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ABSTRACT

During the last decade many flexible assembly systems (FASs) have been adopted as alternatives to traditional labor-driven systems, and the number is expected to grow faster than ever. Design aids for such capital-intensive systems, however, have not been investigated in depth. Existing ones have had limited success to real applications because of simplicity of the underlying assumptions, treatment of isolated design issues, time-consuming techniques, lack of user-friendly design-aid tools, and no machine flexibility consideration.

In this paper, we present an integrated design support system for FASs in an effort to overcome these setbacks. The proposed system takes three basic data (specifications of products and potential machines, and material handling systems) as input, and provides (1) cost-effective flow system designs (layouts and operating policies) which satisfy design and production requirements, and (2) economic assessment for the investment plan for the proposed designs. The proposed system employs three phases of analyses: rough-cut analysis, detailed analysis, and investment plan analysis. The proposed system encompasses various techniques systematically, including queueing networks, optimization methods, discrete-event computer simulation, and engineering economy. Within our knowledge, the proposed system is the first truly integrated method that can support design activities and economic justification for FASs. A case study is presented to demonstrate effectiveness and efficiency of the proposed system.

1. INTRODUCTION

The basic issues in assembly system design are economic and technical. As products become more complex and manufactured in many models and the cost of manual labor involved in assembly remains high, it becomes necessary to design flexible assembly systems (FASs) to respond to these trends (Spur et al. 1987, Gagnon and Ghosh 1992, Boubekri and Nagaraj 1993). According to Sanders (1986), "Estimates based on the statistics of the National Machine Tool Builders Association indicate that the assembly system industry builds about $120 million of new mechanical assembly machines per year. It seems reasonable that the electronics assembly system industry is of at least comparable size. The total amount of industrial, military and consumer products produced on these machines must run to several billion dollars per year." Consequently, research results to be addressed in this paper and their implications could be transmitted into substantial economic impact.

A typical design process for manufacturing systems, and one that is used here can be described in three stages. The first stage is to determine and characterize three key components of the systems: products to be produced, machines, and material handling systems (MHSs) to be used. For each component, a designer usually has many alternatives, each of which has different features and costs. Once alternatives of the three components are determined and characterized, the second stage is to integrate them and generate design alternatives by determining capacities of various resources, task assignment and product flow, layout, and other polices required to operate the system. The third stage is to evaluate these design alternatives to see if they are economically justified and can produce required production volumes with good quality standards. The designers usually repeat this design process with many alternatives before they decide one which will be installed (see Figure 1).

<Insert Figure 1>

The importance of early design activities should be emphasized for highly-automated manufacturing systems. About 80% of total budget is committed at the design stage (Vollbracht 1986) and 55% of engineering cost has been spent at the project authorization point (Harter and Mueller 1988). Design aids for FASs, however, have not been investigated in depth. Flexible and powerful design methods need to be developed to retain an overview of complex interdependencies among the various elements of FASs and to provide a handful of good design alternatives quickly. The variety of possible design alternatives increases with the number of functions integrated in FASs, which leads to a high workload for the designers, a long design lead-time, and the unfortunate potential of overlooking good design alternatives (Spur et al. 1985, Suri and Diehl 1987, Shimizu and Van Zoest 1988, Kouvelis and Kiran 1989).

The objective of this paper is to present an integrated design-aid tool (IDaT) for FASs which provides a small number of cost-effective design alternatives quickly at the early design stage. With three sets of basic input data on products, machines, and material handling equipment, the proposed tool will determine nine key design decisions which completely define a layout and operating policies for FASs such that the investment worth to the proposed FAS can be maximized. In order to handle the complexity of the problem, the tool will encompass various methods systematically, including optimization techniques, queueing networks, simulation, and engineering economy. The benefits of the proposed tool can be enormous in terms of not only reduction of design lead-time but also budgetary savings and better system performance. Within our knowledge, the proposed tool is the first truly integrated one that can support design activities and economic justification for FASs.

The remainder of the paper is organized as follows. In §2, we give descriptions of a generic FAS that is to be supported by the proposed IDaT. In §3, we provide a problem statement, and we give a literature review in §4. In §5, we describe details of IDaT which employs three analyses: rough-cut analysis, detailed analysis, and investment plan analysis. In §6, a case study demonstrates the proposed IDaT. Finally, in §7 and §8, practical considerations of the proposed IDaT and concluding remarks are provided.

2. FLEXIBLE ASSEMBLY SYSTEMS UNDER STUDY

A typical FAS under consideration is a unidirectional-flow multistation system with part feeders at each station. The FAS consists of a set of assembly stations and a load/unload (L/UL) station connected by conveyors or transporter paths. A base part of an assembly is loaded on a pallet and enters the FAS at the L/UL station. As the pallet is carried by conveyors or transporters through assembly stations, components are assembled with the base part. When all of the required components are assembled with the base part, it is carried back to the L/UL station and leaves the FAS.

The FAS under study has three characteristics. The first characteristic is that the FAS is a flow system where a base part enters the system and is processed by a series of stations containing flexible machines of type 1, followed by a series of stations containing flexible machines of type 2, continuing in this manner to completion. A part may bypass one or more stations but does not reenter any station (i.e., unidirectional flow). A flow system is common for FASs since a large volume and short task times necessitate the efficiency of a flow system (Kamath et al. 1988, Liu and Sanders 1991). Similar loop layout designs are often used for flexible machining systems due to their operational simplicity, low cost, and high reliability (Martin and Musselman 1984, Afentakis 1989). Generalization to FASs with reentrant flows will be discussed later in Section 7.

The second characteristic is that flexible assembly machines (for example, automatic insertion machines or assembly robots) have a finite work space due to their physical configurations. Because a component feeding mechanism associated with each assembly task uses some of the finite work space, we can assign only a finite number of tasks to a robot (Ammons et al. 1985, Lofgren 1988) (see Figure 2, similar to Groover et al. 1986). We refer to this finite number of tasks as the *flexibility capacity*. Among the tasks assigned to a robot, there are negligible setup times between task changes (Sethi and Sethi 1990). Components and assembly tools are always available when a base part is ready to be assembled at each station. This is realistic since assembly tools are less perishable than the cutting tools of flexible machining systems (Hall and Stecke 1986) and computer controllers at each station can keep track of the inventory levels of components.

<Insert Figure 2>

The third characteristic is that the FAS operates in mixed-model lines on which different product types are assembled simultaneously with a known or determined mix ratio. Processing a mix of parts makes it possible to utilize the machines more fully than otherwise. This is because different parts spend different amounts of time at the machines. These production lines can also achieve lower inventory of final products than multi-product model lines, where one product type is produced at a time in a cyclic fashion. In the latter, while one product type is being produced, demand for other product types is satisfied from their inventories. These advantages are possible because of the machine flexibility, that is, because of negligible setup times between task or product changes.

3. PROBLEM STATEMENT

The components of the problem which is investigated in this paper are stated in the following order: basic data available, decisions of interest, objectives, and constraints.

3.1. Basic data: We assume that the products to be produced and the types of assembly machines and material handling equipment have already been selected. The basic data are classified into six groups.

(1) Products:
  - for each product type:
    - a set of tasks
    - a precedence diagram among tasks
    - production requirements per period
    - sale price/part, raw material cost/part, WIP cost/part

(2) Assembly Machines (including human workers):
  - a sequence of machine types that a part visits
  - for each machine type:
    - flexibility capacity
    - total available processing time per machine per period
    - processing speed factor (default value is one)
    - a set of assembly tasks that it performs and their task times
    - jam frequency (how often jams occur on average)
    - average jam clear times (time required to clear jams and resume tasks)
    - purchase/maintenance cost, salvage value, life expectancy
    - physical dimensions
    - precision/resolution

(3) Material Handling Systems (MHSs):
  - type of MHSs: conveyors or transporters
  - types of pallets and fixtures
  - transfer speed
  - purchase/maintenance cost, salvage value, life expectancy
  - physical dimensions

(4) System Controller and Communication Network:
  - purchase/maintenance cost, salvage value, life expectancy
  - the maximum number of stations it can support

(5) System Parameters:
  - the number of shifts per day, the number of days per week
  - system life expectancy
  - interest rate

(6) Other direct and indirect cost terms.

3.2. Design decisions: Taking the above basic data as input, the problem is to determine the following nine critical decisions for the best FAS design for each type of FAS under consideration:

(1) the number of stations
(2) the number of parallel assembly machines at each station
(3) assignment of tasks among stations
(4) the number of pallets and fixtures
(5) the number of transporters (not necessary if conveyors are used)

(6) the number of buffer spaces at each station
(7) product mix and part dispatch policies
(8) layout of the proposed FAS
(9) economic indicators for investing in the proposed FAS design.

With the above design decisions as a basis, a physical layout of an FAS can be developed in terms of the detailed layout of machines and the capabilities of MHSs. During the development of the FAS layout, other direct and indirect cost items can be identified and used in the investment plan analysis which will provide economic indicators for the proposed FAS investment. Five indicators that are used here include present worth, annual worth, payback period, unit production cost, and rate of return.

3.3. Objectives: The objective of the problem is to provide FAS designs which maximize the investment worth as measured by the economic indicators.

3.4. Constraints: The solution must satisfy the following three types of constraints.

(1) Production requirements: the expected demand of each product must be satisfied.
(2) Flexibility capacity: the number of tasks assigned to each station must not exceed the flexibility capacity.
(3) Unidirectional flow system: tasks must be assigned to stations such that precedence relationships among tasks ensure that a part does not revisit any station.

