the processor costs will result in the price-time product of one third the size. This definition allows us to rank the relative effectiveness of similar fractional improvements or modifications in any input parameters.

The major sensitivities, for this example, are listed in Table 8.7. When examining these sensitivities it should be remembered that the single part assembly time is a design parameter, and so sensitivities for the other parameters are estimated under the condition that part assembly time is held constant. Major ones are discussed below:

Gross motion ratio. The gross motion ratio is the fraction of the assembly cycle that the assembler spends in gross motion. Increasing the gross motion ratio increases the time allowed for gross motion, keeping the total assembly time constant. The corresponding reduced acceleration requirements mean that smaller, lighter cheaper actuators may be chosen. The practical constraints from fine motion requirements on assembler design are not now sufficiently well understood to model this tradeoff.

Table 8.7 Major Price-Time Product Sensitivities
for Example Three Axis Assembler Design

<u>Design Parameter</u>	<u>Price-Time Product Sensitivity</u>
Gross Motion Ratio	-.376
Torque Transmission Efficiency for Horizontal Axis	-.372
Processor Cost	.301
Range of Motion for Rotary Axis	.243
Single Part Assembly Time [*]	.161
System Integration Cost	.149
Horizontal Axis Length	.128
Torque Transmission Efficiency for Vertical Axis	-.111
Vertical Axis Length	.106
Horizontal Axis Deflection Specification	.104
Other Fixed Costs	.0752
Index Device Segment Cost	.0746
Resolver Converter Costs	.0451

*Sensitivity to Single Part Assembly Time is nonzero
because this design point is not at the minimum price-time
product.

Torque transmission efficiencies for the horizontal and vertical axes. These efficiencies directly affect how much torque is delivered to the load on the axes. However, there is not much room for improvement since ball screws are very efficient. The model assumes a torque transmission efficiency of 0.9 (1.0 is the maximum possible).

Processor Cost. In this example the processor hardware cost, estimated at \$4000, represents a dedicated processor with 20K words of memory. The processor hardware requirement is a rough estimate based on current experimental work. The price estimate corresponds to currently available equipment, and, since computing hardware costs are dropping, corresponding decreases in the price-time product can be anticipated.

Horizontal axis length. Increasing the length of the horizontal axis increases its inertia. This occurs not only because inertia depends directly on the axis length, but also because the axis ball screw must increase in diameter to maintain the deflection criterion, and because larger payloads are specified for larger horizontal axes in this model. The increased inertia and motion distance require a more powerful, and therefore heavier, actuator.

The sensitivity of the horizontal axis length also includes the effects of increases in the other two axes which are necessitated by the increase in the horizontal axis length. The increased inertia from the horizontal

axis and the larger horizontal actuator require a larger and more powerful rotary actuator. The accumulated inertias of the horizontal and rotary axes require a larger and more expensive vertical actuator. The larger rotary and vertical actuators and the larger driving amplifiers that they require add to the sensitivity of the horizontal axis length.

Range of motion for rotary axis. The most powerful, and expensive, motor in the design is the rotary axis motor. Accordingly, among the three axes the range of the rotary axis has the greatest sensitivity. In addition, if the range of motion of the rotary axis is increased, it necessitates an increase in the size of the vertical axis actuator, similar to that described for the sensitivity of the horizontal axis length.

Vertical axis length. An increase in the vertical axis length does not affect either the horizontal or the rotary axis. Therefore, the sensitivity of the vertical axis length depends only on changes in the vertical axis and actuator.

Single part assembly time. At the true minimum price-time product design this sensitivity is zero. However, the value here is nonzero because this design is close to, but not exactly on, the true minimum.

System integration cost. The system integration cost is a large fraction of the total station price. It will be

reduced if the ease of integrating the station is improved, perhaps by creating standard mounting schemes using standard assembler base frames and standard indexing chassis frames.

All of the remaining sensitivities listed in Table 8.7 should be used as an approximate guide to design refinement work. They indicate only the degree of "leverage" of a parameter or component. However, components may differ in their present state of refinement; it may be "easier" to develop a certain fractional improvement in one component than another. A combination of engineering judgment concerning the state of development of a component and an estimate of the component sensitivity should be used to guide design refinement work.

8.6 Summary: Consequences for Research and Development of Assembler Stations and Components

An example design process has been presented to illustrate the use of the price-time product in the design of a programmable assembler. Minimization of the price-time product is a means of resolving tradeoff analyses in favor of the most economic designs. Sensitivity analysis using the price-time product may be used to assess the potential improvement in assembler performance resulting from improved cost/performance of an assembler component.

The example presented in this chapter is only one possible formulation of a design tradeoff issue. Many different formulations could be made for different axis configurations, different numbers of axes, different types of actuators, and so on. As models become available for other aspects of assembler performance, they may be incorporated into similar price-time product analyses.

More research in the area of fine motion is required. The gross motion ratio sensitivity indicates that reduced fine motion time would be significant. Current estimates of fine motion time are based only on limited experience. Research should be directed toward identifying fine motion options and modeling their cost and performance. Then these models could be used in price-time product studies.

The sensitivity of the integration cost indicates more research work is needed here. This is another case in which better models are needed. In particular, how is the integration cost for a programmable assembler affected by:

- 1) Standardization of assemblers and indexing chassis?
- 2) Availability of a range of stock assembly task programs from which to choose?
- 3) Ease with which different programs may be tried in the debugging process?

One way to obtain this modeling information would be to execute a series of experiments in which an assembler

station is set up for a range of products or subassemblies, keeping track of time spent in the various phases of the integration.

The processor sensitivity is large, and, even though processor costs are declining, it is still important to strive for minimum cost processor designs. Delegation of certain computing chores to microprocessors is one way of reducing overall computing costs, and so identification of candidate functions for microprocessors becomes an important research goal.

Finally, both the size of the assembler and the number of axes it contains have a strong influence on the price-time product. Experimental work using real products would provide data relating the lower limits of the practical size of an assembler in relation to the subassembly and would provide practical information about the number and arrangement of degrees of freedom that are required.

9. ECONOMIC IMPACT ANALYSIS: BACKGROUND AND
APPLICATION TO PROGRAMMABLE ASSEMBLY

9.1 Introduction

We live in a complex and interrelated society. Technological innovations impact the society in a process that develops over time and spreads throughout the society as the new technology eventually becomes a part of it. The societal changes which can be brought about by the new technology include many which are economic.

This chapter will first discuss these changes, or impacts, and then will develop the concept of an economic impact analysis. Next, this general economic impact analysis will be discussed with respect to programmable assembly technology. Adequate data bases in a suitable form do not exist yet for a thorough impact analysis of programmable assembly systems, but a procedure for making such a study will be presented.

9.2 Types of Economic Impact

Several different types of economic impact are listed below:

Cost savings

Conservation of scarce resources

Job displacement

Changes in the balance of payments

Changes in business patterns

Although these results of technological change can be identified individually, they are all interrelated. These impacts and their interrelations are discussed in this section.

The most obvious impact is the direct cost savings that occurs when new technology is substituted for old methods. Fewer inputs such as capital, labor, material, or energy are required to produce the same goods. The cost savings in these inputs that occur when a new technology is applied result in an increase in the national wealth, or, alternatively, in conservation of scarce resources.

