INT. J. PROD. RES., 1995, VOL. 33, NO. 3, 757–775

Design and scheduling of flexible assembly lines for printed circuit boards

M. M. DESSOUKY†§, S. ADIGA‡ and K. PARK*

A particular approach for the design of printed circuit board assembly lines integrated with a scheduling methodology is proposed. The goal of the design and scheduling methodology is to maximize the throughput of the system while keeping work-in-process inventory levels to a minimum. The proposed design is based on the notion that it is easier to control and schedule flow lines than general production lines because for a flow line the scheduling problem is reduced to a sequencing problem. Experimental results of the proposed approach for an electronics manufacturer suggest that by implementing the approach the company can reduce inventory and achieve high throughput levels.

1. Introduction

During the past decade, a trend among manufacturers has been to move away from dedicating assembly lines to individual products to having more flexible assembly lines capable of producing more than one product. A flexible assembly line can consist of both automated machines and manually operated machines allowing the firm to assemble a sequence of different products on the same set of machines.

A flexible assembly line must be capable of processing multiple product types but not necessarily at the same time. For effective machine utilization, the set-up times from one product type to another must be small compared with the lot processing time. As a result, machine utilization will not substantially increase with small lot sizes.

The design of flexible assembly lines is becoming increasingly difficult because of the rapid introduction of new products. New products may have different processing requirements and may alter the product mix, which can cause imbalances in the assembly line. Thus, new methods for designing flexible lines that can handle product mix changes are needed.

A particular approach for the design of flexible assembly lines integrated with a scheduling methodology for printed circuit board assembly is proposed here. The goal of the design and scheduling methodology is to maximize the throughput of the system while keeping work-in-process (WIP) inventory levels to a minimum without increasing the capacity of the assembly facility.

The main ideas of the proposed approach arose from a study of an electronics manufacturer that assembled printed circuit boards. The assembly facility produces many different types of printed circuit boards using both surface mount technology (SMT) and plated through hole (PTH). The assembled boards are then shipped to a

---

Revision received December 1993.

† Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, CA 90089-0193, USA.

‡ Department of Industrial Engineering and Operations Research, University of California, Berkeley, CA 94720, USA.

* Department of Management, YeungNam University, Kyoung-San, 712-749, Korea.

§ To whom correspondence should be addressed.

separate facility that assembles the boards into a final product. The characteristics of the assembly system the proposed approach applies to are:

(1) The line assembles multiple board types (appears in the literature as mixed-model line balancing) with each board type belonging to a product group. Each product group follows a fixed route;
(2) there are multiple machine types on the assembly line, and there can be more than one machine per machine type. All machines of the same type are identical;
(3) a board is not processed on the same machine type more than once;
(4) processing time depends on the board type and machine type;
(5) processing time variability is negligible;
(6) the lot size is assumed to be known and is pre-determined by company policy. Typically, the company desires to keep all the boards of the same type that belong to the same final product together in one order (lot);
(7) setup times are small compared to the lot processing time and are sequence-independent so that they can be included in the lot processing time;
(8) machines are reliable. However, the availability of the machines for processing is not 100% since preventive maintenance and major product changeovers need to be scheduled. Typically, the availability of the machines is in the range of 80–90%.

Even though the above assumptions may not be applicable to some industries, these characteristics are very common in printed circuit board assembly lines.

The proposed approach consists of two broad phases. The first groups identical and nonidentical machines into workstations which are visited by each product in the same sequence, thus converting the processing into a flow line configuration. The second phase is to schedule the products on the workstations taking advantage of the flow line configuration.

The proposed design is based on the notion that it is easier to control and schedule flow lines than general production lines because for a flow line the scheduling problem is reduced to a sequencing problem. In addition, the material handling system (MHS) is simpler for a flow line than a general production line because all products follow the same path. Even though the intent of the approach is not to design an MHS, a flow line design is consistent with the MHS of most printed circuit board assembly lines because many such lines use conveyors to transport the boards. In many printed circuit board assembly lines, conveyors are the preferred MHS because of cost, simplicity, and the dimensions of the board are ideal for conveyors. Furthermore, the flow line can accommodate a U-shaped line design which can improve worker productivity as outlined by Black (1991) and Sekine (1991).

In this paper, we propose to use the assembly line balancing problem to group identical and nonidentical machines into workstations. The traditional line balancing problem may be defined as follows. Given a set of tasks with known processing times, it is required to group these tasks into subsets, with each subset assigned to a workstation, such that the total idle time is minimized, and certain constraints are observed. The idle time of a workstation is the difference between the line's cycle time and the sum of processing times of the tasks assigned to the station. The constraints include the integrality of tasks, i.e. no task splitting, and precedence relationships among the tasks. Minimizing the idle time tends to even out the distribution of tasks over the resources, maximize the throughput, and minimize the WIP inventory levels.

The line balancing problem addressed here is similar to the traditional problem except that the tasks in this case are the machines. The approach uses assembly line balancing heuristics to logically group identical and nonidentical machines into workstations. The grouping of machines to workstations is done in such a manner as to distribute the machines evenly across all the workstations which tends to maximize the throughput and minimize WIP inventory levels. The throughput of the system is defined to be the total daily output rate of all boards.

With the grouping of workstations into a flow line, the scheduling problem then becomes one of determining the best sequence to minimize some performance measure such as makespan or average flow time. The flow time is the total time a board spends in the assembly process. Note that minimizing the average flow time is the same as minimizing the average WIP inventory for a system that is in steady state.

The remainder of the paper is organized as follows. § 2 describes the printed circuit board assembly process. A literature survey of line balancing and sequencing rules for flow lines is reviewed in § 3. The proposed approach is presented in § 4. The case study of a printed circuit board assembly line for an electronics manufacturer is contained in § 5.

2. Printed circuit board assembly process

The assembly of printed circuit boards is a relatively straightforward process. Lots of boards are populated with various types of components in a series of operations carried out on a combination of highly automated machines as well as manually operated machines. The assembly process is followed by a testing process in which there is a probability that a given board will fail and require repair.