4. RELATED LITERATURE

Several design procedures appear in the literature which can be used for FASs (Stecke 1985, Browne et al. 1985, Spur et al. 1985, 1987). For example, Spur et al. (1987) give a seven-phase design procedure outline: (1) manufacturing system analysis, (2) determination of basic data, (3) documentation of information, (4) layout planning and assessment, (5) decision of economic feasibility, (6) final detailing of the planned system, and (7) planning of the system installation. The design-aid tool presented in this paper supports the fourth to sixth phases.

Research works on FAS design problems can be divided into three groups, based upon the modeling techniques employed. These are simulation, queueing networks, and integer programming. Simulation has been used by several researchers (Bullinger and Sauer 1987, Shang and Tadikamalla 1989, Thompson et al. 1989, Dessouky et al. 1991, Rajamani and Singh 1991, Yano et al. 1991, Nandkeolyar and Christy 1992, Winters and Burstein 1992). Simulation can represent an FAS at any level of detail. However, in the early stages of the design of complex systems such as FASs, one may understand very little about them. Hence, one may not know which aspects of the system to represent in the model and at what level of detail, or which aspects to ignore or aggregate. It can be also costly and time-consuming to develop, and to validate and run simulations for many design alternatives before one good alternative is chosen. Further, one cannot tell how good the chosen alternative is because simulation does not usually provide an optimal solution or benchmark with which the chosen alternative can be compared.

Many researchers have used queueing network models to solve design problems for flexible manufacturing systems (FMSs). A Markovian closed queueing network model is used by Vinod and Solberg (1985), Stecke and Solberg (1985), Dallery and Frein (1986), Shanthikumar and Yao (1987, 1988a), Dallery and Stecke (1990), Lee et al. (1991a), and Schweitzer and Seidmann (1991), while a Markovian open queueing network is used by Pourbabai (1987), Das et al. (1989), and Shanthikumar and Yao (1989). Non-Markovian queueing models also appear in the literature (Yao and Buzacott 1985, Whitt 1985, Kamath et al. 1988, Seidmann and Nof 1989). All of these works deal with specific decisions, assuming that many other design decisions are already known. Also, they make several assumptions for ease of analysis, and they do not consider issues such as machine flexibility and task assignment.

Researchers have also used integer programming (Whitney and Suri 1985, Graves and Redfield 1988, Afentakis 1989). These integer programming models do not take into account the aspects of MHSs and product flows, of resource contention and machine idle time, and of random events occurring on the assembly floor such as machine breakdowns or machine tool jams.

In addition to these studies, several researchers propose hybrid methodologies using the two modeling techniques in order to provide a more complete analysis than when only one technique is used stand-alone. Such research works include queueing networks and simulation by Seliger et al. (1987a, 1987b), Shimizu and Van Zoest (1988), Brown (1988), Liu and Sanders (1988), and Bulgak and Sanders (1991); integer programming and simulation by Suresh (1990); integer programming and queueing networks by Lee et al. (1991b), Lee and Johnson (1991), and Schweitzer et al. (1991); neural networks and simulation by Chryssolouris et al. (1990).

However, these works may not be complete enough for real applications and may not be effective decision support systems for FAS designers or investors. They sometimes deal with a few isolated design issues, assuming that other key design issues are already given. At the early design stage of complex manufacturing systems like FASs, different design issues are highly related and should not be treated independently. Highly significant interactions between the design factors may invalidate simple one-factor-at-a-time procedures for finding a minimum-cost system design (Dessouky et al. 1991). Also most previous studies may have one or more of the following deficiencies: simplicity of underlying assumptions, no machine flexibility consideration, a time-consuming nature, and no investment plan analysis for the proposed design alternatives. The number of design alternatives increases fast by considering many design decisions together. A powerful design-aid tool is essential in reducing the number of design alternatives quickly to a handful of potential candidates to which detailed analysis can be applied. Physical configuration design and financial evaluation are rarely integrated for FMSs (Suresh 1990). Traditional design and economic justification processes are separate corporate functions where the added iteration increases the time to analyze a design, resulting in a potential distortion of detail in the communication of information during the design process (Noble and Tanchoco 1993). In this paper, we present an integrated design-aid tool in an attempt to address these potential drawbacks. A simple demonstration of the ideas behind such a tool is presented in Lee and Stecke (1993).

5. AN INTEGRATED DESIGN-AID TOOL (IDaT) for FASs

In order to make the problem tractable, the proposed IDaT consists of three phases of analyses: rough-cut analysis, detailed analysis, and investment plan analysis. Rough-cut analysis (RA) deals with the simplified problem through aggregation of the given basic data. RA assumes large buffer spaces (no buffer blocking) and makes the first five decisions described in Section 3.2, minimizing key resource costs for machines and material handling equipment. RA uses optimization and queueing techniques and identifies a small number of cost-effective designs quickly. Thus, at this phase, many inferior designs are identified and eliminated from further analysis.

Detailed analysis (DA) takes the designs from RA as input, and evaluates and tunes them under real operating conditions. Decisions of part dispatch polices and buffer spaces are made as well. Simulation and search methods are used for DA and the design decisions made in RA may need to be slightly changed for more cost-effective designs. Decisions from both RA and DA satisfy all of the constraints stated in Section 3.3.

Investment in FASs can be very expensive; therefore, it is important to quantify all the potential benefits of FASs in financial terms like any other investment decision (Primrose and Leonard 1991). After providing cost-effective system designs satisfying design and production requirements at the first two stages of IDaT, IDaT proceeds to the third stage, which is the investment plan analysis (IPA). This analysis takes specifications of the system designs with other direct and indirect cost terms as input, and provides crucial economic indicators to FAS investors. Numerous indicators are available, but the present worth, rate-of-return, and payback period methods are the most popular (White et al. 1989). Other useful indicators include annual profit and unit production cost. This analysis employs engineering economy techniques and is implemented on spreadsheet software like LOTUS. This three-stage IDaT is depicted in Figure 3. In the remainder of this section, we present more details of the first two analyses, RA and DA. IPA will be further discussed through a case study presented in Section 6.

<Insert Figure 3>

5.1. Rough-Cut Analysis (RA)

In RA, some detailed aspects of the system are simplified or aggregated for ease and speed of the analysis. One aggregate product is used to collectively represent all of the individual products assembled in mixed-model production. Precedence diagrams of all the individual products are merged and represented as one super precedence diagram for the aggregate product, as in Thomopolous (1970), Macaskill (1972), and Graves and Redfield (1988). This assumption makes sense for assemblies such as automobiles or PCBs where products have similar task sequences. Demand and task times for the aggregate product are specified as the sum of demands and the weighted average task times among the individual products, respectively. Processing times lost from small but regular disturbances such as tool jams are also added as part of the average task time since such disturbances are not explicitly modeled in RA. The following example illustrates how the aggregate product is constructed.

Example. Suppose an FAS produces two products simultaneously. The precedence diagram and demand per period of each product are shown in Figures 4a and 4b. Product 1 has six tasks, (1,2,3,4,5,6), while product 2 has five tasks, (1,2,6,7,8). Tasks 1, 2, and 6 are common in both products. Each task j is associated with a three-tuple (p_j, z_j, c_j), where p_j= processing time for task j, z_j= jam probability for task j, meaning probability that an assembly tool is jammed when performing task j, and c_j= average jam clear time for task j. A jam occurs when a component fed is defective. When a jam occurs, a human worker intervenes to clear the jam and resume the flexible assembly machine. Figures 4a and 4b show (p_j, z_j, c_j) for each task j. The resulting aggregate product is shown in Figure 4c.

The weighted average task time for task j, t_j, is computed for j=1 to 6 as $t_j = \sum_{i=1}^{2} (p_j + z_j \cdot c_j) Y_{ij} \frac{d_i}{d}$, where d_i is demand for product i, d is the aggregate demand, and Y_{ij} is set to 1, if product i requires task j and set to 0, otherwise. In this computation, we assume that jams do not recur for the same task. Note that processing times lost from tool jams are added as part of the average task time in the aggregate product.

<Insert Figure 4>

5.1.1. Models

In order to build a model representing the FAS, we need to describe a dispatch policy which controls the release of base parts into the FAS. One dispatch policy under consideration releases a pallet carrying a base part into the system when a pallet carrying a completed assembly arrives at the L/UL station and leaves the system. This is the typical case when a base part is fixtured on a pallet outside the system and waits for a pallet carrying a completed assembly to arrive at the L/UL station. At this point, the two pallets are exchanged by a human worker or automated pallet changer. Thus, under this policy a constant number of pallets and fixtures perpetually circulate in the system. This policy is most commonly used in the literature on FMSs (Solberg 1977, Whitt 1984, Stecke and Morin 1985, Kamath et al. 1988, Tempelmeier and Kuhn 1993). Also this policy is similar to CONWIP (Constant WIP) by Hopp et al. (1989) and Spearman et al. (1990), which is shown to be superior to both pull and push systems in more general production environments. The popularity of this policy is attributed not only to high costs of material handling equipment such as pallets and transporters, but also to its ability to easily control WIP inventories and production rate while finishing production requirements.