If a new technology reduces labor requirements, then job displacement can be a problem even though the per capita national wealth has increased. The distribution of the wealth has changed. Certain jobs have been eliminated and others created by new technology; for example, frequently, the new technology reduces unskilled labor requirements and produces fewer jobs requiring greater skill. This can bring industries back to the United States that have moved overseas in search of cheaper unskilled labor. If new technology can produce the goods cheaper than they can be made overseas, then skilled jobs are created in this country, the per capita national wealth is increased, and the balance of payments is improved. However, although the net effect of certain technologies may be the creation of employment in the long run, those workers who are displaced will be adversely affected unless compensatory measures are taken.

New technology can affect business patterns, particu-

larly if it affects the ease with which manufacturing lines can be set up and modified. Inflexibility of present manufacturing processes has often blocked product improvements, so that if the new technology increases manufacturing flexibility, modifications can be made more easily in the process and the product. Products can then be improved without substantial modifications to the production equipment, and product improvement will become more routine.

9.3 Economic Impact Analysis

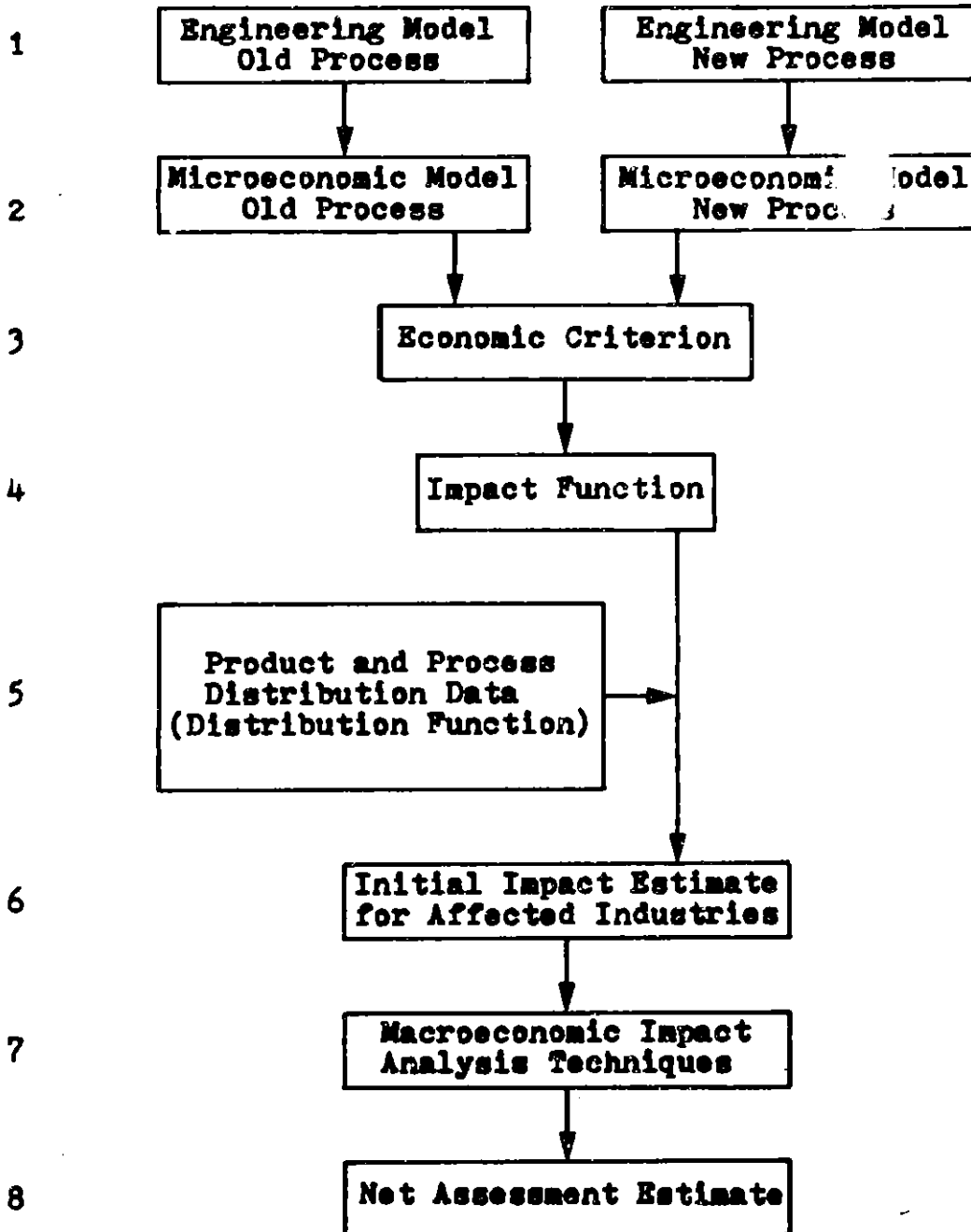
9.3.1 General Description

Economic impact analysis is a study of the economic impact of a new technology upon society. One method for such an analysis is illustrated in Figure 9.1. First, the method will be described in general, and then an example will illustrate the use of the method.

The impact study of a specific new technology must begin with a thorough understanding of the basic technological processes (Level 1 in Figure 9.1). The next step is a microeconomic analysis in which the technical performance is related to its costs (Level 2). Then the microeconomics of the new technology is compared to the microeconomics of the present methods to determine under what conditions the new technology is economically superior and, if so,

Figure 9.1: Economic Impact Analysis Method

Level



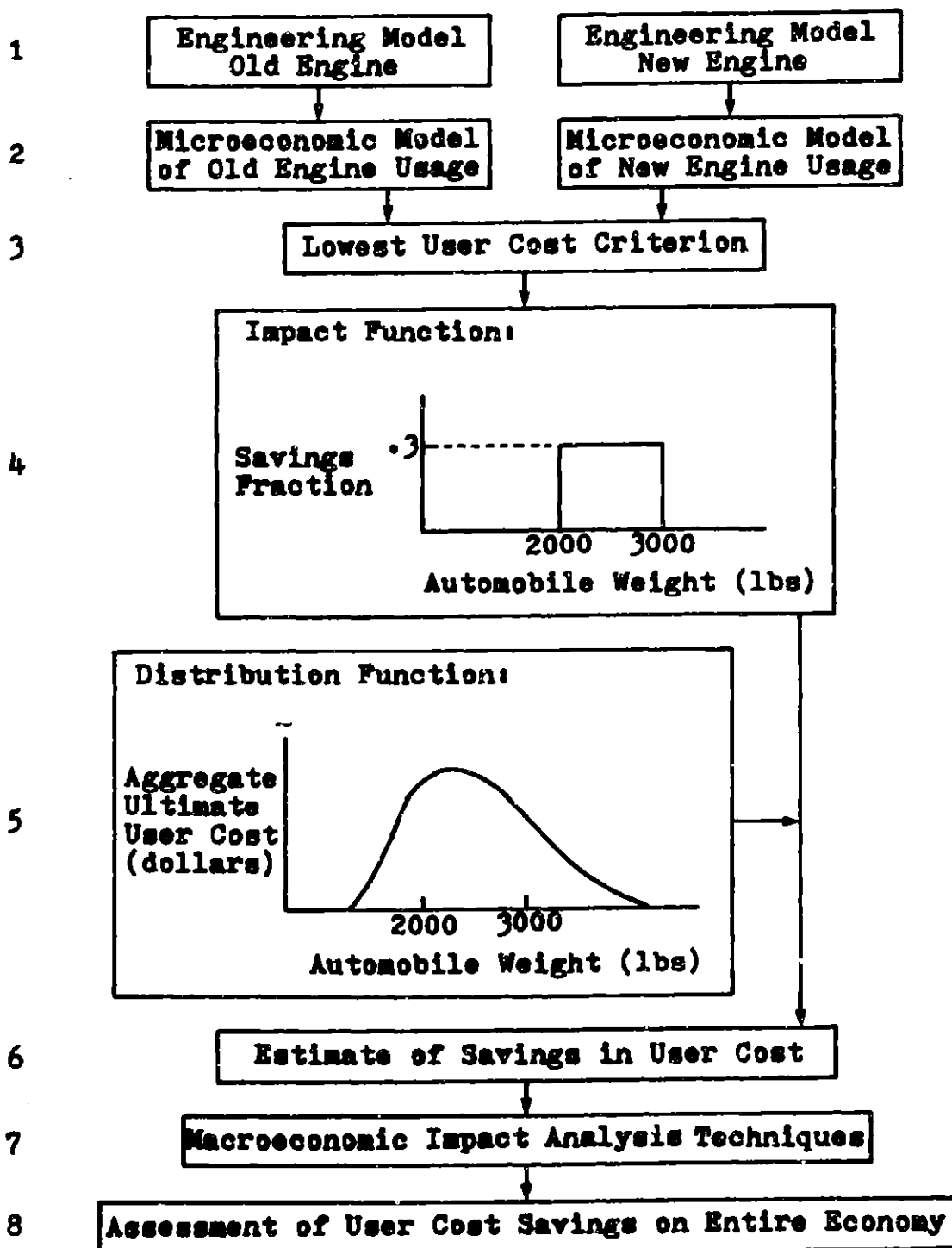
how superior it is (Levels 3 and 4). These conditions may be expressed as an "applicability rule" or impact function for the new technology. This impact function expresses impact variables as a function of product and/or process variables. An example of an impact variable is manufacturing cost per unit, and examples of product or process variables are size of product and number of product units made per year. Next, the impact function should be applied to industrial or national data concerning the important product or process variables (in the form of a distribution function) to determine the extent of application of the new technology and its direct economic impacts throughout the entire economy (Level 8).