Most printed circuit board assembly facilities manufacture different product types that have unique routes. This situation is especially common when the assembly facility uses two different types of assembly technologies such as PTH and SMT. The older board types tend to use PTH while the newer board types use SMT. In addition, some board types use a combination of both technologies.

A typical printed circuit board manufacturing process is shown in Fig. 1. The first step is to release a production order. The timing of the release of production orders as well as the lot size is usually performed by a material requirement planning (MRP) system. The kitting process places the components that will be assembled on the raw board into kits. From kitting certain components are sent directly to the automated insertion process while others are routed to prepping.

The prepping process includes marking the raw boards and component lead-forming. The automated insertion process has numerically controlled machines inserting a variety of components onto the raw board. The machines are typically classified as radial, axial, and dip insertion. A vast majority of boards require at least some manual loading or insertion of components (particularly, the odd-shaped or non-standard components).

The last step before testing involves wave soldering the printed circuit board. The first test process is nodal impedance test which is used to identify assembly defects such as wrong or missing components. The burn-in process mounts the boards on racks and places the racks in an environmental stress chamber to cycle electrically for 24 h in order to induce component infant mortality. The last test performed on the printed circuit boards is referred to as a functional test.

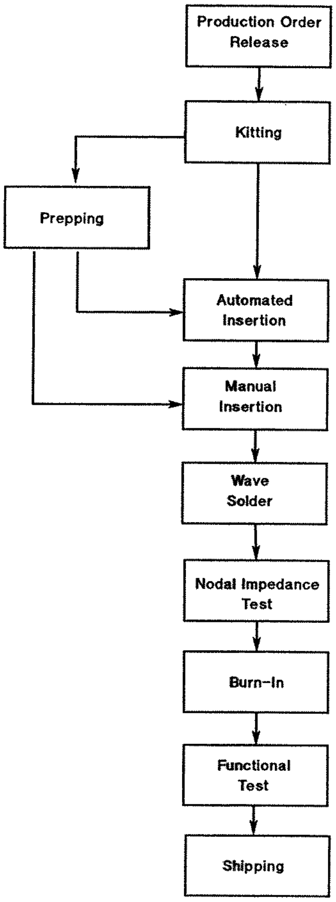

Figure 1. Generic diagram for printed circuit board assembly.

3. Literature survey

The proposed design and scheduling approach uses both line balancing and flow line sequencing rules. Section 3.1. reviews line balancing, and § 3.2 reviews some sequencing rules for flow lines.

3.1. *Line balancing*

Historically, the assembly line balancing problem has dealt with the assignment of tasks to operators in a mass production line (Bedworth and Bailey 1982). The assembly line balancing problem has also been used to determine the assignment of tasks to resources other than operators such as machines or robots. In this paper, we propose to use the assembly line balancing problem to group identical and nonidentical machines into workstations.

The objective of the assembly line balancing problem is to minimize the total idle times, which is the sum of the idle time of all the operators on the assembly line, resulting from the unequal distribution of task times over the operators. A common measure of lack of balance is the balance delay which is defined as the ratio of the total idle time to the total available time at all operators. A perfect balance is achieved when all operators are assigned an equal amount of work to perform, and the balance delay is zero. The constraints that need to be considered are precedence relationships among the tasks and restrictions on the assignment of some tasks to certain operators.

Most of the common heuristics for the assembly line balancing problem assume that only a single-product type is being assembled. We first present these heuristics then consider how they can be altered to consider the assembly of more than one product type.

Kilbridge and Webster (1961) observed that the three predominant contributors to high balance delay for an assembly line system for a specific product are a wide range of tasks times, inflexible task assignment to operators, and indiscriminate choice of cycle time. Since the cycle time of a single-product assembly line is simply the reciprocal of the throughput, the proper choice of the cycle time is crucial to the design of flexible assembly lines.

The following steps involved in designing an assembly line as proposed by Moodie (1981) are:

(1) determine the cycle time;
(2) compute the number of operators needed to support the desired cycle time;
(3) prepare a network diagram of precedence relationships among the elemental tasks;
(4) assign tasks to operators considering the restrictions on labour assignments.

Typically, the tasks are ranked based on some heuristic rule to minimize the total idle time. In the single-product case, minimizing the total idle time is equivalent to minimizing the number of operators for a given cycle time. The assignment of tasks to operators is performed by selecting tasks in the order of their ranking to assign to operators while maintaining precedence relationships among tasks and restrictions on labour assignments.

Numerous heuristics for the assignment of tasks to operators have been proposed in the literature. One such heuristic is the Ranked Positional Weight method developed by Helgeson and Birnie (1961). This method defines the positional weight as the sum of the task's processing time plus the processing times of all succeeding tasks. The basic logic of this method is to assign tasks to operators in decreasing order of the positional weight whenever the precedence restrictions and remaining unassigned idle time for the operator permit.

Mansoor (1964) developed a procedure to find the near 'optimal' task to operator assignment that involves interchanging tasks after an initial feasible assignment has been found. However, for a large set of tasks the solution procedure can be impractical since a large amount of interchanges need to be considered. Bedworth (1973) developed a heuristic referred to as the Region method that builds on the concepts of the Helgeson and Birnie and Mansoor procedures.

It is common to find that the same assembly facility produces more than one product type. One means of managing this situation is to dedicate a separate assembly line for each product. The drawback with this approach is that it can yield an inefficient utilization of the operators. An alternative design involves the simultaneous processing of more than one product type on the same assembly line. Two approaches to multiple-product assembly line balancing are aggregate task balancing and sequential single-product balancing.

In the aggregate task balancing method, the same task across different products is combined into one aggregate task. Since different products may have different processing times for the same task, then as Milas (1990) points out a manufacturing planner usually attempts to design the line either on the basis of an average task or on the task with the largest processing time (the worst case). In the latter case, the amount of idle time can be unnecessarily large. Thus, the processing time of the aggregate task is the weighted average processing time of the processing times of the individual tasks for each product (the weights may be based on the products demand). A precedence diagram that combines all the tasks for all the product types is developed. Then, using the heuristics for the single-product case, the line is balanced based on the weighted average processing times.