The FASs using this dispatch policy can be modeled as a single class closed queueing network (CQN). CQN models have been popular since Solberg (1977) first suggested their use to model an FMS. These models can capture the aspects of product flows, of resource contention, and of the stochastic behavior of work flows due to the uncertainty and dynamics of an FMS in a reasonably adequate manner. With assumptions of exponential processing time at each station with FCFS service and of no buffer blocking, we use a product-form CQN model from which several performance measures can be computed exactly (Buzen 1973, Reiser and Lavenberg 1980, Sauer 1983). A particular performance measure of our interest is the throughput, which is defined as the number of completed assemblies that leave the system per period. When the throughput is greater than or equal to the aggregate demand per period, we consider the FAS to have sufficient capacity to meet demands of individual products.

This product-form CQN model has been successful and widely used for effective representation of several practical systems, such as computer and communication systems and FMSs, despite the fact that the underlying assumptions are often seriously violated by real systems (Kleinrock 1976, Spragins 1980, Hildebrant 1981). Denning and Buzen (1978) explain this phenomenon using the concept of operational analysis. Particularly, the performance measures such as throughput and utilization are very robust to violations in the Markovian assumptions (Suri 1983, Stecke and Solberg 1985, Co and Wysk 1986).

These two assumptions can be realistic in some FASs. The large variance of the exponential processing time can be justified in two ways: (1) there is a product mix that sometimes changes over time in mixed-model production, and (2) there are random perturbations such as tool wear or tool jams. The assumption of no buffer blocking can be valid since most electronic assemblies are small and some PCB assembly systems have large buffer spaces. For example, there are 30 buffer spaces at *each* of the four stations in the FAS described in Akella et al. (1985). Some FASs do have only a small buffer. The effects of buffer blocking can then be explicitly considered in the detailed analysis, where the necessary and required buffer spaces are determined.

5.1.2. Mathematical Formulation

With the use of the CQN model to compute the throughput for FASs, we now present a mathematical formulation for the RA. We first define some of the necessary notation in Table 1.

<Insert Table 1>

The RA can be mathematically stated as:

(P0) Minimize $z(N,S_0,K_1,K_2,\ldots,K_C)$

subject to: $$K_c = \sum_{i\in A_c} S_i \qquad c=1,\ldots,C \qquad (1)$$

$$TH \geq d \qquad (2)$$

$$\sum_{j=1}^{n} t_j X_{ij} = W_i \qquad i=1,\ldots,M \qquad (3)$$

$$\sum_{j=1}^{n} X_{ij} \le R_c \qquad i=1,\ldots,M \text{ and } i \in A_c \qquad (4)$$

$$X_{ij} = 0 \text{ or } 1 \qquad i=1,\ldots,M, \quad j=1,\ldots,n \qquad (5)$$

$$\sum_{i=1}^{M} X_{ij} = 1 \qquad j=1,\ldots,n \qquad (6)$$

$$\sum_{i=1}^{M} i\,X_{ij} \le \sum_{i=1}^{M} i\,X_{ik} \qquad \text{when task j must precede task k.} \qquad (7)$$

Equation (3) defines W_i, the workload at station i, as the sum of the task times of the tasks assigned to station i. Constraint (4) is the flexibility capacity constraint which limits the number of tasks assigned to each station. Constraints (5) and (6) are assignment constraints which force each task to be assigned to exactly one station. Constraints (7) model the precedence relations among tasks and ensure that a part does not revisit any station in a flow system.

5.1.3. Solution Methods

Problem (P0) is very difficult to solve optimally for two reasons. First, the problem is highly nonlinear since the throughput of the CQN model is very complex and nonlinear, and the total cost function may also be nonlinear. Second, all of the decisions are integer-valued, which limits the size of the problem that can be solved optimally.

Two heuristic methods have been developed to solve Problem (P0). The first method (Lee and Johnson 1991) is based on a strategy of balancing average workload per machine which is often the objective in designing assembly systems. This method combines a search technique utilizing CQN throughput properties with an algorithm which generalizes the fast optimum-producing assembly line balancing algorithm by Johnson (1988). The second method (Lee et al. 1991b) is based on the observation by Stecke and Solberg (1985) that unbalanced workloads can be superior to balanced workloads, and searches over a larger solution space, both balanced and unbalanced configurations. Consequently, the second method is more complete and uses several operations research techniques in an integrated manner. These techniques include nonlinear programming, integer programming, discrete optimization, and graph-related combinatorial algorithms. Experimental results show that this method finds the near-optimum solution with the maximum deviation from the lower bound cost not exceeding 4.4 percent. With the lower bound cost known, the second method can also find all design alternatives that fall within a given cost range and meet the constraints of Problem (P0). The two methods were implemented in about 2,000 lines and 6,000 lines of FORTRAN and PASCAL programs, respectively. Refer to Lee and Johnson (1991) and Lee et al. (1991b) for details of the methods and computational results.

5.2. Detailed Analysis (DA)

After determination of a few potential designs from RA, IDaT proceeds to the second stage, which is a detailed analysis (DA). DA examines each potential design obtained from the first stage, considering all detailed and operating aspects of the system. Such aspects include production of individual products rather than the aggregate product, different types of pallets/fixtures, realistic assembly times rather than exponential processing times, limited buffer spaces, jam clear activities, and a real-time part input policy which determines when to input which product to the system. In this analysis, some of the parameter values (e.g., the number of pallets) in the potential design may be adjusted to find a new design that is more cost-effective yet still able to meet production requirements. However, it does not make a major change in the potential design, for example, the number of assembly stations or the number of parallel machines at these stations remain unchanged. DA employs discrete-event simulation and search methods.

We first present an overview of the DA procedure which consists of three steps. Details of each step follow the procedure.

Procedure 1: A Procedure for Detailed Analysis

Step 1. Specify real-time part dispatch policies.

Step 2. Given the real-time part dispatch policies from Step 1, find the minimum number of pallets/fixtures that satisfies production requirements for all individual products. Assume sufficient buffer spaces which ensure no buffer blocking.

Step 3. Given the real-time part dispatch policies and the number of pallets/fixtures from Steps 1 and 2, find the minimum number of buffer spaces required to satisfy production requirements for all individual products.

The real-time part dispatch policies of Step 1 need not comply with those used in the CQN model. Other dispatching policies could be used. The CQN model results for FASs are robust. The parameter values optimized in the RA can be meaningful in the DA as well.

There are two types of part dispatch policies. One specifies a process rule at each assembly station determining *when* to process *what type* of a partially completed part, while the other specifies an input rule at the L/UL station determining *when* to input *what type* of a base part to the system. One process rule used in DA is FCFS at each assembly station, as in RA. One input rule determining when to input is the same as in the CQN model of RA, releasing a pallet with a base part to the system when a pallet with a completed assembly arrives at the L/UL station to be unloaded. The type of a base part to be input is chosen such that ratios among completed plus WIP parts are maintained throughout the entire production as close to ratios among their production requirements as possible. Formally, the part input sequence rule is to input a part of type k to the system at time t such that

$$I(t) = \max_{k \in \Psi(t)} \{ d_k / d - \text{prod}_k(t) / \text{total\_prod}(t) \} \tag{8}$$

where

t = the current time when a complete part is unloaded and the input rule is executed,
d_k = demand per period of product type k,
$\text{prod}_k(t)$ = the number of parts of type k produced until t as well as in process at t,
total_prod(t) = the total number of parts produced until t as well as in process at t,
$\Psi(t)$ = { k | the number of parts of type k in process at t is less than the number of pallets/fixtures dedicated to part type k }, and
if there is a tie, one is chosen arbitrarily.

The rationale behind this input sequence rule is that processing a mix of parts can make it possible to utilize the machines more fully than otherwise because different parts spend different amounts of time at the machines. Also note that the aggregate product of RA is constructed with perfect product mix among individual products (see the example in Section 5.1) and this rule tries to maintain the perfect product mix throughout the entire production. This rule is very simple to implement since it requires only monitoring how many parts are produced or are in process for each type. Experimental results show that this rule works very well, allowing as high as machine utilizations obtained by the RA even under small buffer spaces and the smaller number of pallets. The representative examples are given in the following case study section. Although we assume initially that the same flexible pallet/fixture is used for all product types, this rule can be generalized easily with the notion of $\Psi(t)$ to evaluate effects of the limited number of pallets/fixtures dedicated to a certain part type.

Most of the literature dealing with the determination of part input sequences in a flexible flow system is restricted in that it only searches for cyclic input sequences that are permutations of a minimal part set (MPS) (McCormick et al. 1988) or of mix ratios balancing the workload per machine (Stecke and Kim 1991, Smith and Stecke 1993). An MPS is defined as the part mix ratios that are the smallest integer multiple of the production requirements for every part type. When a mix ratio is large, or, when the greatest common divisor among production requirements is small, there are many possible input sequences, which makes it difficult to find one good sequence. The proposed method in this paper does not use a mix ratio and the generated input sequences are not necessarily cyclic. The previous methods are static (i.e., the input sequences are obtained before production), while the proposed one is dynamic. Further research is required to compare such input methods in the context of FASs and the IDaT.

Given the above real-time dispatch polices, Step 2 of DA seeks the minimum number of pallets required to satisfy the production requirements. Keeping the number of pallets/fixtures at the minimum ensures not only a small number of material handling equipment and WIP inventories but also a small number of buffer spaces, and consequently, short conveyor length, short transfer time, and small floor space. This is because, under the chosen pallet input policy, the total number of pallets/fixtures circulating in the system remains unchanged throughout the entire production. This rationale gives a natural hierarchy of Steps 2 and 3. Iterations among Steps 2 and 3 are clearly possible.