9.3.2 Example of Economic Impact Analysis

A simple example show in Figure 9.2 will serve to illustrate this process. Suppose that a new type of automobile engine is developed. First, the performance of the new engine design must be well understood, especially the relationships between weight, power, fuel consumption, types of exhaust gases, serviceability, type of fuel required, and so on (Level 1). The microeconomic analysis would include relating the technological design parameters such as operating cost, manufacturing cost, servicing cost, and ultimate user cost (Level 2). If we assume that ultim-

Figure 9.2: Example of Economic Impact Analysis Using a Hypothetical Automobile Engine

Level



ate user cost is the important cost parameter that governs the acceptance of the new engine design, then the ultimate user cost of the new engine design should be compared to the ultimate user cost of conventional engines in similar automobiles. Minimum ultimate user cost is the selection criterion. The comparison between the new technology and the old will then yield the impact function. The form of the impact function will depend on the important variables in the comparison. For example, a conceivable result of the comparison might be that the new engine results in a 30 percent savings in ultimate user cost in automobiles weighing between 2000 and 3000 pounds and no savings for other weight ranges (Level 4). The impact function then relates percentage savings of ultimate user cost to automobile weight. The function is equal to zero for all engine weights except those between 2000 and 3000 pounds, where it is equal to .3 . The direct economic impact estimate is obtained by applying this function to distribution data for the total national user cost (Levels 5 and 6). This data would be in the form of a distribution function representing the total national user cost for all automobiles in different weight ranges. Finally, macroeconomic techniques (Level 7) are used to estimate the way this savings in cost stimulates the rest of the economy (Level 8).

9.3.3 Inclusion of Dynamic Factors

The example presented above is a static analysis because it does not directly take into account the dimension of time. A static analysis shows the impact that would occur if a new technology were instantly applied to all the processes in the economy. However, conversion from an old technology to a new technology is not, in general, instantaneous. Alternatively, the analysis can be perceived as an approximation of the current state of the economy if the new technology had been available for a sufficient length of time so that it had been fully integrated into the society.

Another problem of a static analysis is that it does not take into account trends which may affect the impact of the new technology. For example, in the case of the hypothetical automobile engine analysis presented in section 9.3.2, a better impact analysis would result if the impact function were compared to the predicted future distributions of automobile weight. If cars are growing smaller, then the fraction of new cars in the relevant weight range will become smaller so that the actual resulting impact is less. The impact analysis should not be just a static estimate but should incorporate any dynamic factors. Some examples and a discussion of each are given below:

1) Changes in Product Demand

Impacts estimated using recent industry data must be adjusted in light of the overall trends of product demand leading to a growth or decline of the industry, especially if the growth or decline is fast. Growing industries may realize the benefits of the new technology as a means of production growth and cost savings with fewer of the job displacement problems than a more stable or declining industry would experience. Declining industries contemplating a conversion to new technology face a potentially greater risk of job displacement problems because they would be losing jobs even without the introduction of the new technology. Therefore, the reasons for the decline have to be examined in order to perform an accurate impact analysis. If the product of an industry has simply become obsolete for many uses, as vacuum tubes did when transistors were introduced, then reduced costs of production would not materially affect the decline. But, if the industry has declined because of cheaper foreign competition, then reduced production costs in the United States may well revive the industry and create new jobs here.

2) Changes in Manufacturing Technology

Technologies are continually emerging which profoundly affect existing industries. Therefore, an important initial part of an impact study is a technological forecast both within the industry and outside of it. The purpose

would be to identify dominating trends which would affect the fate of the industry beyond the influence of the new technology considered for assessment. For example, it is possible that changes occurring now will eventually eliminate the process for which the new technology was intended. If a product that was assembled from a few pieces is being replaced by a similar product that is molded in one piece, then not only will the assembly jobs be eliminated, but the entire assembly process will be eliminated as well.

The process being considered for improvement by the introduction of one new technology may be changed indirectly by another new technology in such a way that the planned improvement is no longer applicable. For example, a change in the material of a product from metal to plastic may require a change in the final inspection procedure for plastic parts.

3) Changes in Product Technology

Most new technologies do not last forever—they are eventually replaced by improved technologies. Realistic impact analysis should take into account a reasonable life cycle for the new technology. The history and traditions of the industry could be used to help make this estimate as well as any knowledge of advanced work in research laboratories.

9.4 Economic Impact Analysis of Programmable Assembly

The discussion up to this point has been about impact analysis of technological production innovation in general terms. We now turn to impact analysis of programmable assembly systems. A thorough study cannot be done at this time because of the lack of adequate data on the industrial or national level that is suitable for use in the impact analysis described in this chapter. However, a simplified impact analysis is presented in section 9.4.1, and the remaining sections of the chapter discuss the important issues of programmable assembly impact analysis.

9.4.1 The Impact Analysis Process

We now examine how an impact analysis appropriate for the level of modeling presented in previous chapters could be performed for programmable assembly automation.

The engineering modeling of the alternate assembly technologies (Level 1) and the microeconomic modeling (Level 2), the first steps of the impact analysis, have already been performed in previous chapters. The comparison of the alternate assembly methods using an economic criterion (Level 3) has also been discussed. The economic criterion used was to choose the assembly method that yields the lowest assembly cost per unit. (It was from

this comparison criterion that the design criterion of minimizing the price-time product was chosen.)