An alternative approach to solving the multiple-product assembly line balancing problem is to sequentially balance one product at a time (Mackaskill 1972). In this approach, the proportion of time the line is dedicated to a product needs to be estimated. The products are ranked in descending order based on these estimates. Then, single-product assembly line balancing is performed on each product in the ranked order. A drawback of this approach is that the number of operators is iteratively calculated for a given cycle time. Also, this approach does not ensure that the same task across different products is assigned to the same operator.

For this reason, the proposed approach uses the aggregate task method to determine the machine grouping to workstations to ensure that the same machines are always assigned to the same workstations. For a further discussion of the multiple-product assembly line balancing problem see Thomopoulos (1967), Roberts and Villa (1970), Mackaskill (1973), Okumura and Yamashina (1979), Dar-El *et al.* (1975, 1977, 1978, 1981), Kotani (1982), and Chakravarty and Shtub (1985).

3.2. *Flow line sequencing rules*

The flow line consists of K machines in series with flow of work being unidirectional with each job required to be processed on each machine. The scheduling problem is to determine the best sequence of jobs to minimize some performance measure such as makespan or average flow time. Although the flow line scheduling problem is the simplest multi-stage scheduling problem, it still requires a considerable amount of computation time to find an optimal sequence for any realistic problem size (Hax and Candea 1984).

A schedule that maintains the sequence down the line is called a *permutation schedule*. The optimal schedule for the two-machine flowshop with any performance criterion and three machine flowshop with the makespan criterion is guaranteed to be a permutation schedule (Conway *et al.* 1967). For a larger machine flowshop, it is reasonable to believe that the best permutation schedule, even if not optimal, cannot be too far away from optimum (Hax and Candea 1984).

The optimal permutation schedule can be found by branch-and-bound integer programming techniques. These have been studied by Ignall and Schrage (1965), Brooks and White (1965), Lominicki (1965) and Bestwick and Hastings (1976). As previously mentioned, it is computationally infeasible to find an optimal sequence for any realistic problem size. For this reason, numerous heuristics have been developed to determine a 'good' permutation schedule. The most common performance criterion that the heuristics pursue is to minimize the makespan. As Bitran and Tirupati (1988) point out, makespan is an important performance measure because it represents unfinished work and can be used as a surrogate measure of work-in-process.

Park *et al.* (1984) tested 12 heuristics in the literature on a large number of sample problems for both the makespan and average flow time criteria. They employed the

Campbell heuristic (Campbell *et al.* 1970) as the standard to which all other heuristics are compared because of its effectiveness and simplicity. The other heuristics in the study include heuristics developed by Palmer (1965), Petro (1966), Gupta (1971), Bonney and Gundry (1976), Dannenbring (1977), Gelders and Sambandam (1978), King and Spachis (1980) and Nawaz *et al.* (1983). The results showed that the Campbell heuristic outperformed most of the heuristics in terms of both the makespan and average flow time criteria. In some sample data sets, the Nawaz *et al.* heuristic outperformed the Campbell heuristic in terms of the makespan criteria. However, this heuristic requires a significant amount of computation to solve compared to the Campbell heuristic.

The Campbell heuristic treats the K-machine flowshop sequencing problem as $(K-1)$ independent two-machine flowshop subproblems. The two machines in each subproblem are an artificial combination of the existing machines, and Johnson's algorithm (1954) is used to find the optimal sequence in each subproblem. Let $t_{i,k}$ be the processing time of job i on machine k; let $T_{i,m}(l)$ be the processing time of job i on the mth artificial machine in the lth subproblem. The following processing times that are used for each subproblem in the Johnson algorithm are:

$$T_{i,1}(l) = \sum_{k=1}^{l} t_{i,k}$$

$$T_{i,2}(l) = \sum_{k=K-l+1}^{K} t_{i,k}$$

Thus, the heuristic generates a total of $(K-1)$ sequences. Then, the sequence that gives the smallest average flow time is selected.

4. Proposed approach

The goal of the proposed approach is to develop a new design and scheduling methodology that maximizes the throughput of the system while keeping the WIP inventory levels to a minimum without increasing the resources of the assembly process. One of the main ideas behind the proposed approach is to the reduce the network of machines to a single flow line of workstations. Each workstation is a combination of identical and nonidentical machines. Then, the order in which the boards will visit the workstations is determined.

The notation for the parameters and computed variables of the proposed approach are as follows:

(1) Indices:
  i = board type index $i = 1, \ldots, N$, where N is the number of board types;
  k = machine type index $k = 1, \ldots, K$, where K is the number of machine types;
  l = workstation type index $l = 1, \ldots, L$ where L is the number of workstations.

(2) Parameters:
  $t_{i,k}$ = board processing time of board type i on machine type k;
  s_k = setup on machine k;
  b_i = lot size of board type i;
  q_i = number of boards of type i assembled in the final product;

c_k = number of machines of type k;
a_k = fraction of time machine type k is available for processing;
T = length (duration) manufacturing time in a day at the assembly facility in minutes.

(3) Computed variables:
T_k = processing time of 'average board' on machine type k;
$T_{i,k}$ = lot processing time of lot type i on machine type k (includes board processing time and setup time);
$T_{i,l}$ = lot processing time of lot type i on workstation l;
C_a = cycle time used in the assembly line balancing heuristic;
D_k = output rate of machine type k;
D = output rate of the assembly line;
F_i = flow time of lot type i;
$\bar{F}$ = average flow time;
$O_{i,l}$ = completion time of lot type i on workstation l.

The first step of the proposed approach is to determine the theoretical maximum daily output rate of each machine type in terms of the final product which is equal to:

$$D_k = \frac{T^*c_k{}^*a_k}{\sum_{i=1}^{N} t_{i,k}{}^*q_i}.$$

The maximum daily output rate of the assembly line is then the smallest output rate of any machine type k. The maximum daily output rate in terms of individual boards is:

$$D = \min_k \{D_k\}^* \sum_{i=1}^{N} q_i.$$

The grouping of machines into workstations is accomplished by using the assembly line balancing techniques discussed in § 3.1. Note that identical machines, i.e. machines of the same type, are restricted to belong in the same workstation. The cycle time, C_a, used in the assembly line balancing heuristics is T/D. C_a can be interpreted as the average time between board departures from the assembly line. C_a is minimized when it is equal to the inverse of the maximum output rate. Besides yielding higher throughput, a small C_a provides the manufacturer with the flexibility to respond to changes in available resources and demand.