In order to find the minimum number of pallets, a bisection search method is used with the following lower and upper bounds. The lower bound on the number of pallets can be derived using a variant of the asymptotic bound analysis of Muntz and Wong (1974) as $\lceil \Sigma k\ d_k \cdot (TW_k + TT_k) / P \rceil$, where $\lceil x \rceil$ is the smallest integer greater than or equal to x, P is system up time per period, and TW_k and TT_k are total average times for processing and travel, respectively, required to produce one unit of type k. When minor disturbances such as tool jams occur, TW_k includes mean jam clear times experienced to produce one unit of type k. The good initial upper bound is the number of pallets provided by RA. This is because researchers have shown that the CQN model underestimates system throughput due to large variance of the exponential service time assumption.

The previous search method requires an assumption that system throughput of the described FAS nondecreases as a function of the number of pallets. This assumption has an intuitive appeal. The production rate of a system can increase, as more work is input into the system. Also, the production rate function of a CQN model, TH(N), is shown to be nondecreasing concave with respect to the number of pallets (Shanthikumar and Yao 1988b). In our numerous experiments, we have not encountered any problem that violates the assumption.

Ample buffer spaces have been assumed so far. Step 3 evaluates the effect of limited buffer spaces on performance of the potential FAS designs, and seeks the smallest number of buffer spaces which satisfy production requirements. Unnecessarily large buffer spaces cause waste of floor space and long travel time. On the other hand, too small buffer spaces cause machine blocking, resulting in low machine utilizations. Step 3 employs the following heuristic.

Procedure 2: A Buffer-Sizing Heuristic

Step 3.1. When the simulation is run under the assumption of sufficient buffer spaces at the minimum of pallets found from Step 2, collect statistics on the largest number of pallets queued at each station. Let B_i be this number for station i. Let B_{ic} be the incumbent solution of the buffer size at station i and initialize it to B_i.

Step 3.2. Set $B_i \leftarrow B_i - 1$ for all i such that $B_i > 0$, and rerun the simulation with the minimum number of pallets found from Step 2. If production requirements are met for all individual products, update $\bar{B}_c \leftarrow \bar{B}$ and repeat this step until either $\bar{B} = 0$ or production requirements are not met for at least one product. Go to Step 3.4 for the former condition ($\bar{B} = 0$). For the latter, let $\Gamma = \{1, ..., M\}$ and update $\Gamma \leftarrow \Gamma - \{i\}$ for all i such that $B_i = B_{ic}$. If Γ has only one element, go to Step 3.4. Otherwise, go to Step 3.3.

Step 3.3. Search the buffer spaces which lie between the two vectors, $\bar{B}$ and $\bar{B}_c$. Among the stations in Γ, find the station i which is most blocked, i.e., which has the largest number of machines that are forced to be idle due to buffer blocking. Add one buffer unit to station i (i.e., $B_i \leftarrow B_i + 1$) and rerun the simulation. If all production requirements are satisfied, then update $\bar{B}_c \leftarrow \bar{B}$ and go to Step 3.4. Otherwise, update $\Gamma \leftarrow \Gamma - \{i\}$ and repeat this step until Γ has only one element. When Γ has only one element, go to Step 3.4.

Step 3.4. Output $\bar{B}_c$ and terminate.

Once the initial buffer spaces are determined from Step 3.1, Step 3.2 gradually reduces buffer spaces evenly across stations. The rationale behind this is that RA eliminates potential designs with bottleneck stations from consideration and, consequently, WIP parts are seldom congested in one station. Examples for Procedure 2 will be presented in the following case study section. Although the buffer-sizing heuristic empirically works well, its performance can be improved further. Its speed may be enhanced by adopting perturbation analysis (Ho et al. 1984), since it can evaluate several different buffer-space sizes at a single simulation run. The smaller number of buffer spaces can be also found by applying a more sophisticated search method similar to one used by Liu and Sanders (1988), at the expense of more CPU time.

DA was implemented in about 3000 lines of FORTRAN, PASCAL, and SIMAN V (Pegden et al. 1990) programs. The simulation program reads the parameter values of the potential design from RA and makes numerous runs according to search logics stated in Procedures 1 and 2. The warm-up period and simulation length depend on design problems being considered, and should be determined accordingly in order to reflect steady-state performance. Table 2 summarizes the environments and implementation of the three analyses of the proposed IDaT.

<Insert Table 2>

6. A CASE STUDY

In this section, we provide a case study on FAS design which is hypothetical but closely reflects a real scenario and realistic cost data from vendors, and demonstrate how the developed IDaT can help an FAS designer with the complex design process and economic assessment of the investment plan. This case study compares three alternative possible assembly methods: two flexible assembly machines with different flexibility capacities and one manual assembly. The proposed IDaT is applied to each assembly method and finds a minimal-cost system design satisfying design and production requirements. Then, three potential system designs obtained from the three assembly methods are compared with respect to the five economic indicators (net annual profit, present worth, unit production cost, payback period, and rate of return), and one design is suggested for the FAS investment and installation. We first consider an assembly method with a less flexible assembly machine. Then two other candidate assembly methods are analyzed with the IDaT.

6.1. Specifications of Basic Data

Suppose that a design team wants to build an assembly system which produces four products, A, B, C, and D, simultaneously. Their production requirements are estimated at

500, 1,000, 1,500, and 2,000 parts/week, respectively. A marketing survey shows that each product can be sold for $20 per part regardless of the type. Each product consists of a base part and many components assembled with the base part. There are a total of 100 different components used in the four products. The number of components used in each of the four products is 46, 54, 39, and 61 components, respectively, with some components in common. Raw materials (a base part and components) cost $10 per part for all of the four products. There are precedence relationships among some component assemblies, which restrict assembly sequence. Product life is estimated as 10 years for all four products.

Considering factors such as production volume, the number of product types, the number of components, and product life, the design team selects FASs over manual or dedicated systems (Boubekri and Nagaraj 1993). The design team considers one type of flexible assembly machine, which is capable of assembling all 100 components. Assembly times of the 100 components are deterministic and range from 1 to 40 seconds. The number of components that are assembled by one assembly machine at a time must not exceed 30 because the machine has a limited work space and component feeders and kits take some of the limited space. That is, the flexibility capacity of the machine is 30. The machine is jammed once every 100 component assemblies on average and it takes 60 seconds on average to clear a jam and restart the machine (assuming geometric and exponential distributions, respectively). A flexible machine has a purchase cost of $100,000 (including accessories, controller, and installation) and annual maintenance is 10% of the purchase cost.

The design team considers the use of conveyors to move parts between machines because of large product flows. A base part of an assembly is clamped onto a pallet by a fixture so that it does not move during assembly operations. The same pallet and fixture serves all four products and carries one base part. Judging from the conveyor speed and pallet size, the design team estimates that it takes 10 seconds on average to move a pallet to the next machine after finishing the assembly of all components at one machine. Purchase of one pallet and one fixture costs $2,500 with 10% annual maintenance cost. Annual WIP inventory cost is $10 per part. Conveyors and supporting equipment cost $400 per foot with 10% annual maintenance.

All assembly stations and MHSs will be coordinated by one central computer, namely, a system controller. Part programs and control information can be transferred between the system controller and assembly stations via a local area network. Purchase of this controller and communication network costs \$200,000 with 10% annual maintenance. The system will run for two 8-hour shifts/day, 5 days/week and 50 weeks/year. The life expectancy of the system and all the equipment is estimated as 10 years. We assume 10% annual interest rate and zero salvage value of the system after 10 years.

6.2. System Design Obtained from IDaT

With the above input information, the design team prepares three input data files that are read by IDaT. These files are named PRODUCT.DAT, RESOURCE.DAT (for machines and MHSs), and COST.DAT. IDaT is applied with the three stages of analyses in the order: rough-cut analysis, detailed analysis, and investment plan analysis. Results obtained from each analysis are summarized below.

Rough-cut Analysis: First, an aggregate product is created to represent all four individual products collectively. Its precedence diagram is constructed by superimposing precedence diagrams of the individual products. Aggregate demand d is 5,000 parts/week and there are a total of 100 unique tasks; n=100. Weighted average task times, t_j's, are computed using the ratios of the individual production requirements. Next, the total annual cost function, $z(\cdot)$, to be minimized is constructed as $z(N,K_1) = (10+500)\ N + 20000\ K_1$, where \$10 is the annual WIP cost/part, and \$500 and \$20000 are the annualized purchase and maintenance cost per pallet and per machine, respectively. The method by Lee et al. (1991b) is applied to solve Problem (P0) and an optimal solution is obtained.

The solution from RA consists of four assembly stations (ASs) and one load/unload station (L/UL). For each part type, a pallet with a base part is loaded at the L/UL station and visits AS-1 to AS-4 in order, being assembled with several components at each AS. After AS-4, the pallet with a completed assembly returns to the L/UL station and is unloaded. The 100 component assembly tasks are assigned among four assembly stations as follows: 27 components to AS-1, 29 to AS-2, 30 to AS-3, and 14 to AS-4. Note that each AS is assigned no more than 30 component assemblies, as required due to the limited machine flexibility. These component assignments also satisfy all precedence relations and unidirectional flow requirements, so that after being loaded at the L/UL station, a pallet visits AS-1 to AS-4 in order without the need to revisit any assembly station.