The next step in the impact analysis is to develop an impact function. This function should represent the savings that occur with programmable assembly as a function of product and process variables. In the analysis of the preceding chapters, there are several variables that affect the application of programmable assembly as a function of product and process variables. In the analysis of the preceding chapters, there are several variables that affect the application of programmable assembly, but the two most important variables are the required product production volume and the physical size of the product. The production volume is used explicitly in the examples and the equations, but the influence of the size of the product is implicit in the values of the parameters of the equations. For example, the price of a programmable assembler must increase as its size increases to handle larger products. The average cost of the parts feeding tooling will also increase with an increase in product size. As was shown in Chapter 3, the transfer machine cost per part increases with product size. Finally, the average manual assembly time, and therefore cost, will also increase with product size.

We will assume that all products will be divided into a set of product size classes. The smallest size class

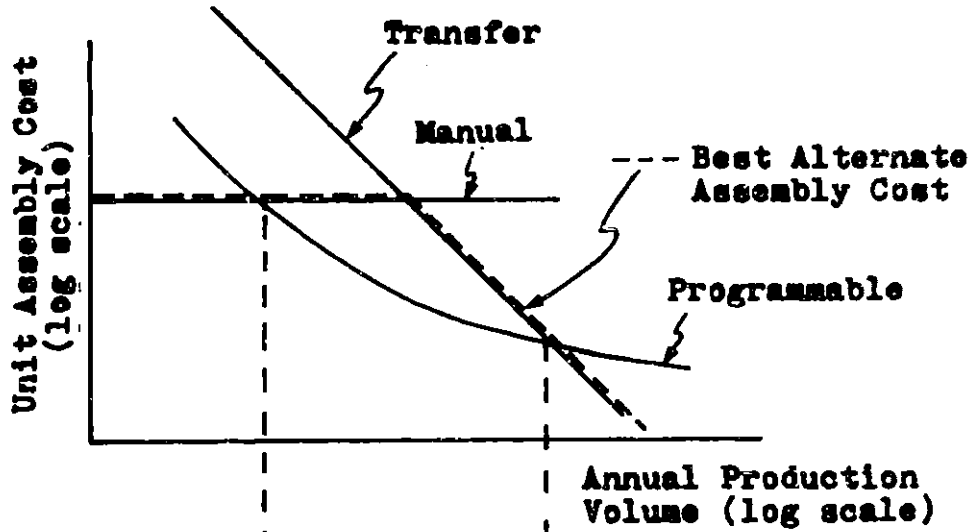
will be perhaps a maximum of four inches in dimension and would correspond to the limits of the smallest transfer assembly machine—the small rotary table. The largest size class would perhaps be for products up to 30 inches in length and would correspond to the size limits for the non-synchronous transfer assembly machines. A few intermediate size classes could correspond to the limits of intermediate transfer assembly machine methods.

The impact analysis process will be repeated for each product size class and the results will be summed for the total impact. By choosing the set of product size classes to correspond to the set of the major different types of transfer machines or programmable methods, the results can then have specific meaning for these major different types, as well as contribute to the overall impact analysis.

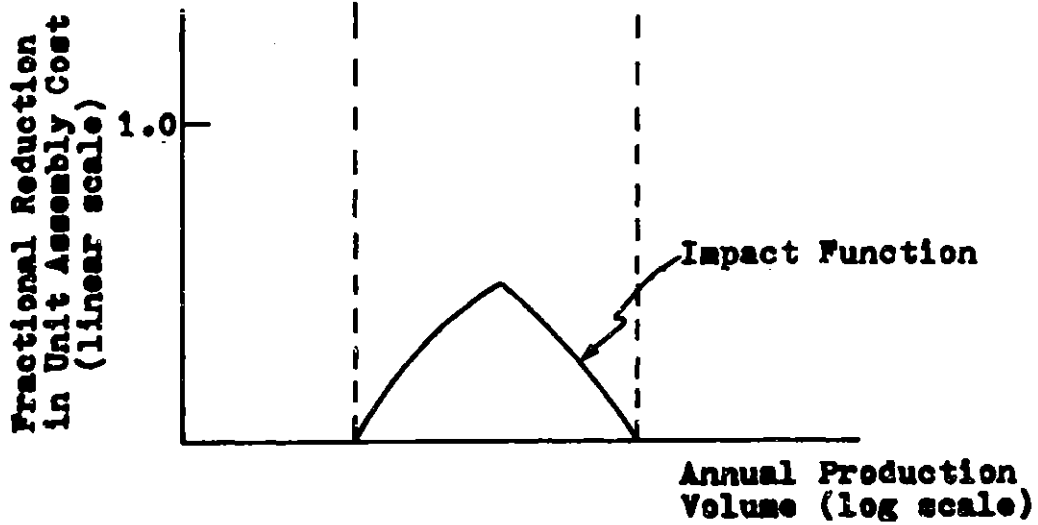
Within the impact analysis for a particular size class, the remaining important variable is production volume. Figure 9.3 illustrates the derivation of the impact functional relationship with product volume. The set of curves at the top represents the unit assembly costs for the major alternate methods of assembly as developed in Chapter 6. If we assume that assembly methods are chosen to obtain the lowest assembly cost per unit, then the savings attributable to programmable assembly over manual and transfer machine assembly are represented by the impact function in the lower part of Figure 9.3. The impact function can be

Figure 9.3: Graphical Derivation of Impact Function

Unit assembly costs as a function of annual production volume:



Impact Functions:



expressed as follows:

$$FCS_j(VOL) = \frac{BACPU_j(VOL) - PCPU_j(VOL)}{BACPU_j(VOL)}$$

if $BACPU_j(VOL) - PCPU_j(VOL) > 0$

$$FCS_j(VOL) = 0 \quad \text{if} \quad BACPU_j(VOL) - PCPU_j(VOL) \leq 0$$

(9.1)

where $FCS_j(VOL)$ = fractional cost savings as a function of volume for product size class j

$BACPU_j(VOL)$ = unit assembly cost for the best alternate method as a function of volume for product size class j

$PCPU_j(VOL)$ = unit assembly cost for a programmable system as a function of volume for product size class j

Here, $FCS_j(VOL)$ is the impact function. The best alternate assembly cost per unit is either manual assembly or transfer machine assembly, whichever is cheaper at a given production volume. We are making the assumption that the best alternate assembly function describes the present day, average unit assembly costs. The savings that programmable assembly bring must be calculated in relation to the unit assembly costs of the best alternate assembly function.