The machines are assigned to the workstations in a manner that tends to equalize the total processing times at the workstations and achieve the maximum output rate D. This assignment minimizes the average percentage of time any workstation is idle. As previously discussed, in the single-product case, minimizing the total idle time is equivalent to minimizing the WIP inventory levels for a given cycle time. Let W_l be the set of machine types k assigned to workstation l.

Since the assembly facility can produce more than one board type, the precedence diagram of visits to machines needs to include all possible board to machine routes. The processing time at each node (machine type) in the precedence diagram is the weighted average processing time across all board types. The weight for each board type is the number of boards of the type, q_i, to be processed divided by the total number of boards in the final product. In essence, the collapsing of machines to workstations is performed for the 'average board'. The processing time of the average board on machine type k is:

$$T_k = \frac{\sum_{i=1}^{N} t_{i,k} * q_i}{\sum_{i=1}^{N} q_i}.$$

Note that the boards that do not require to be processed on machine type k are also included in the calculation of T_k. Although this does not affect the numerator of the above equation the denominator is larger than if we had averaged only those boards that are processed on this machine type. The justification for this is that in a balanced line, all products will flow through all machines though they may spend zero time in some machines.

After the machines are grouped into workstations, the schedule is determined. Since the grouping of workstations is organized into a flow line, the scheduling problem is reduced to a sequencing problem. The sequence of boards on workstation l is summarized in the vector $\mathbf{\Omega}_l \equiv [\Omega_{l1}, \ldots, \Omega_{lN}]$, where the assignment $\Omega_{lu} = i$ means that the board type i is the uth board type to be assembled by workstation l. This analysis is performed on the individual board type not on the average board as in the previous step. A job is considered to be a lot of printed circuit boards for a particular board type. The company desires to keep all the boards of the same type that belong to the same final product together in one lot. Hence, the lot size, b_i, is set equal to q_i which also tends to keep the number of setups to a minimum. The time to complete the lot at a machine in the workstation includes the processing times of all the individual boards in the lot plus the lot setup time. The calculation of $T_{i,k}$ is as follows:

$$T_{i,k} = (q_i * t_{i,k} + s_k)/(a_k * c_k).$$

Since the flow line heuristics assume the capacity of each machine type is 1, the processing time of each job on each machine type used in the sequencing heuristics is adjusted to account for the capacity.

The time to complete the lot at the workstation is then the sum of the time to complete the lot at all the different machine types that the board will be processed on in the workstation. The calculation of $T_{i,l}$ is as follows:

$$T_{i,l} = \sum_{k \in W_l} T_{i,k}.$$

Since Hax and Candea (1984) show that the best permutation schedule cannot be too far away from optimal and the simplest type of schedule to control in the factory is a permutation schedule, we are only concerned with the initial sequence of lots at the first workstation and do not worry about dispatching decisions at subsequent workstations. Hence, the vector $\mathbf{\Omega}_1$ is only determined. The Campbell heuristic is used to determine the initial sequence at the first workstation which is the release sequence of boards into the assembly process. This sequence is maintained as much as possible through the assembly process by using the release sequence as the dispatching priority rule at subsequent workstations. This approach makes sense when the material handling system connecting the workstations follows a fixed path such as conveyors.

It should be pointed out that any sequencing heuristic could have been used at this step. The reasons why the Campbell heuristic is selected even though its objective is to minimize the makespan are: (1) Park *et al.* (1984) show that this heuristic performs very well compared to other heuristics in terms of both the makespan and average flow time criteria; (2) Bitran and Tirupati (1988) point out that makespan can be used as a surrogate measure of work-in-process; and (3) it is simple to implement and a solution can be found quickly.

The flow time can be calculated by deterministic formulas because the variability in the system is negligible (the processing time variability is small and the machines have no random failures.). The non-availability of machines is assumed to be due to scheduled maintenance, and there is sufficient slack in the utilization of machines to schedule the maintenance without disrupting production. The non-availability factor, $1 - a_k$, is accounted in the calculation of the cycle time, C_a. The flow time calculations of lot type i assuming the lots are ordered in the sequence $\mathbf{\Omega}_1$ is as follows (Bellman 1982):

$$F_i = C_{i,L} - C_{i-1,1}$$

$$C_{i,1} = C_{i-1,1} + T_{i,1} \qquad \text{for all } i \text{ and } C_{i,0} = 0$$

$$C_{1,l} = C_{1,l-1} + T_{1,l} \qquad \text{for all } l > 1$$

$$C_{i,l} = \max(C_{i,l-1}, C_{i-1,l}) + T_{i,l} \qquad \text{for all } i > 1, \text{ and for all } l > 1.$$

Finally, the average flow time can be summarized as follows:

$$\bar{F} = \sum_{i=1}^{N} F_i/N.$$

In summary, the proposed approach determines the set W_l for all l and vector $\mathbf{\Omega}_1$ to maximize the throughput while maintaining low WIP inventory levels. This is accomplished by performing the following steps:

Step 0. Draw a precedence diagram that shows the order in which the machines are processed on for all the different product groups.
Step 1. Determine C_a.
Step 2. Calculate T_k for each machine type k.
Step 3. Determine the set W_l for each workstation l by using one of the assembly line balancing heuristics such as the Ranked Positional Weight method or the Region method.
Step 4. Calculate $T_{i,l}$ for each board type and workstation combination.
Step 5. Determine the vector $\mathbf{\Omega}_1$ by using the Campbell heuristic.
Step 6. Set $\mathbf{\Omega}_l = \Omega_1$, for $l \neq 1$.

5. A case study

The studied assembly facility currently produces a total of 60 boards/day. The company desires a new system design of the assembly facility that can support higher levels of throughput while keeping WIP inventory levels to a minimum. The management of the company believes they currently have sufficient machine capacity to handle the increase throughput, and the higher throughput can be achieved by improved system design and scheduling. The company currently follows no systematic scheduling policy and is suffering from high WIP inventory levels even at the low output levels.