Two parallel machines are assigned to AS-1, each performing the same set of component assemblies of 27 components. Thus, an arriving part to AS-1 can be assembled by one available machine of the two. When both machines are busy, the arriving part will be held on the conveyor in front of AS-1 until one is free. Similarly, two machines each are assigned to AS-2 and AS-3, while only one machine is assigned to AS-4. The number of pallets circulating in the system is found to be 16. The system throughput computed from the CQN gives 5069 parts/week, thus meeting the aggregate demand of 5000.

Detailed Analysis: After a few pilot runs, the simulation length is determined to be three replications, one week for each replication, with two days of a warm-up period to avoid transient results. The process rule used in the simulation is FCFS at each assembly station. The type of a base part to be input is chosen according to the input sequence rule I(t). Ratios among completed assemblies for the four products are maintained throughout the entire production as close to ratios among their production requirements (i.e., 500:1000:1500:2000=1:2:3:4) as possible. Thus, part types to be input to the system at time t=0 are obtained by executing I(t=0) and ordered according to the following sequence: 4, 3, 2, 1, 4, 3, 4, 2, 3, 4, ···. This sequence continues until the total number of parts (pallets) in the system reaches the constant number that will be maintained throughout the entire production. Thereafter, each time a completed part is unloaded, the input sequence rule I(t) is executed to determine the next part type to input.

Next, Step 2 of Procedure 1 is performed to seek the minimum number of pallets/fixtures circulating in the system. The lower and upper bounds are specified as 7 and 16, respectively. Nine pallets/fixtures are found sufficient to meet production requirements. Simulation also shows the largest number of pallets queued in each station. With 9 pallets, these numbers are (6, 5, 5, 8) for the four stations, respectively, and serve as the initial buffer sizes for the buffer-sizing heuristic of Procedure 2. The search iterations of Procedure 2 are summarized in Table 3. After iteration 7, it finds the number of buffer spaces (1, 1, 1, 3) sufficient to satisfy all individual production requirements, producing 507, 1014, 1521, 2029 parts/week for the four products, respectively. The fact that these small buffer spaces can still satisfy production requirements is attributed to the combination of two facts. One is that there are only nine pallets circulating in the entire system. The other is that machine utilizations for each machine at the four stations are 0.85, 0.86, 0.83, and 0.71, and there exist some machine capacities available that can be taken away by buffer blocking without preventing the production requirements from being met. Note that each machine in the pooled stations (AS-1 to AS-3) is more highly utilized than the single machine of AS-4, as recommended by Stecke and Solberg (1985) and Dallery and Stecke (1990). RA to solve Problem (P0) employs a workload allocation algorithm which takes advantage of this concept. When these numbers are used for buffer spaces with the above system configuration, the total length of the conveyor is estimated as 125 feet. The proposed layout is shown in Figure 5.

<Insert Table 3 and Figure 5>

Investment Plan Analysis: For the above proposed design, IDaT performs economic justification next in IPA. IPA considers all related cost items, both direct and indirect (see Table 4), and presents five economic indicators on the investment plan for the proposed design. Table 4 shows that the net annual profit is $505,000 and the present worth is $3,099,281, and the unit production cost is $17.98. Table 4 also shows that the payback period is 1.47 years and the rate of return is 67.8%. This payback period means that it will take only 1.47 years to recover the initial investment on the proposed FAS design. For simplicity of presentation, issues such as taxes, depreciation, and risk analysis (Kulatilaka 1984) are not discussed, but IPA can easily include them for a more thorough analysis.

<Insert Table 4>

6.3. Comparison Among Three Assembly Methods

We elaborate this case study further to show a full spectrum of design-aiding capability that IDaT can provide. Suppose that two other assembly methods are under consideration as alternatives to the one considered above which we will refer to as an assembly method by a type A machine. These two other methods include another type of flexible machine, referred to as type B, and manual assembly. A type B machine is more flexible than type A in that type B can perform up to 45 tasks with negligible changeover times whereas type A can perform up to 30 tasks. It is also more precise and 20% faster than type A (i.e., the type B speed factor=1.2). However, it is more expensive and costs $150,000 for purchase and installation with 10% annual maintenance. On the other hand, for manual assembly, the design team decides to assign an assembly worker no more than 10 tasks. When she/he performs more than 10 tasks, her/his efficiency drops rapidly and changeover times between tasks become significant. An assembly worker is less precise and 20% slower than type A (i.e., the type C speed factor = 0.8). Annual salary per assembly worker per shift is $30,000. Manual assembly requires a simple system controller which mainly controls conveyors. This costs $50,000 to purchase and install with 10% annual maintenance. Table 5 summarizes the comparisons among these three assembly methods.

<Insert Table 5>

IDaT is reapplied to each new assembly method, and the resulting designs and their economic indicators are summarized in Table 6. For the type B assembly method, IDaT provides a design with three stations, a total of five machines, and sixteen pallets and fixtures. All other cost items are the same as those in Table 4, except that this design requires one less worker for inspection and rework due to the better precision of the type B machine. For the manual assembly method, IDaT uses the first method of RA (Lee and Johnson 1991) and seeks a balanced design where each worker is assigned near equal workload. This design consists of 17 stations with one worker per station, and 27 pallets and fixtures. A small flexibility capacity (10) results in a large number of stations (17), which subsequently results in spread workload allocation (no machine pooling) and large material handling times, and consequently, a large number of pallets (27). This long assembly line requires 250 foot-long conveyors and large floor space. There are several changes in personnel. Manual assembly does not require NC programmers, machine repair persons, or workers for component refill and jam clearing. However, poorer precision by the manual assembly method requires five workers for inspection and rework, as contrasted with two workers for the type A assembly method. Table 7 shows details of cost items to derive the five economic indicators for the manual assembly method.

<Insert Tables 6 and 7>

Among the three assembly methods, the investor should go for the type B method since it gives the most annual profit ($547,500), the most present worth ($3,362,648), the least unit production cost ($17.81), and the second shortest payback period (1.45 years). The manual assembly method gives the shortest payback period (1.29 years) and the highest rate of return (77.0%) because of the smallest initial investment cost ($217,500), which is contrasted with $972,500 for the type A method (see Tables 4 and 7). However, the manual assembly method is not an attractive choice due to the smallest annual profit ($132,500) and the smallest present worth ($814,670), which are less than one fourth of the counterparts that the type B method gives.

The reason that the type B method has large buffer spaces (12, 11, 12) is because of tool jam stoppages and high machine utilizations, 0.98 for each machine in AS-1, 0.98 in AS-2, and 0.91 in AS-3. Even small lost machine capacities due to buffer blocking prevent the production requirements from being met. In order to ensure the high machine utilizations, the type B method requires 15 pallets and WIP parts, that is, 6 more than the type A method requires.

All of the above analyses can be done within one hour on an IBM PC-486. Most of the analysis time is spent in the detailed analysis, where simulation is used to seek for the minimum number of pallets and buffer spaces under real operating conditions subject to a constraint of meeting the production requirements. For example, one iteration of the buffer-sizing heuristic takes about 7 minutes for the type C method. This clearly demonstrates the importance of RA, which prunes many inferior designs from further analysis before DA can be applied.

7. PRACTICAL CONSIDERATIONS OF IDaT

Although the mathematical formulation for RA looks complex, it is transparent to IDaT users. The SIMAN simulation program for DA is also transparent to users and is automatically generated using the output from RA. Users simply need to prepare three data files for products, machines, and MHSs, following the formats of the provided sample examples, and to type a few batch commands. The IPA module is also simple to use, since users can enter various costs, modifying a provided sample spreadsheet file.

Assembly sequence can affect difficulty of assembly steps, needs for fixturing, the potential for part damage during assembly, and the unit cost of assembly (DeFazio and Whitney 1987). Although the current IDaT cannot evaluate the effect of different assembly sequences quantitatively, certain assembly sequences that are inferior can be identified (DeFazio and Whitney 1987) and eliminated prior to applying the IDaT by adding extra precedence arcs in the partial precedence diagram of products.

In-process testing/rework can be viewed as a task with a variable task time, which can be performed by an assembler or a dedicated inspector (viewed as a separate machine type). This testing/rework task can be placed between assembly tasks in coordination with quality control planning (Shin et al. 1995). If rework requires a part to be sent to the preceding stations to have some tasks repeated (Bulgak and Sanders 1991), task times for such tasks can be adjusted for RA according to a geometric distribution. This is possible since the CQN model used in RA is of product-form, which is independent of a topology or flow pattern of assembly systems. In fact, the CQN model can represent jobshop-like FMSs as well as flow-line FASs (Dallery and Stecke 1990) and the proposed IDaT can be extended to aid other types of FMS design.

IDaT provides FAS designs based on long-term steady demand. This is because once such systems are installed, they will last several years. In reality, however, demand may vary from period to period. Short-term demand fluctuations can be absorbed in short-term production planning by controlling operation policies such as real-time part dispatch rules, product mix or the number of pallets in system, by reassigning tasks among stations, or by adopting overtime work or subcontracts. IDaT can also help short-term production planning. This can be done by fixing some of the design decisions such as the number of machines and buffer spaces and tuning the rest of the decisions for optimal performance. For this purpose, RA and DA may need to be modified slightly.