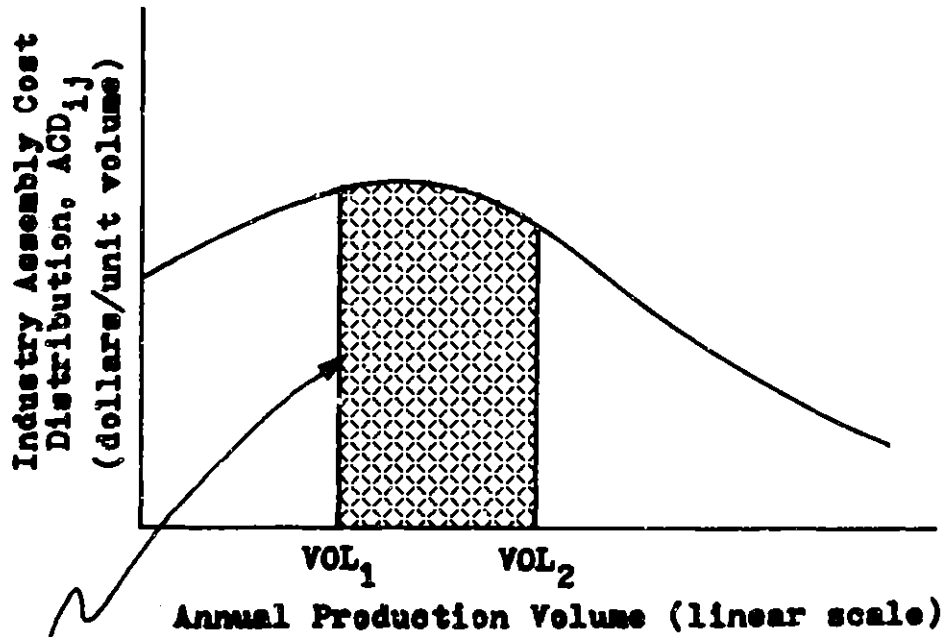
Next, the impact function may be used in combination with a distribution function of the assembly costs incurred at different production volumes to estimate the total cost

savings in an industry due to the introduction of programmable assembly. For the purpose of this analysis an industry is defined as a collection of establishments or firms which manufacture a similar type of product. Examples of industries would include all manufacturers of motor vehicles, "the motor vehicle industry," and all manufacturers of farm machinery, "the farm machinery industry." Different industries will be denoted by a subscript i , and different product size classes by a subscript j . A sample distribution is illustrated in Figure 9.4. A point on the horizontal axis represents products of a specific production volume. The total area under the curve represents the total assembly cost for industry i for all eligible products in product size class j . (The concept of the eligible products will be discussed later.)

The area under the curve between two vertical lines representing two different production volumes VOL_1 and VOL_2 represents the total assembly cost for products which are made in that range of production volumes. For any specific product the production volume is measured with respect to the firms making the product, not the total number of similar products made throughout the industry. For example, assume there are two firms making motorcycles -- Firm A and Firm B. The annual motorcycle production for Firm A is 20,000 while that for Firm B is 30,000. The assembly cost of motorcycles

Figure 9.4: Cost-Volume Distribution Function

Applies to industry i and product size class j



Area represents total assembly cost throughout industry i for products in size class j

would then be represented in the cost-volume distribution function for two separate production volumes, 20,000 and 30,000, rather than combined under the industry total of 50,000.

The only products that should be counted in these distribution functions are the eligible products -- those that can physically be assembled by programmable assembly methods. In this way products that cannot be assembled programmably are eliminated from the impact analysis. The rules that determine eligibility should be broad for ease of data manipulation; for example, rigid machined parts should be considered ineligible. It is not necessary for these broad rules to be absolutely correct in all cases; there may be exceptions to them, and, as research progresses in this area the concept of eligibility can be more accurately and precisely defined.

The impact function and the distribution function can be multiplied to obtain a cost savings distribution function for industry i and product size class j . (See Figure 9.5). Then, the cost savings distribution function is integrated over its volume range to obtain the total assembly savings for industry i in product size class j .

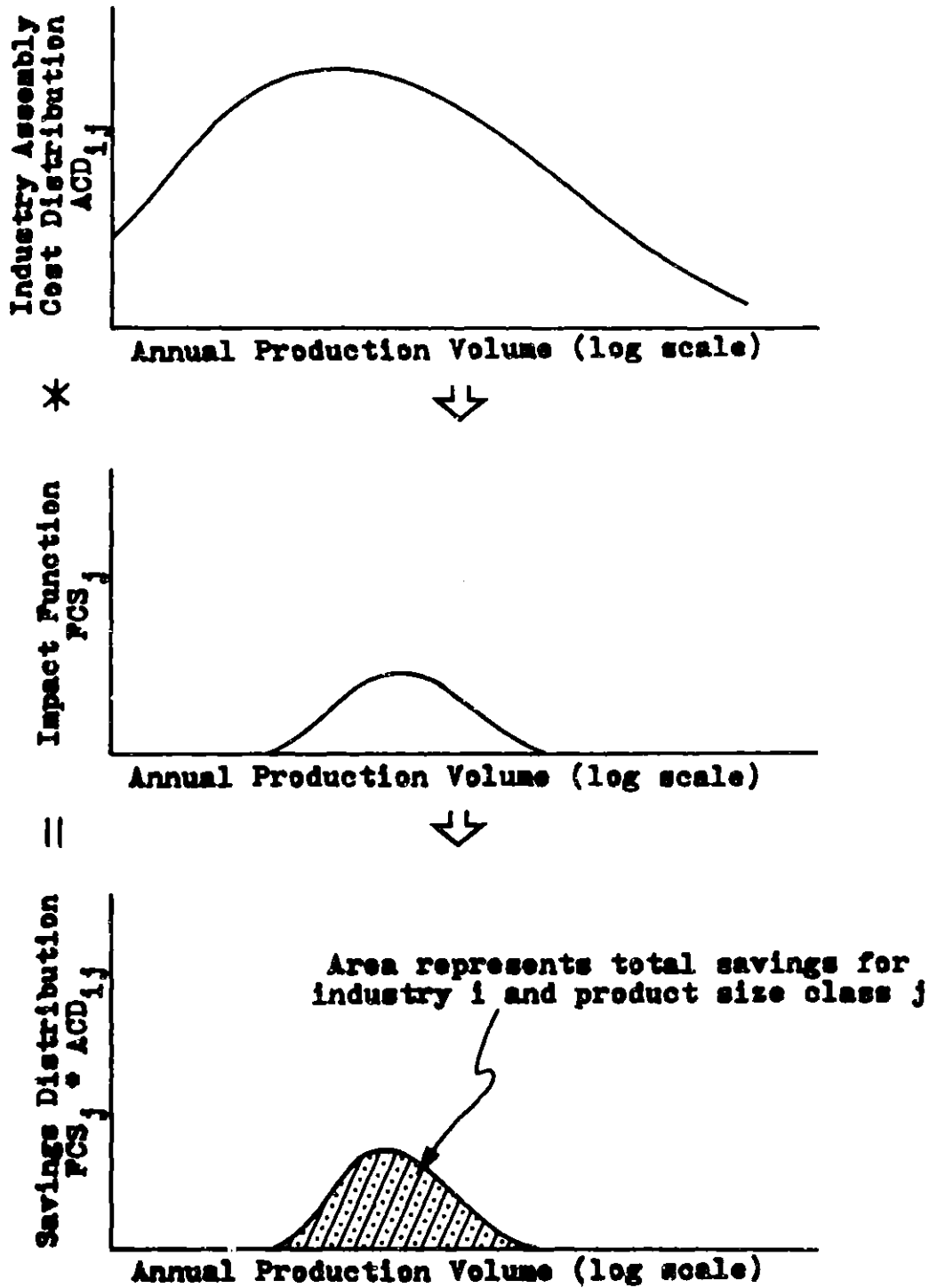
$$SAV_{ij} = \int FCS_j(VOL)ACD_{ij}(VOL)dVOL \quad (9.2)$$

where SAV_{ij} = savings in the i^{th} industry for the j^{th} product size class

$ACD_{ij}(VOL)$ = assembly cost function for i^{th}

Figure 9.5: Application of Impact Function to Distribution Data

Applies to industry i and product size class j



industry in product size class j

Then, this procedure may be repeated for all industries with assembly processes and the results summed for a total industrial sector impact for the programmable assembly automation for that particular product size class.