The assembly and test operations for all the different types of printed circuit boards are performed at the same manufacturing facility. Since the material flow between these two stages is usually unidirectional, there is a clean separation between the assembly

Machine name	Description
AUTO	Inserts components for PTH boards
BIRTH	Retrieves the bar code number from a computer database
CONTA	Removes contaminants like excess gold
ETCH	Cuts circuits according to the desired configurations
LASER	Etches the bar code number on the raw board
MANUA	Manual insertion
PRINT	Places paste through holes in the board
PLACE	Places the small electronic components onto the board
ROBOT	Inserts the large electronic components onto the board
RFLOW	An oven that causes solder to flow through grooves
TTIN	Lead tinning the components
WMECH	Inserts electronic connectors alongside the boards
WAVE	Soldering machine for PTH boards
WASH	Removes all the residuals and wax using water

Table 1. Machine type description.

Machine name	No. of machines	Availability factor	Lot setup time (min)
1. AUTO	1	0·80	12·36
2. BIRTH	1	1·00	0·00
3. CONTA	1	0·80	8·25
4. ETCH	1	0·80	1·50
5. LASER	2	0·80	4·14
6. MANUA	1	1·00	0·00
7. PRINT	2	0·88	24·89
8. PLACE	2	0·85	2·29
9. ROBOT	1	0·74	6·08
10. RFLOW	1	0·89	0·00
11. TTIN	1	0·88	0·00
12. WMECH	1	1·00	0·00
13. WAVE	1	0·79	0·00
14. WASH 0	1	0·77	0·00
15. WASH 1	1	0·77	0·00

Table 2. Machine data.

and test operations. The proposed approach considers in detail the assembly operation and treats the test operation as a 'black box' that all boards must visit.

The assembly of printed circuit boards consist of boards being processed on various machine types. Table 1 shows the machine types that the company has in its assembly facility. The assembly facility contains 14 different machine types. Each machine type can consist of more than one identical machines. The WASH machine type consists of two different washing operations performed on separate machines referred to as WASH 0 and WASH 1. For this manufacturer, a board is not processed on the same machine type more than once. The number of machines, availability factor, and the lot setup time of each machine type are listed in Table 2.

The company is assembling boards that use both PTH and SMT. The route of different printed circuit board types can vary significantly. However, a subset of the board types will have a common route. The boards that follow the same route are

Board type	Product group	q_i	Processing times at each machine (min)														
			2	5	4	14	7	8	11	9	10	15	6	1	3	12	13
1	1	60	4·23	3·00	4·26	11·90	26·11	30·20		3·00	16·97	11·90				4·58	5·48
2	1	10	4·23	3·00	15·61	11·90	25·78	30·20		3·00	16·97	11·90				4·58	5·48
3	1	6	4·23	3·00	15·61	11·90	25·78	34·40		3·00	16·97	11·90				4·58	5·48
4	1	40	4·23	3·00	15·61	11·90	25·78	30·86		3·00	16·97	11·90				4·58	5·48
5	2	9	4·23	3·00	22·29	11·90	25·78	30·08		3·00	16·97	11·90			20·06	4·58	5·48
6	2	1	4·23	3·00	30·37	11·90	25·78	30·08		3·00	16·97	11·90		17·80	20·06	4·58	5·48
7	2	8	4·23	3·00	22·29	11·90	25·78	30·08		3·00	16·97	11·90		17·80	20·06	4·58	5·48
8	3	1	4·23	3·00			26·11	25·72		3·00	16·97	11·90				4·58	5·48
9	3	20	4·23	3·00			26·11	24·52		3·00	16·97	11·90				4·58	5·48
10	3	2	4·23	3·00			26·11	28·93		3·00	16·97	11·90				4·58	5·48
11	3	2	4·23	3·00			26·11	14·20		3·00	16·97	11·90				4·58	5·48
12	3	1	4·23	3·00			26·11	23·99	2·00	3·00	16·97	11·90				4·58	5·48
13	3	20	4·23	3·00			25·78	24·52		3·00	16·97	11·90				4·58	5·48
14	3	1	4·23	3·00			25·78	26·80		3·00	16·97	11·90				4·58	5·48
15	4	5	4·23	3·00	4·20	11·90	26·11	24·49		3·00	16·97	11·90				4·58	5·48
16	4	5	4·23	3·00	30·13	11·90	26·11	24·52		3·00	16·97	11·90				4·58	5·48
17	4	5	4·23	3·00	18·05	11·90	25·78	28·93		3·00	16·97	11·90				4·58	5·48
18	4	5	4·23	3·00	4·99	11·90	25·78	24·52		3·00	16·97	11·90				4·58	5·48
19	4	35	4·23	3·00	9·30	11·90	25·78	27·42		3·00	16·97	11·90				4·58	5·48
20	4	2	4·23	3·00	17·17	11·90	21·83	32·16		3·00	16·97	11·90				4·58	5·48
21	4	2	4·23	3·00	13·81	11·90	25·78	29·29		3·00	16·97	11·90				4·58	5·48
22	4	1	4·23	3·00	10·77	11·90	25·78	27·30	2·00	3·00	16·97	11·90				4·58	5·48
23	4	1	4·23	3·00	8·16	11·90	25·78	29·41	2·00	3·00	16·97	11·90				4·58	5·48

24	4	1	4·23	3·00	16·50	11·90	25·78	34·11	2·00	3·00	16·97	11·90				4·58	5·48
25	4	6	4·23	3·00	19·86	11·90	25·78	34·40		3·00	16·97	11·90				4·58	5·48
26	5	1	4·23	3·00											19·94		5·48
27	5	1	4·23	3·00	3·60								4·10	18·05	32·68		5·48
28	5	4	4·23	3·00	14·40								0·50	18·88	14·09	4·58	5·48
29	5	1	4·23	3·00	23·40								8·40		32·68	4·58	5·48
30	5	1	4·23	3·00										29·31	12·01	4·58	5·48
31	5	1	4·23	3·00											14·09		5·48
32	5	1	4·23												13·70		5·48
33	5	1	4·23	3·00	12·00									24·85	32·68		5·48
34	5	1	4·23	3·00										25·00	13·83		5·48
35	6	21	4·23										2·94				
36	6	7	4·23										2·94				
37	6	14	4·23										2·06				
38	6	1	4·23										5·46				
39	6	3	4·23										5·28				
40	6	1	4·23	3·00									9·60				
41	6	1	4·23										12·36				
42	6	1	4·23										8·10				
43	6	5	4·23										5·46				
44	6	1	4·23										5·46				
45	6	1	4·23										5·46				
46	6	1	4·23										5·28				
47	6	2	4·23										12·24				