8. CONCLUSIONS AND FUTURE RESEARCH ISSUES

FMSs require large capital investment and a large portion of this investment is committed at the early design stage. Designing cost-effective yet functional manufacturing systems has been a challenging task for both practitioners and researchers. This becomes even more evident for integrated manufacturing systems such as FMSs, where many design issues need to be specified that are highly related. Existing studies on FMS designs, however, sometimes deal with isolated design issues, often simple one-factor-at-a-time procedures for finding a minimum-cost system design. Existing methods may have limited success toward real applications due to one or more of the following deficiencies: simplicity of underlying assumptions, no machine flexibility consideration, and a time-consuming nature. Physical configuration design and financial evaluation are often rarely integrated for FMSs, which can cause economic justification of FAS investments to be inaccurate. In this paper, we present an promising integrated design-aid tool that can address these potential drawbacks.

In this paper, we present IDaT for FASs, which uses various techniques that are structured into three analyses: rough-cut, detailed, and investment plan analyses. IDaT takes specifications on products, machines, and MHSs as input, and provides nine key decisions for FAS design (layouts and operating policies) and economic assessment. IDaT possesses an important design capability, which is to explicitly capture the effect of machine flexibility on system design and investment strategies. Within our knowledge, the proposed IDaT is the first integrated method that can support design activities and economic justification for FASs. We present a case study to demonstrate that IDaT can be very useful in finding cost-effective designs for FASs quickly at the early design stage. This enables a design team to reduce design lead times, evaluate more alternatives thoroughly, and assess their investment plans for FASs.

For the detailed analysis, we introduce new promising methods for buffer sizing and part input sequencing that are coherently tied with the rough-cut analysis. They are intuitive and efficient, yet seem to be effective according to a small number of experiments. Further research is needed to compare them with other existing methods.

IDaT can be improved further by enhancing the following three aspects.

(1) Machine flexibility. The current IDaT treats machine flexibility as the number of tasks (operations) a machine can perform with negligible changeover times between task changes. In other words, an underlying assumption is that each task requires the same amount of flexibility from the limited flexibility capacity. In a more realistic setting, however, machine flexibility is determined by the finite size of tool magazines or finite work space of assembly robots, and tasks may require unequal amounts of this limited size. For example, in PCB assembly, tube feeders feeding large components such as plastic leaded chip carriers require more work space than tube feeders feeding small components such as capacitors. In flexible machining systems, where a CNC metal cutting machine may have 60 slots on the tool magazine, one operation may require 20 slots while another operation may require only 9 (Stecke 1992).

(2) Machine breakdowns. The current IDaT considers small random disturbances such as tool jams, but does not yet consider large disturbances such as machine breakdowns. In FASs assembling PCBs, the mean time between failures for an insertion machine can be of the order of ten hours while the mean time to repair the machine can be approximately an hour (Akella et al. 1985). In flexible machining systems, such disturbances can be tool breaks and replacements, for example (Vinod and Sabbagh 1986).

(3) Multi-criteria design support methods. The current IDaT seeks minimal-cost design under several constraints. In practice, the design process is driven not only by design cost but also by other design criteria such as maximum flexibility to adapt to future changes (Tavora 1989). Rampersad (1995) proposes an FAS design method which has the dual design criteria of maximizing a production value while minimizing design cost. Future research could investigate a possible generalization of the proposed IDaT to handle multi-criteria design methods.

With the above improvements, IDaT can be applied to a broader class of manufacturing systems. These are some suggestions for future research studies.

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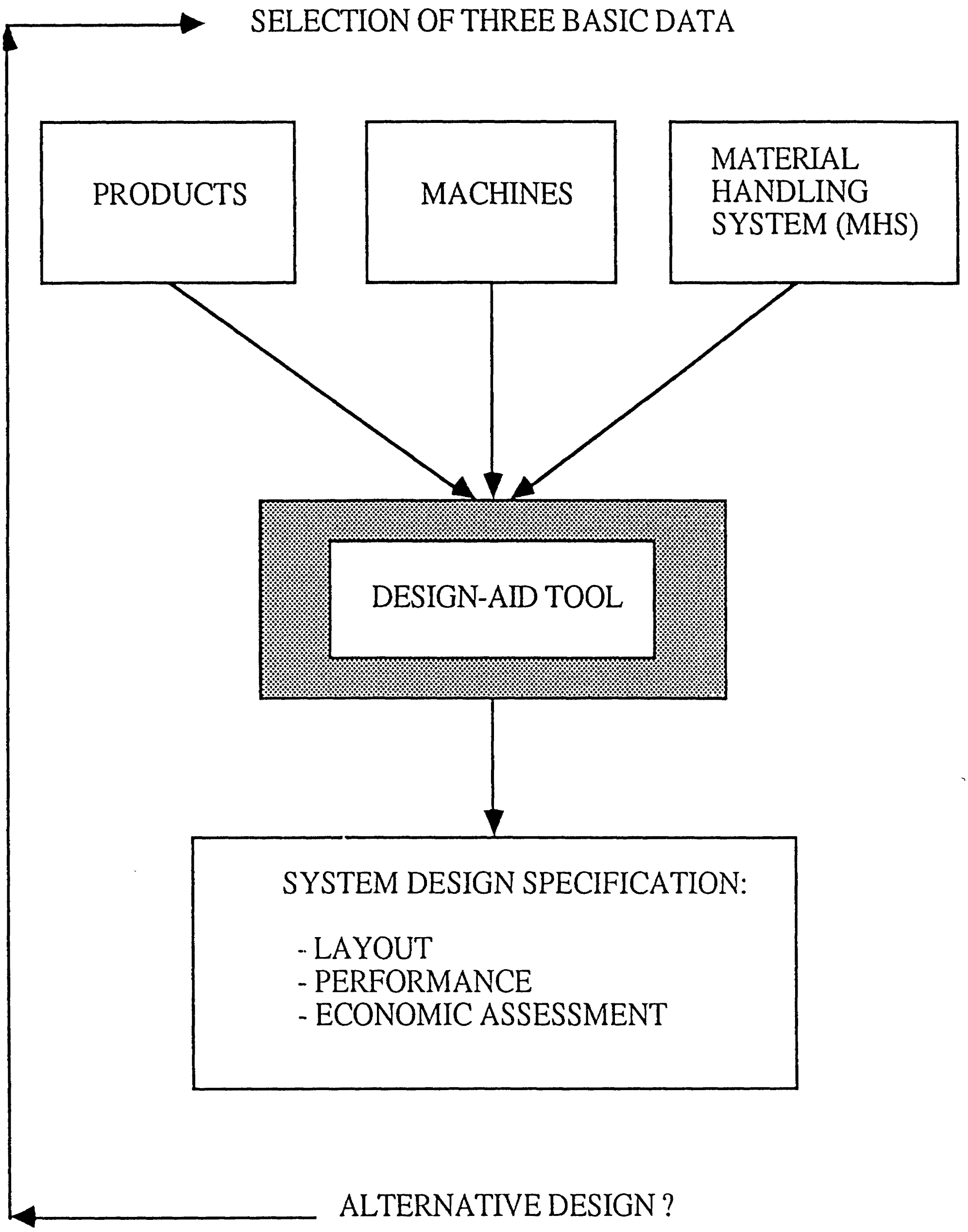


Figure 1. Manufacturing System Design Process.

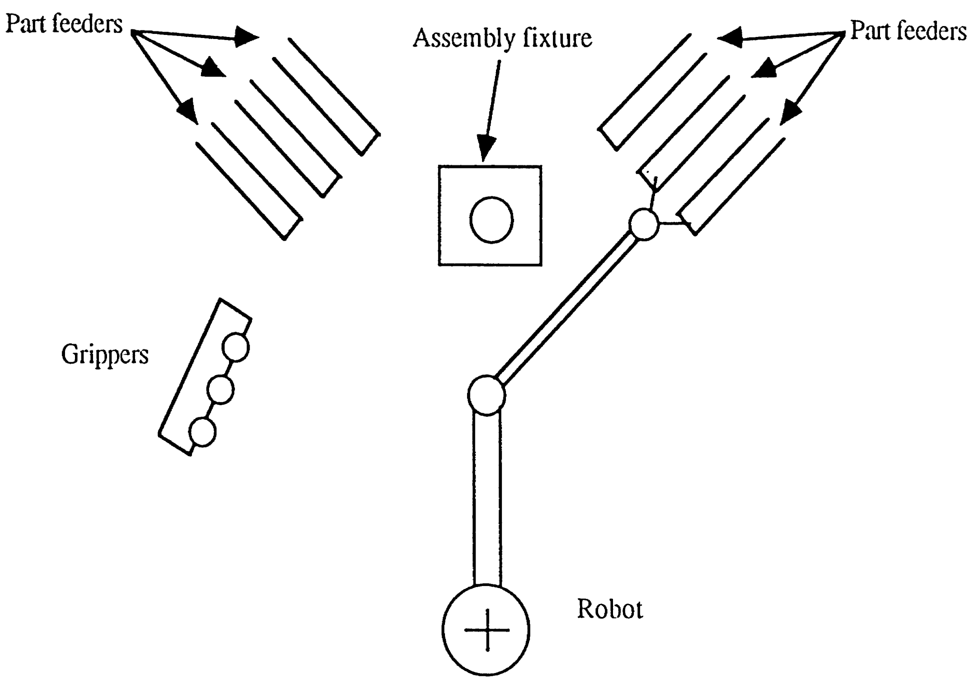


Figure 2. A Robot Assembly Cell.