$$SAV_j = \sum_i SAV_{ij} \quad (9.3)$$

where SAV_j = total industry impact for the j^{th} size class

The entire foregoing procedure may be repeated for products of different size classes and these results summed to obtain an estimate of the total impact of programmable assembly systems for all product size classes.

$$SAV = \sum_j SAV_j \quad (9.4)$$

where SAV = total direct cost savings

Now the techniques of macroeconomic analysis, particularly input/output analysis, can be used to study how the effects of these costs savings on certain industries spread throughout the economy. These techniques have been developed quite well by others and can be used in their present form in connection with the impact analysis of programmable assembly systems. This completes the major steps of the impact analysis. Two comments concerning the preceding analysis should be made at this point. First, this impact analysis is concerned only with the use of programmable assembly in the manufacture of uniform products;

that is, this is not an assessment of the impact of programmable assembly on the manufacture of product families. Second, even though this was a restricted, simple assessment process, the amount of data required is large. Distribution data of the assembly cost by product size and industry is required for the entire economy. To obtain this distribution data would require large amounts of data obtained originally at the level of the firm and then aggregated by industry over many industries and then repeated for a few different product size classes.

9.4.2 Extension of Impact Analysis to Product Families

To assess the impact of programmable assembly on the manufacture of product families would require detailed information obtained at the level of the firm and aggregated to the industry level. Distribution data would be needed relating the total assembly cost in an industry to the annual volume of product families for a given product size. It may be necessary to define a set of product family classes in which the members of each class have roughly the same degree of variation. At one extreme would be a product family class in which only a small fraction of the parts of a product varied between family members. At the other extreme a large fraction of parts may vary between family members. A microeconomic and engineering analysis of

programmable and hybrid systems applied to product families such as described in Chapter 6 could be used to develop a set of impact functions for products of different sizes which belong to product families with different degrees of differentiation.

9.4.3 Identification of Impact Costs

A thorough impact analysis of programmable assembly systems should include as many affected costs as possible. However, a simplified analysis such as that just presented which looks at only the major costs is much easier to work with and points out the major trends. The analysis of earlier chapters has been based on only the major costs of capital equipment and labor, but in specific circumstances other costs may determine whether or not the system is economically justifiable. These other affected costs include the following:

1. Production material costs. If the programmable system results in lower material wastage, production materials costs may be reduced.
2. Inventory costs. A programmable system can allow very fast changeover of assembly from one product to another, and, therefore the assembly system can respond very quickly to variations in orders for a product. This means that less product need be maintained in stock to meet the orders

(lower inventory), and this means there are lower inventory costs because less company capital is tied up in nonproductive form. This savings can be particularly important if the product unit is expensive.

3. Individual part costs. Programmable systems with adaptability will sometimes be able to assemble lower quality parts than transfer machine methods because the transfer machine requires tighter tolerances on the part dimensions than is necessary for proper functioning of the product. The tighter tolerance parts are more expensive either because they are made more carefully or because they are inspected to weed out the out-of-tolerance parts, and thus individual part costs are lower for the programmable system.

4. Part design costs. Programmable assembly may lead to increased part design costs because of necessary modifications in the design and manufacture of the incoming parts. However, the required modifications are often either simplifications of the parts or redesign of the product to reduce the number of parts. Consequently, the part redesign for the assembly system may also reduce the manufacturing cost of the parts. Whether or not the part redesign is ultimately an additional expense or savings depends on the circumstances.

5. Energy costs. Programmable systems will almost certainly use more energy than manual assembly support equipment, but whether they will use more energy than transfer machine

assembly is unknown at this time.

These non-capital and non-labor costs should be examined in the justification of any particular programmable installation to see if they represent any significant effect. However, because they are less important than the principal capital and labor costs, they have been omitted in the simple economic impact analysis of section 10.3.2 and from the preceding discussion of a method for programmable assembly impact analysis.

9.5 Summary

As our modern society becomes increasingly complex and interrelated, it becomes more important for the economic effects of a new technology to be assessed prior to its introduction into the economy. One possible method for such an assessment has been presented here. The outline of this economic impact analysis is as follows:

- 1) A technical and microeconomic analysis of the new technology is made.
- 2) From this technical and microeconomic analysis an impact function is derived.
- 3) The impact function is used with industrial statistical data to estimate the direct impact of the new technology.
- 4) Traditional macroeconomic methods of assessment are used to estimate the effect of the direct impact on the economy

as a whole.

The application of economic impact analysis to assess the effect of the introduction of programmable assembly systems has been demonstrated by use of a simplified analysis because at the present time an adequate data base does not exist for a thorough analysis. The type of data required includes data showing the distribution of industry assembly costs as a function of parameters such as production volume and product size.

Although the simplified analysis considered only the major impact costs of capital equipment and labor, other important impact costs should also be considered in a thorough analysis. These are listed below:

- 1) Production material costs
- 2) Inventory costs
- 3) Individual part costs
- 4) Part design costs
- 5) Energy costs

These costs should all be considered in the justification of any individual programmable installation.

10. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

Programmable assembly offers an alternative to manual and transfer machine assembly. Modeling both the performance and the costs of a programmable assembly system can

help define design and research goals for programmable assembly systems and to identify the circumstances under which programmable assembly offers an economic alternative to manual and transfer machine assembly methods.

This research used microeconomic analysis to provide a framework for comparison of programmable assembly to manual and transfer machine assembly methods, three widely varying assembly technologies. A common base of assumptions was used so that the assembly alternatives could be compared consistently. The economic model that was developed for programmable assembly is simple and general, so that many different technical approaches to programmable assembly can be compared on the same grounds. An important measure of programmable assembly performance -- the price-time product -- was identified, and the minimization of the price-time product was presented as a criterion to achieve reduced assembly cost.

The type of microeconomic analysis used here can also provide a means to estimate critical values of price-time product that form boundaries between competitive designs and non-competitive ones. The microeconomic analysis provides a framework in which the sensitivity of the competitive advantage of programmable assembly to various economic factors--such as labor cost, required annual rate of return, and price-time product--can be examined.

The formulation of the economic analysis identified

certain noneconomic, sometimes difficult to quantify, factors which influence the economics. For example, the configuration efficiency, a measure of the "line balance" of the programmable assembly system and the utilization efficiency, a measure of the extra production capability of the system, both play important roles in the economics. Their presence in the model raises questions about how they may be related to other properties of programmable assembly systems and so identifies certain natural areas for further research.

The price-time product is a useful means of evaluating alternative assembler designs. It is not dependent upon the way that the assemblers are organized into an assembly system. It can be used to compare assemblers with widely varying numbers and configurations of axes and widely varying component technologies. The price-time product is useful to the designer of an assembly system because it helps him to choose cost effective assemblers. It is useful to the designer of an assembler because it can help to resolve design tradeoffs in favor of an economic design. Finally, sensitivities defined in terms of the price-time product can be used to assess directions for further research and development for classes of assembler configurations.

The research of this thesis has been primarily involved with the development of the price-time product as an assembler criterion and the ways in which it and the supporting

analysis can be used to study programmable assemblers.

Two classes of further research work are apparent: First, work directed toward developing improved models of assembler cost and performance; and, second, areas of research that will be identified by the price-time product sensitivities.