Table 3. Board data.

referred to as a product group. The studied company currently produces a final product that contains 320 boards consisting of 47 types of boards. The 47 board types can be combined into 11 product groups giving rise to a non-serial material flow of the assembly process. Since a board is not processed on a machine type more than once, the material flow is acyclic showing the order in which the boards get processed by the various machine types. Table 3 contains the board data. Included in the table are the number of boards of each type in the final assembly, the product group the board belongs to, and the processing times of the board on each machine type. A blank in the table indicates that board type does not require processing on that machine type.

The current design of the assembly process follows no general pattern because the product groups have different routes. Each board travels only to the machines on its route. Because of the layout of the assembly process, the company finds it difficult to use a systematic scheduling policy integrated in a factory control system. Hence, the material flow of the new system design should be logical and simple so that systematic scheduling policies can be implemented easily.

The machine that is most heavily utilized is RFLOW. Assuming that the facility operates three shifts a day for a total of 22·5 h, the maximum daily output rate is 92

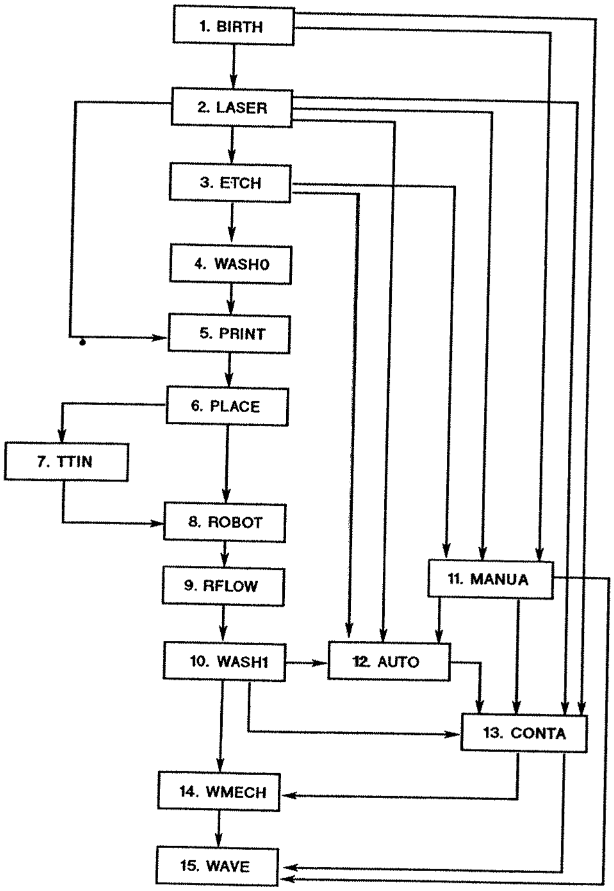

Figure 2. Common precedence diagram.

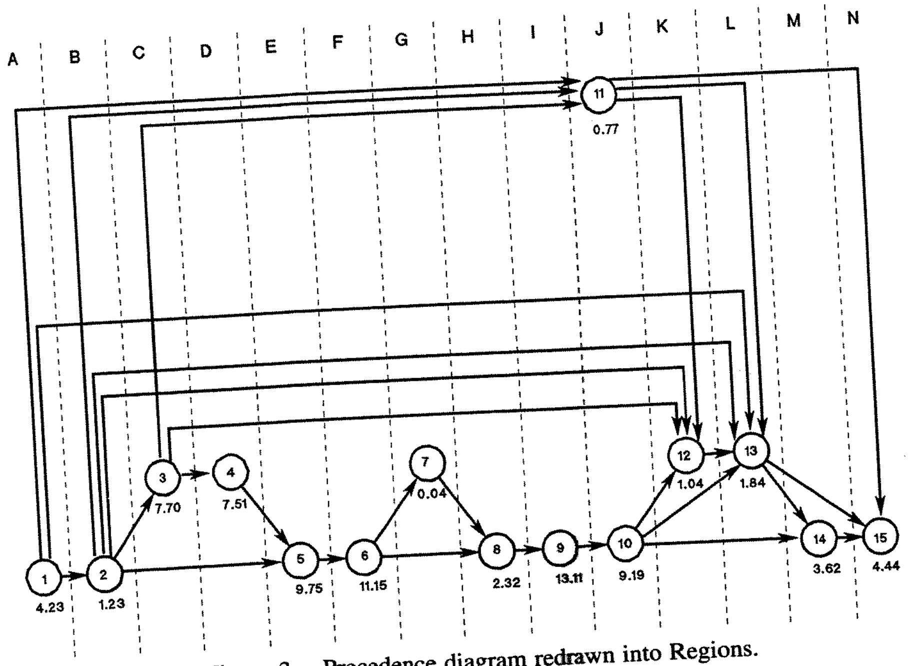

Figure 3. Precedence diagram redrawn into Regions.

Workstation	Machine type (in order of assignment)
1	BIRTH, LASER, ETCH, MANUA
2	WASH 0
3	PRINT
4	PLACE, TTIN, ROBOT
5	RFLOW
6	WASH 1, AUTO, CONTA
7	WMECH, WAVE

Table 4. Grouping of machines to workstations for the Region method.

Workstation	Machine type (in order of assignment)
1	BIRTH, LASER, ETCH
2	WASH 0
3	PRINT
4	PLACE, TTIN, ROBOT
5	RFLOW
6	WASH 1, MANUA, AUTO, CONTA
7	WMECH, WAVE

Table 5. Grouping of machines to workstations for the Ranked Positional Weight method.

boards which yields a C_a of 14·7 min. To be conservative, we then set C_a to 15 min (equivalent to a daily output rate of 90 boards).