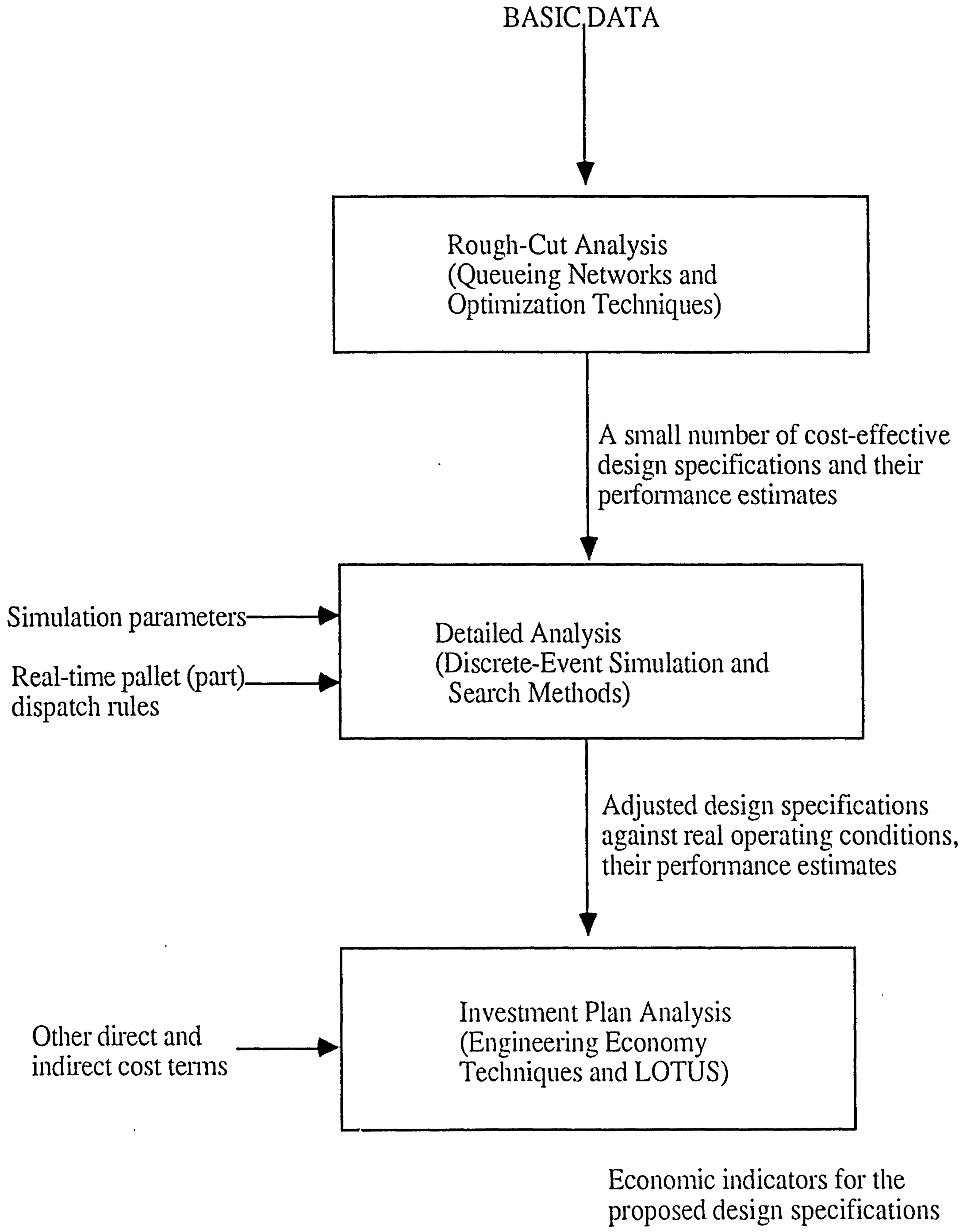
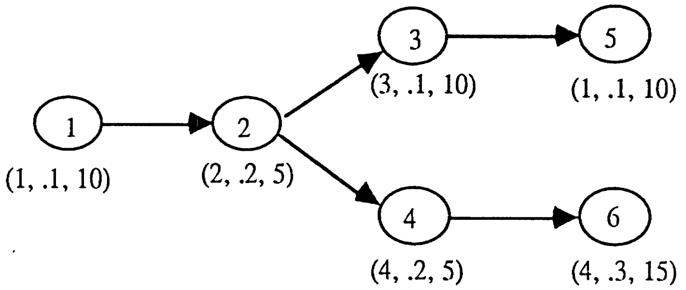
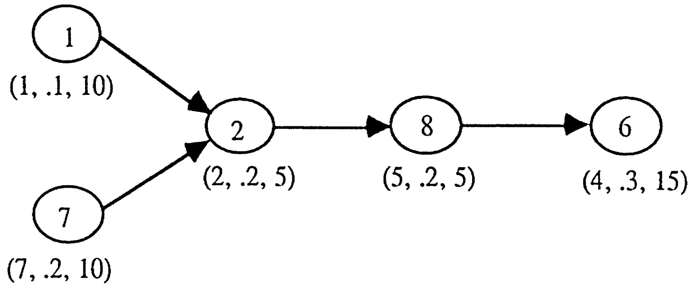


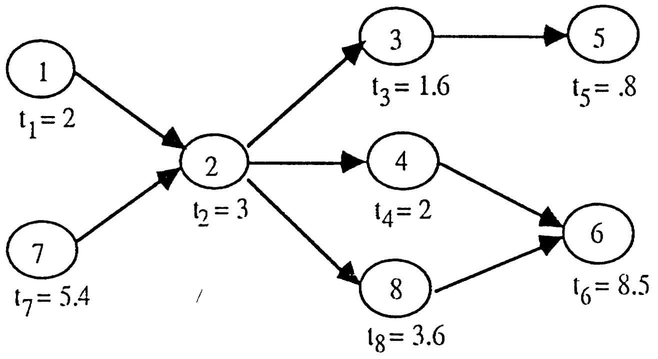
Figure 3. IDaT Structure for FASs.



(a) Product 1 and demand $d_1 = 200$



(b) Product 2 and demand $d_2 = 300$



(c) Aggregate product and aggregate demand d = 500

Figure 4. Two Products and Their Aggregate Product

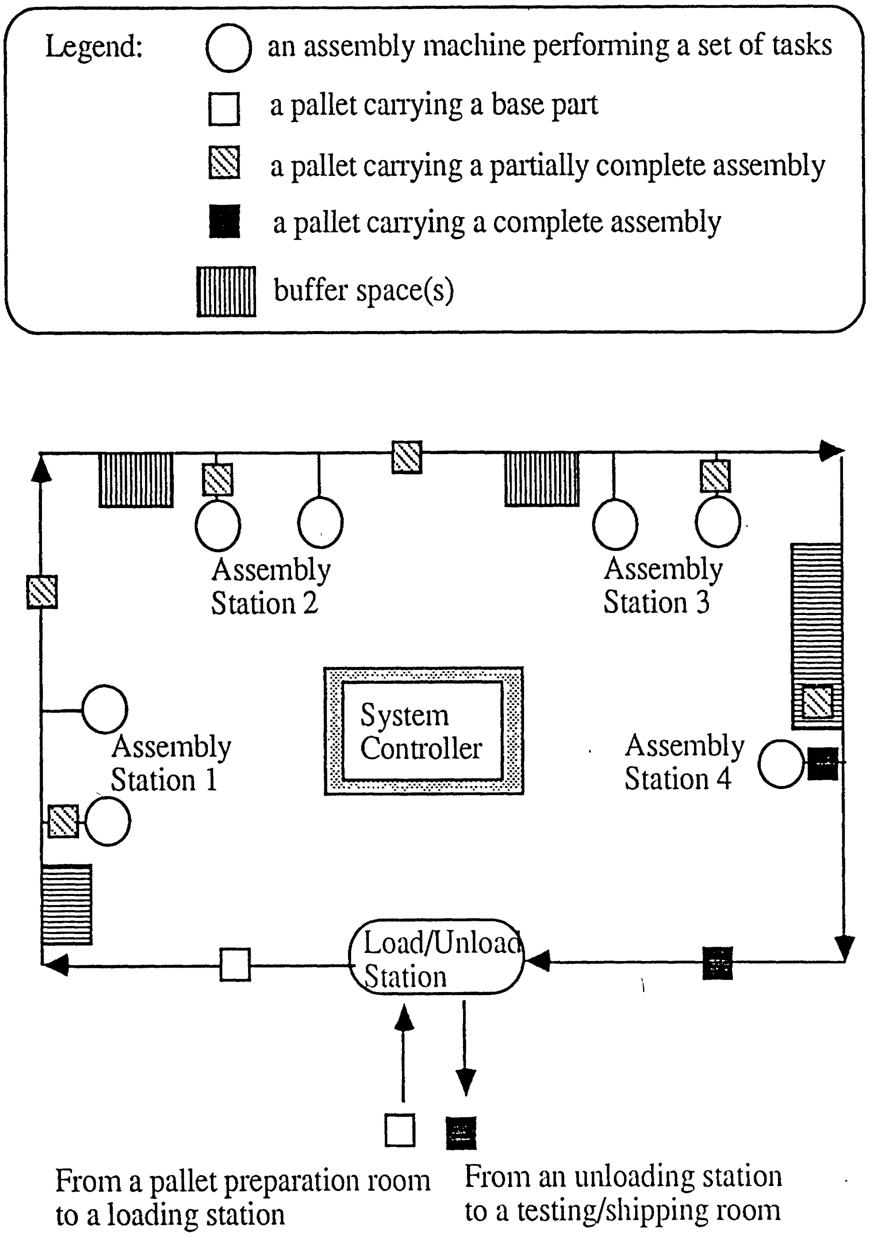


Figure 5. A Closed-loop FAS Design.