More work is necessary to model the cost and performance of the fine motions of assembly. The modeling of gross motion for a given assembler configuration can be quite straightforward, as was illustrated in the example design process that was presented earlier; but the fine motion process is not yet sufficiently well understood to lead to a useful price-time product model. Research in assembly fine motion should be directed at understanding not only the basic processes but also the cost and performance of the hardware implementation. Better models of assembler fine motion requirements and performance are necessary to analyze the trade-off between the cost and performance of special jigs to aid in fine motion as opposed to the cost and performance of more sophisticated strategies to be implemented by the assembler. Accurate models for both gross and fine motions can lead to better price-time models for assembler configurations.

Research should also be directed toward producing better models for system integration costs and processor costs and requirements. Just how programmability will influence

the system integration process is only speculation now, although it certainly should be an improvement over transfer machine integration.

Similarly, the functions necessary to the processor dedicated to an assembler are not sufficiently well understood to permit an accurate model. The existence of such processor models is necessary to price-time tradeoff analysis between processor capacity and special tooling.

Further research can also be done in developing a more complete model of the economics of programmable assemblers. This analysis was limited to assemblers in system configurations that were dedicated to a particular product or product family. The costs of tearing down a system and reusing the assemblers in a new system was not analyzed explicitly, although different useful lives for assemblers and assembly feeding tooling were modeled.

The price-time product would survive such an analysis as one measure of assembler performance, but new measures may emerge that describe the cost effectiveness of the assembler with respect to the system reconfiguration process.

More work can be done to verify or modify the assumptions used in the economic modeling. Is the tooling price per part really independent of production volume? Is configuration efficiency related to the number of parts per station and thereby to the production volume? Is station price related to the number of parts per station (because

of the number of degrees of freedom required) and, consequently, to the production volume?

A logical next step in the development of the economic model would be to reformulate the model without constraining the assumptions to allow for easy symbolic manipulation. Such a model would be largely limited to numerical analysis by computer. It could be more complete by including many more cost factors than were practical here. It could use the actual return on investment instead of the annual rate of return as an approximation to it, and could allow the results obtained in earlier chapters to be obtained more accurately.

However, most of the results of such a model would have to be expressed only graphically rather than symbolically and so would be somewhat more difficult to study. This more complete model could be used to identify circumstances in which other economic factors besides the basic equipment or labor costs would be important considerations in the application of programmable assembly. The simple model presented here was sufficient to identify the price-time product as a useful measure of assembler performance; the more complex model can be used to obtain better estimates for the critical values for it.

As an assembler price-time model is developed, price-time product sensitivity analysis can be used to identify assembler components that have the greatest potential

influence on the price-time product. Research applied in these areas can have the greatest impact on improving programmable assembly technology.

The assembler design process of Chapter 8 provides an example of identification of research areas by sensitivity analysis. The processor and system integration components were identified as important areas of research. Also, it was shown that the assembler size and number of degrees of freedom are important factors in the price-time product. This means that it is important to understand, for real products, how the minimum assembler size is related to the product size as well as the required number and arrangement of the degrees of freedom.

As programmable assembly actually comes into use, it will also be important to verify the modeling concepts presented here empirically. These results can then be used as a basis for further study.

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Appendix 1.	List of Variable Definitions
ACC	Magnitude of required acceleration
$ACD_{ij}(\text{VOL})$	Assembly cost function for i^{th} industry in product size class j
APCST	Driving amplifier cost, dollars
APLCST	Annual labor cost for a programmable system
ASM CST	Direct manufacturing costs of the assembler
ASMPRC	Purchase price of assembler
ATLCST	Annual labor cost for transfer machine operation
ATU	Assembly time per unit, sec.
AVTSQ	Average value of square of torque
$BACPU_j(\text{VOL})$	Unit assembly cost for the best alternate method as a function of volume for product size class j
BSCST	Ball screw cost, dollars
C	Conversion constant from rotary to linear motion

CAP _i	Number of parts that can be assembled annually by the i th station
CAT	Net annual cash flow after taxes
CEF	Configuration efficiency
CONTRQ	Maximum continuous torque rating of the motor, newton-meters
D	Length of ball screw, meters
DH	Length of horizontal axis, meters
DIST	Distance of gross motions
DPME	Annual straight line depreciation rate for manual equipment
DPPA	Annual straight line depreciation rate for the programmable assembler stations
DPTL	Annual straight line depreciation rate for the parts feeding tooling
DPTM	Annual straight line depreciation rate for the transfer machine
DY	Number of days worked per year
EM	Effective mass to be moved in x direction

F	Force in x direction
FCS _j (VOL)	Fractional cost savings as a function of volume for product size class j
FMT	Total time for all fine motions during the single part assembly cycle
FR	Required force in x direction
GRATIO	Fraction of part assembly time in gross motion
HATU	Hybrid transfer-programmable assembly time per unit, sec.
HCPU	Hybrid system assembly cost per unit
HCST	Hybrid system cost
HD	Number of hours worked per day
HPCPU	Unit assembly cost component due to programmable assembler stations and associated feeding equipment
HTCPU	Unit assembly cost component due to transfer machine stations
HTMPCPU	Unit assembly cost for the hybrid transfer-manual system
HTPCPU	Hybrid transfer-programmable cost per unit

I	Initial investment
IDXCST	Cost of portion of index or conveying device dedicated to the assembler (assumed constant)
INDEXTIME	Average time between completed product units
INTCST	Cost of engineering, building, and debugging station (assumed constant)
J	Rotary inertia
JM	Motor rotor inertia, newton-meter-second ²
LABCST	Cost rate of labor, dollars/second
M	Linear moving mass
MATP	Manual assembly time per part, seconds
MAXVOL	Potential production volume of the product
MCPU	Manual assembly cost per unit, dollars/unit
MCPUI	Manual unit assembly cost, improved model
MECPP	Manual equipment cost per part
MECST	Total manual equipemnt cost
MOTCST	Motor cost, dollars
ML	Motor length, meters

MM	Motor mass, kilograms
MSCPU	Unit assembly cost for the parts assembled manually
n	Number of years of investment project
NPART	Number of parts in the product
NPPRT	Number of parts assembled by programmable stations
NPT	Number of parts assembled by transfer stations
NSEF	Net station efficiency of the system
NSPY	Effective number of working seconds in the years, including the effects of downtime, number of shifts, and so forth
NSTA	Number of programmable stations in the system
NWPP	Number of workers assigned per part
NWRKR	Number of workers assigned
P	Motor power rating, watts
P_j	Parameter j
PARTTIME	Single part assembly time for one assembler

PARTTIMET	Theoretical single part assembly time
PCPU	Programmable assembly cost per unit
PCPU _j (VOL)	Unit assembly cost for a programmable system as a function of volume for product size class j
PCPUI	Programmable cost of assembly per unit product for the improved model
PECPU	Programmable equipment cost per unit
PFCTR	Price factor
PL	Payload, kilograms
PLCPU	Programmable system labor cost per unit of product
POPT	Total yearly operational time for the programmable system
PRATIO	NPPRT/NPART, Programmability ratio
PSCST	Programmable system cost
PTS _j	Price-time product sensitivity of parameter j
PUEF	Utilization efficiency of the programmable system

R	After tax rate of return
ROI	Return on investment
SAV	Total direct cost savings
SAV _j	Total industry savings impact for the j th size class
SAV _{ij}	Savings in the i th industry for the j th product size class
SETLF	Fractional duration of the actual gross motion time beyond the theoretical time; i.e., the settling time fraction
SF	Salvage fraction
SLOPE	The slope of the staircase of the price-capacity chart
STAP	Single station price
STAP*PARTTIME	Price-time product
T	Tax rate
TAX	Taxes on income allocated to the transfer machine
TCPU	Transfer machine assembly cost per unit
TCPUI	Improved estimate of the unit assembly cost of the transfer machine