Both the ranked positional weight and region methods are applied to this data set to determine the grouping of machines to workstations. Figure 2 shows the precedence relationship of the machine types. Figure 3 shows the network drawn into regions. The number next to the circle is the processing time for the average board on that particular machine type. The Region method provided a grouping of machines into workstations that had the same line efficiency as the Ranked Positional Weight method. The assembly line efficiency for both methods is 74%. The grouping of machines into workstations is given in Table 4 for the Region method and Table 5 for the Ranked Positional Weight method. The resulting flow line of both methods contains 7 workstations. The only difference in the grouping of machines between the two methods is the location of the manual insertion operation.

The Region method places the manual insertion operation in the first workstation while the Ranked Positional Weight method places the manual insertion operation in the sixth workstation. Note that all the boards that require the manual insertion operation are also processed by the BIRTH machine which is contained in the first workstation while only three of the board types (27–29) that require the manual insertion operation are processed by either the AUTO or CONTA which are contained in the sixth workstation. Thus, placing the manual insertion operation in the sixth workstation balances the line better than putting the manual insertion operation in the first workstation. As such, the results of the Ranked Positional Weight method are used to determine the sequence. Figure 4 shows the recommended grouping of machines into workstations.

The next step is to determine the sequence of boards through the workstations. The company's current scheduling policy is based on a 'macro pull, micro push' strategy. An order for the complete set of the 320 boards that will be assembled into the final product is sent to the beginning of the assembly process as dictated by the master production schedule which triggers the release of raw boards to the factory. The raw boards are not released in any predetermined sequence with the only restriction being that all boards of the same type are released consecutively. Hence, the company's scheduling policy can be summarized as follows: random release sequencing and FIFO dispatching.

For the assembly system design given by the Ranked Positional Weight method, we compare the company's current scheduling policy with the Campbell and Dannenbring heuristics (Dannenbring 1977). The company's current scheduling policy is replicated by generating a random lot release sequence and then enforcing that sequence throughout the assembly process. The flow line sequencing rules are compared based on the average flow time performance measure as outlined in § 3. The Dannenbring heuristic is included in the study because a comparison to the Campbell heuristic is desired, and French (1982) points out the Dannenbring heuristic is also simple to implement and tends to perform well when combined with a 'Close-Order-Search', the interchanging of adjacent jobs in the sequence to improve the solution.

The Dannenbring heuristic creates a single, two-machine subproblem in which the processing times are weighted by the position of the machine on the flow line and then uses the Johnson algorithm to find the sequence. The processing times at the first machine are weighted by their position from the end of the line while the processing times at the second machine are weighted by their position from the beginning of the line. This weighting method is based on the notion that early sequenced jobs should

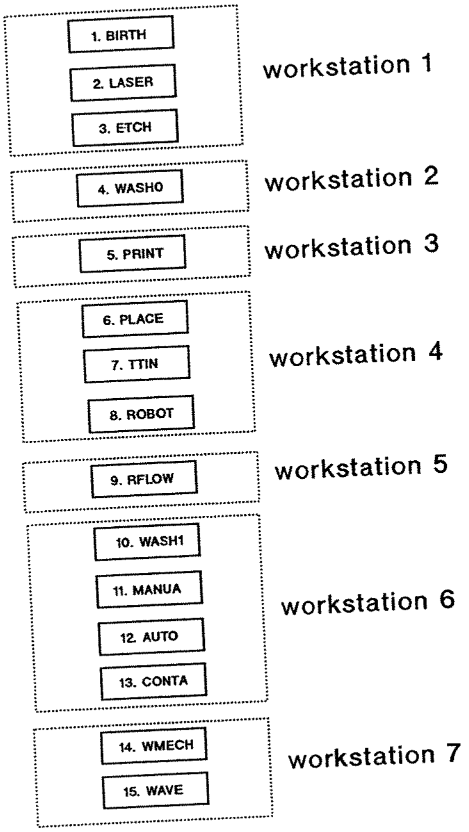

Figure 4. Organization of Machines into Workstations.

have processing times that tend to increase from machine to machine down the line, while later sequenced jobs should have processing times that tend to decrease.

The resultant overall average flow time from sequences generated by using the Campbell heuristic, Dannenbring heuristic, and Random are 34·8, 46·1 and 71·0 h respectively. The overall average flow time for the Campbell heuristic is the minimum of the 6 sequences that the Campbell heuristic generates. The overall average flow time for the Random sequence is calculated by averaging the flow time of 10 sequences that are generated randomly by running Monte Carlo simulations.

There is a 24·5% reduction in average flow time from the Dannenbring heuristic to the Campbell heuristic, and 51·0% reduction in the average flow time from the Random method to the Campbell heuristic. The fact that the Campbell heuristic outperforms the Dannenbring heuristic is not surprising since previous experimental studies by Parks *et al.* (1984) showed that the Campbell heuristic outperforms the Dannenbring heuristic. What is surprising is the magnitude of the difference. We can only conjecture that the difference is due to the fact that the Dannenbring heuristic bases the weighting scheme, on the position of the workstation on the line and the workstation's processing time. Since the processing times for the workstations in the middle are zero for some of the lots, the weights for the middle workstations do not vary significantly.

In summary, the new system can increase the daily production rate by 30 boards with the WIP inventory levels reduced by 51%. These results suggest that a systematic design and scheduling approach can dramatically improve the companies throughput while reducing the inventory levels. In addition, the new design can implement a simple MHS since the material flow is straight-forward for a flow line configuration.

6. Conclusions

The main contribution of this study is that it proposes a design approach, which addresses real-life requirements related to scheduling such as high throughput, smooth production flow, and less WIP without reinventing the heuristics. The proposed design approach integrates heuristics for line balancing, sequencing, dispatching, and release. Traditionally, balancing assembly lines and developing schedules to minimize WIP have been treated as separate problems.

Our approach worked well for printed circuit board assembly lines for the given company, but we believe that it may be adapted to solve similar problems in other factories by applying the appropriate heuristic suited for their particular application.