Table 1. Notation.

Input: n = total number of tasks in the aggregated product

C = number of machine types

d = demand of the aggregated product

t_j = task time of task j in the aggregated product

A_c = the set of stations using machines of type c

R_c = flexibility capacity of machines of type c

$\overline{T}$ = vector indicating transfer times between adjacent stations.

Output: M = total number of assembly stations in an FAS

N = number of pallets circulating in the system

K_c = number of machines of type c

S_0 = number of transporters if required

$z(N,S_0,K_1,K_2,\ldots, K_C)$ = total annualized cost of $N,S_0,K_1,K_2,\ldots, K_C$

$\overline{S}$ = vector indicating the number of parallel machines at each assembly station

$\overline{W}$ = vector indicating the workload at each station (average time taken to process one unit of the aggregate product at each assembly station)

TH = throughput of the CQN for given M, N, S_0, $\overline{S}$, $\overline{T}$, $\overline{W}$

X_{ij} = an assignment variable, which is set to 1 if task j is assigned to the i^{th} station, and set to 0, otherwise.

Table 2. IDaT Environments and Implementation.

Analysis	Techniques	User Interface	Software	Operating System	Platform
RA	Queueing Network and Mathematical Programming	Prepare three text input files for basic data	programs written in FORTRAN and PASCAL, DOS batch file	DOS 3.0 or higher	PC 486 or higher
DA	Discrete Simulation and Search Methods	Prepare one text input file for simulation parameters	programs written in FORTRAN, PASCAL, and SIMAN V, DOS batch file	DOS 3.0 or higher	PC 486 or higher
IPA	Engineering Economy	Modify a sample spread work sheet	LOTUS	DOS 3.0 or higher	PC 486 or higher

Table 3. Results from the Buffer-Sizing Heuristic.

Iteration No.	Buffer Spaces of Four Stations	Total Parts Produced*
1	(5, 4, 4, 7)	5,167
2	(4, 3, 3, 6)	5,157
3	(3, 2, 2, 5)	5,153
4	(2, 1, 1, 4)	5,080
5	(1, 0, 0, 3)	4,552
6	(1, 0, 1, 3)	4,756
7	(1, 1, 1, 3)	5,071

*Total parts produced = total number of parts produced for all four products (average of three replications); Total parts produced are evenly spread among the four individual products according to their production ratios. For example, at iteration 7, total parts 5,071 consist of 507, 1014, 1521, and 2029 parts for the individual types.

Table 4. Economic Assessment for the Proposed FAS Design:
Flexible Assembly System of Type A

Initial Investment (Purchase and Installation)	
1. Machines: 7 units x $100,000 =	$700,000
2. MHSs:	
pallets/fixtures: 9 units x $2,500 =	$22,500
conveyors: 125 feet x $400/foot =	$50,000
3. Central system controller which coordinates four stations and MHSs:	$200,000
Total Initial Investment	$972,500
Average Annual Revenues	
5000 parts/week x 50 weeks/year x $20/part =	$5,000,000
Annual Maintenance and Expense Items	
1. Machines: 7 units x $10,000 =	$70,000
2. MHSs:	
pallets/fixtures: 9 units x $250 =	$2,250
conveyors: 125 feet x $40/foot =	$5,000
3. Central system controller which coordinates four stations and MHSs =	$20,000
4. WIP inventory cost: 9 parts x $10 =	$90
5. Personnel ($30,000 per worker per shift; run 2 shifts):	
one worker at the pallet preparation room:	$60,000
one worker at the L/UL station:	$60,000
two workers to inspect and rework:	$120,000
one worker to ship out completed assemblies:	$60,000
two workers to refill feeders and clear jams:	$120,000
one NC programmer:	$60,000
one repair/maintenance worker:	$60,000
6. Annual material cost: 5000 parts/week x 50 weeks/year x $10/part =	$2,500,000
7. Annual rent and other overhead: 12 months x ($50,000 + $50,000) =	$1,200,000
Total Annual Expenses:	$4,337,340
Net Annual Cash Flow = $5,000,000 - $4,337,340 =	$662,660
Economic Indicators	
Payback Period = $972,500 / $662,660 =	1.47 years
Present Worth = - $972,500 + $662,660 x (P/A,10%,10 years)§ =	$3,099,280
Unit Production Cost = {$4,337,340+$972,500 x (A/P,10%,10 years)}/250000 =	$17.98
Net Annual Profit = $5,000,000 - $17.98/part x 250000 parts/year =	$505,000
Rate of Return {i.e., i% such that $972,500 = $662,660 x (P/A,i %,10 years)} =	67.8%

§ (P/A,10%,10 years) is a discrete compound interest factor that provides present worth, given 10 annual cash flows with 10% annual interest.

Table 5. Comparison Among Three Assembly Methods.

Assembly Method	Low Flexible m/c (Type A)	High Flexible m/c (Type B)	Manual
flexibility capacity	30	45	10
speed factor*	1	1.2	0.8
precision (quality)	good	better	poor
no. of shifts	2	2	1
mean jam rate	1 per 100 tasks	1 per 100 tasks	no jam
mean jam clear time	60 sec.	60 sec.	no jam
assembler cost/unit			
-purchase	$100,000	$150,000	-
-annual maintenance	$10,000	$15,000	-
-annual labor/shift	-	-	$30,000
system controller			
-purchase	$200,000	$200,000	$50,000
-annual maintenance	$20,000	$20,000	$5,000

*speed factor = ratio of processing time by the type A assembly method to processing time by the chosen assembly method

Table 6. Comparison Among Three System Designs.

Assembly Method	Low Flexible m/c	High Flexible m/c	Manual
	(Type A)	(Type B)	
no. of stations	4	3	17
parallel machines at each station	2, 2, 2, 1	2, 2, 1	1 per station
buffer spaces at each station	1, 1, 1, 3	12, 11, 12	2,1,2,2,2,2,2,1,1, 1,1,2,3,3,1,2,1
assignment of 100 tasks among stations	27,29,30,14	39, 38, 23	6,4,5,5,6,8,7,5,4, 5,9,5,7,6,7,7,4
route sequence			
product 1	stations 1 to 4	stations 1 to 3	stations 1 to 17
product 2	stations 1 to 4	stations 1 to 3	stations 1 to 17
product 3	stations 1 to 4	stations 1 to 3	stations 1,2, 4 to 8, 10 to 17
product 4	stations 1 to 4	stations 1 to 3	stations 1 to 17
no. of pallets/fixtures	9	15	27
conveyor length	125 feet	125 feet	250 feet
dispatch policies			
at assembly stations	FCFS	FCFS	FCFS
at L/UL station	input sequence rule I(t)	input sequence rule I(t)	input sequence rule I(t)
completed assemblies	507; 1014; 1521; 2029	502; 1003; 1504; 2006	512; 1024; 1537; 2047
net annual profit	\$505,000	\$547,500	\$132,500
present worth	\$3,099,281	\$3,362,648	\$814,670
unit production cost	\$17.98	\$17.81	\$19.47
payback period (years)	1.47	1.45	1.29
rate of return	67.8%	68.7%	77.0%
analysis time on a PC	22 min	12 min	58 min

Table 7. Economic Assessment for the Proposed FAS Design:
Manual Assembly

Initial Investment (Purchase and Installation)	
1. MHSs:	
pallets/fixtures: 27 units x $2,500 =	$67,500
conveyors: 250 feet x $400/foot =	$100,000
2. System controller; in this case a conveyor controller:	$50,000
Total Initial Investment	$217,500
Average Annual Revenues	
5000 parts/week x 50 weeks/year x $20/part =	$5,000,000
Annual Maintenance and Expense Items	
1. Manual assembly: 27 workers x $30,000 =	$510,000
2. MHSs:	
pallets/fixtures: 27 units x $250 =	$6,750
conveyors: 250 feet x $40/foot =	$10,000
3. A conveyor controller =	$5,000
4. WIP inventory cost: 27 parts x $10 =	$270
5. Personnel ($30,000 per worker per shift; run 1 shift):	
one worker at the pallet preparation room:	$30,000
one worker at the L/UL station:	$30,000
five workers to inspect and rework:	$150,000
one worker to ship out completed assemblies:	$30,000
6. Annual material cost: 5000 parts/week x 50 weeks/year x $10/part =	$2,500,000
7. Annual rent and other overhead: 12 months x ($80,000 + $50,000) =	$1,560,000
Total Annual Expenses:	$4,832,020
Net Annual Cash Flow = $5,000,000 - $4,832,020 =	$167,980
Economic Indicators	
Payback Period = $217,500 / $167,980 =	1.29 years
Present Worth = - $217,500 + $167,980 x (P/A,10%,10 years)§ =	$814,670
Unit Production Cost = {$4,832,020+$217,500 x (A/P,10%,10 years)}/250000 =	$19.47
Net Annual Profit = $5,000,000 - $19.19/part x 250000 parts/year =	$132,500
Rate of Return {i.e., i% such that $217,500 = $167,980 x (P/A,i%,10 years)} =	77.0%

§ (P/A,10%,10 years) is a discrete compound interest factor that provides present worth, given 10 annual cash flows with 10% annual interest.