TEF	Torque transmission efficiency (less than one)
TG	Constant gravitational torque
TGM	Average time for one gross motion
TGMT	Theoretical gross motion time
TI	"Square wave" inertial torque
TLCPU	Transfer machine labor cost per unit
TMCPP	Transfer machine cost per part
TOLPP	Price of parts feeding tooling per part
TOPT	Total annual transfer machine operational time, seconds
TORQ	Torque about axis θ
TR	Torque required on load
TRATIO	Transfer ratio
TSCPU	The unit assembly cost for the parts assem- bled by the transfer stations
TSCST	System cost for transfer machine
TSTCST	Total cost of the transfer stations
TTIME	Average time between the production of single product units, seconds

UT	Uptime fraction
VMAX	Peak velocity in x direction
VOL	Actual production volume of the product
VOLMT	Volume boundary between economic manual and transfer machine systems
VOLMTI	Volume boundary between economic manual and transfer machine assembly improved model
VOLPM	Volume boundary between economic manual and programmable systems
VOLPMI	Volume boundary between economic programmable and manual assembly, improved model
VOLPT	Volume boundary between economic programmable and transfer machine systems
VOLPTI	Volume boundary between economic programmable and transfer machine assembly, improved model

Appendix 2. Annual Rate of Return as an Approximation
to the Return on Investment

In the economic modeling work of this thesis the annual rate of return, defined using the annual cash flow after taxes by equation 6.3, was used as part of the method of computing unit assembly costs for programmable and transfer machine assembly methods. This rate of return is an approximation to the return on investment, ROI, that is most commonly used in capital allocation analysis. Unfortunately, the return on investment is often difficult to work with and is more complex to calculate. The annual rate of return is simple to work with and calculate, but is only an approximation. In exploratory work such as this, the ease of manipulation was more important, and so the annual rate of return was used. In future work in this area, true ROI should be used in all capital allocation analyses.

In this appendix an example is provided to indicate the accuracy of the annual rate of return as an approximation to the ROI. In general, the annual rate of return is a better approximation when the rate of return is lower and the life of the project is longer. The annual rate of return is not affected by the salvage value of a project (except insofar as the annual depreciation rate affects taxes) nor is it affected by the life of the project. In fact, the annual rate of return is simply the inverse of the "payback period," the time required for a

project to earn an amount of money equal to its original investment.

To formulate an example, we consider a project in which the original investment, at time equal to zero, is I . This project earns an annual cash flow after taxes of CAT at the end of each year, extends for n years, and recovers a salvage fraction SF of the original investment at the end of the n^{th} year. The ROI of the project is that discount rate for which the present value of all cash flows over time is zero (21).

$$0 = -I + \sum_{i=1}^n \frac{CAT}{(1+ROI)^i} + \frac{SF \cdot I}{(1+ROI)^n} \quad (A2.1)$$

where ROI = return on investment

In general, this expression must be solved numerically, to find the value of the ROI. However, this expression can be used to relate annual rate of return as defined by equation 6.3 to the ROI. Equation A2.1 can be rewritten

$$\frac{CAT}{I} = \frac{1 - \frac{SF}{(1+ROI)^n}}{\sum_{i=1}^n \frac{1}{(1+ROI)^i}} \quad (A2.2)$$

using equation 6.3 and simplifying the summation gives

$$R = ROI * \frac{(1+ROI)^n - SF}{(1+ROI)^n - 1} \quad (A2.3)$$

where R = annual rate of return

Examination of equation A2.3 reveals that the annual rate

of return R will equal the return on investment if the salvage fraction is one; i.e., no loss of value on the original equipment, an unrealistic situation.

As an example calculation, consider the programmable assembly example of Section 6.1.5. Assume a production life of 4 years over which the parts feeding tooling is fully depreciated but the programmable assemblers are depreciated to half of their original value. All other variable values remain the same as in Section 6.1.5. We consider two different systems; one designed to operate at 100,000 units per year (with few assemblers) and one designed to operate at 1 million units per year (with more assemblers). We assign an ROI of .25 and then compute the corresponding annual rate of return required to give that ROI for these two systems.

System Production Volume	Salvage Fraction after 4 Years	R
0.1×10^6	.06	.41
1.0×10^6	.289	.37

As can be seen, there can be a 50 percent difference between the ROI and the annual rate of return. If the tooling lasted for eight years, as long as the assemblers are assumed to last, then the entire system will fully depreciate after 8 years ($SF = 0$). In this case a 25 percent ROI would require an annual return of only 30 percent.

Appendix 3. The I.C. Insertion Machine: A
 Currently Available Programmable Assembler

The I.C. insertion machine is a currently available, but highly specialized, programmable assembler that inserts electrical components into printed circuit boards very quickly (2800 to 19000 per hour). There are actually two types of machines--those for assembling axial lead components and those for I.C.'s (DIP's).

The systems that insert axial lead components have the following parts:

1. Insertion machine (about \$49000). The insertion speed is about 8000 per hour with one work head, but 16000 with two workheads working on two identical boards.
2. Controller (about \$14,000, but one controller can handle up to 5 insertion machines).
3. Sequencer (about \$31,000). The sequencer prepares a tape containing the components in the proper sequence at about 16000 per hour. Thus, the sequencer is balanced with a dual workhead insertion machine.

The systems that insert DIP's have the following parts:

1. Insertion machine (about \$48,000). The insertion speed is about 2800 to 3600 per hour.
2. Controller (about \$14,000, but one controller can handle up to 5 insertion machines of either type.)

These machines do their own sequencing.

In these assembly systems, the feeding hardware is really incorporated into the assembly station; this can be done because the nature of components assembled is highly restricted. In order to interpret these machines in terms of the model developed in this thesis, the sequencer should be considered part of the assembler. For example, counting a single dual head axial insertion machine, one fifth of a controller, and a sequencer, the price time product of the axial lead system is 18,630\$-sec. The price time product of the DIP system ranges from 50,800\$ -sec to 65,500\$-sec depending on the speed. Using the price-time bound of equation 6.16, with some information about manual insertion rates (i.e., labor cost \$8500 per year, 1.67 people operating collectively at 200 to 800 insertions per hour) and some other assumptions ($R=.25$, $T=.48$, $DPPA=.125$, $CEF=.8$, $PUEF=1.0$), the upper bound on the price-time product becomes 2.2×10^5 to 8.9×10^5 \$-sec depending on the manual rate. Hence, the component insertion machines have price-time products well below the upper bound.

BIOGRAPHY

Paul Michael Lynch was born in Laramie, Wyoming, on April 15, 1948. Most of his public school education was in Richardson, Texas. He entered MIT in the fall of 1966, receiving a Bachelor's Degree in 1970, a Master's Degree in 1972, and an Engineer's Degree in 1975, all in Mechanical Engineering. In his senior year he won a Wunsch Foundation Design Prize for outstanding student design, and during his undergraduate years was active in the student section of the ASME and the MIT Concert Band. As a graduate student he was a National Science Foundation Graduate Fellow (1970-1973) and a research assistant (1973-1976) working at the C. S. Draper Laboratory. He is a member of Pi Tau Sigma and Tau Beta Pi. His publications include:

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