Acknowledgments

The authors wish to thank Ajit Patankar, Mazen Haddad, and Dehua Huang for aiding in the research efforts and performing some of the analysis.

References

BEDWORTH, D. D., 1973, *Industrial Systems: Planning, Analysis, Control* (New York: Wiley).

BEDWORTH, D. D., and BAILEY, J. E., 1982, *Integrated Production Control Systems* (New York: Wiley).

BELLMAN, R., 1982, *Mathematical Aspects of Scheduling and Applications* (New York: Pergamon).

BESTWICK, P. F., and HASTINGS, N., 1976, A new bound for machine scheduling. *Operational Research Quarterly*, **27**.

BITRAN, G. R., and TIRUPATI, D., 1988, Development and implementation of scheduling system for a wafer fabrication facility. *Operations Research*, **36**, 377–395.

BLACK, J. T., 1991, *The Design of the Factory with a Future* (New York: McGraw-Hill).

BONNEY, M. C. and GUNDRY, S. W., 1976, Solutions to the constrained flowshop sequencing problem. *Operational Research Quarterly*, **27**.

BROOKS, G. H., and WHITE, C. R., 1965, An algorithm for finding optimal or near-optimal solutions to the production scheduling problem. *Journal of Industrial Engineering*, **16**, 34–40.

CAMPBELL, H. G., DUDEK, R. A., and SMITH, M. L., 1970, A heuristic algorithm for the *n* job *m* machine sequencing problem. *Management Science*, **16**, B630–B637.

CHAKRAVARTY, A. K., and SHTUB, A., 1985, Balancing mixed-model lines with in-process inventories. *Management Science*, **31** 1151–1174.

CONWAY, R. W., MAXWELL, W. L., and MILLER, L. W., 1967, *Theory of Scheduling* (Reading, MA Addison-Wesley).

DANNENBRING, D. G., 1977, An evaluation of flow shop scheduling heuristics. *Management Science*, **23**, 1174–1182.

DAR-EL, E. M., 1978, Mixed-model assembly line sequencing problems. *Omega*, **6**, 313–323.

DAR-EL, E. M., and COTHER, R. F., 1975, Assembly line sequencing for model mix. *International Journal of Production Research*, **13**, 463–477.

DAR-EL, E. M., and CUCUY, S., 1977, Optimal mixed-model sequencing for balanced assembly lines. *OMEGA*, **4**, 333–342.

DAR-EL, E. M., and NADIVI, A., 1981, Mixed-model sequencing application. *International Journal for Production Research*, **19**, 69–81.

FRENCH, S., 1982, *Sequencing and Scheduling: An Introduction to the Mathematics of the Job-Shop* (London: Ellis Horwood).

GELDERS, L. F., and SAMBANDAM, N., 1978, Four simple heuristics for a flowshop. *International Journal of Production Research*, **16**, 221–231.

GUPTA, J. N. D., 1971, A functional heuristic algorithm for the flowshop scheduling problem, *Operations Research Quarterly*, **22**.

HAX, A. C., and CANDEA, D., 1984, *Production and Inventory Management* (Englewood Cliffs: Prentice Hall).

HELGESON, W. B., and BIRNIE, D. P., 1961, Assembly line balancing using the ranked positional weight technique. *Journal of Industrial Engineering*, **12**, 394–398.

IGNALL, E. J., and SCHRAGE, L. E., 1965, Application of the branch-and-bound technique to some flow-shop scheduling problems, *Operations Research*, **13**, 400–412.

JOHNSON, S. M., 1954, Optimal two and three stage production schedule with setup times included. *Naval Research Logistics Quarterly*, **1**, 61–68.

KILBRIDGE, M., and WEBSTER, L., 1961, The balance delay problem. *Management Science*, **8**, 69–84.

KING, J. R., and SPACHIS, A. S., 1980, Heuristics for flow-shop scheduling. *International Journal of Production Research*, **19**, 345–357.

KOTANI, S., 1982, On the sequencing problem of the mixed model line. *Proceedings of the Japan Operations Research Society Spring Conference*, pp. 149–150.

LOMINICKI, Z., 1965, A branch-and-bound algorithm for the exact solution of the three-machine scheduling problem. *Operational Research Quarterly*, **16**, 89–100.

MACKASKILL, J. L., 1972, Production-line balances for mixed-model lines. *Management Science*, **19**, 423–434.

MACKASKILL, J. L., 1973, Computer simulation for mixed-model production lines. *Management Science*, **20**, 341–348.

MANSOOR, E. M., 1964, Assembly line balancing–an improvement on the ranked positional weight technique. *Journal of Industrial Engineering*, **15**, 73–77.

MILAS, G. H., 1990, Assembly line balancing—let's remove the mystery. *Industrial Engineering*, **22**, 31–36.

MOODIE, C. L., 1981, Assembly line balancing. In *Industrial Engineering Handbook*, G. Salvendy (ed.) (New York: IME), Ch. 3.4.

NAWAZ, M., ENSCORE, E., and HAM, I., 1983, A heuristic algorithm for the *m* machine, *n* job flow shop sequence problem. *OMEGA*, **16**.

OKUMURA, K., and YAMASHINA, H., 1979, A heuristic algorithm for the assembly line model-mix sequencing problem to minimize the risk of stopping the conveyor. *International Journal of Production Research*, **17**, 233–247.

PALMER, D. S., 1965, Sequencing jobs through a multi-stage process in the minimum total time-a quick method of obtaining a near optimum. *Operational Research Quarterly*, **16**, 101–107.

PARK, Y. B., PEGDEN, C. D., and ENSCORE, E. E., 1984, A survey and evaluation of static flow-shop scheduling heuristics. *International Journal of Production Research*, **22**, 127–141.

PETRO, V. A., 1966, *Flow Line Group Production Planning* (London: Business Publications).

ROBERTS, S. D., and VILLA, C. D., 1970, On a multi-product assembly line balancing problem. *AIIE Transactions*, **2**, 361–364.

SEKINE, K., 1991, *One Piece Flow: Cell Design for Transforming the Production Process* (MA: Productivity).

THOMOPOULOS, N. T., 1967, Line balancing-sequencing for mixed-model assembly. *Management Science*, **14**, B59–B75.