Design of Flexible Assembly Line for Printed Circuit Board (PCB) Manufacturing of Amdahl Company

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요 약

생산라인의 Line Balancing이 흐름생산에 있어서 일관된 생산을 하기 위한 필수조건이다. 여러 다양한 제품을 생산하는 Printed Circuit Board (PCB) 공장에서의 Line Balancing을 얻기 위해서는 Sequencing을 고려한 생산라인 설계가 필요하다. 본 논문에서는 Amdahl 회사의 예를 들어 이 Mixed Model Line Balancing절차를 설명하고자 한다.

I. Introduction

During the last decade, we saw a trend among manufacturers to move away from dedicating production lines to individual products to having more flexible production lines capable of producing different models. Design of these lines has become more difficult because most firms need to introduce new products more often than before resulting in changes to the product mix. We would like to characterize a flexible production line as one having the following characteristics:
a) It allows the firm to produce different products on the same set of equipment,
b) Operators are trained to perform more than one task.
This change in needs of industry calls for new methods to design production lines. In this paper, we propose a new approach to design flexible production lines for Printed Circuit Board Manufacturing.

II. Background and Literature Review

1. Background

Assembly of PCBs in the plant is a relatively straightforward process. Bare circuit boards are populated with various types of components in a series of operations carried out on a combination of automated machines and manually operated workstations. Production of PCBs is usually carried out in batches. Assembly is followed by a testing operation. At each test there is a probability that a given board will fail and require repair and retesting. When assembly is performed progressively, an even distribution of the assembly work elements along the assembly line is considered to be important as it allows smoothed production.

Most of the work on line balancing was done to achieve almost constant daily consumption of parts required for different products (cars) in the automobile industry. Automobile industry typically requires the continuous production flow of more than one model of the same general product on the same assembly line (conveyor line). It is a mass production assembly work where multiple products pass through single flow line with basically same route. In contrast, a PCB may have multiple flow lines with same start (BIRTH) and finish (TEST) workstation to produce many different types of circuit boards. This kind of situation exists when factories are producing models with two different technologies such as Plated-Through-Hole (PTH) and Surface Mount Technology (SMT). This is often the case when a factory is producing two different models, an older model using PTH and a later model in SMT. It is not unusual to use a combination of both technologies.

In this paper, we examine the literature for appropriate heuristics and adapt them into an approach to design lines for mixed model production of PCBs.

2. Line Balancing

The basic idea of an assembly line is that a product is progressively assembled as it is transported past relatively fixed assembly stations by a material handling device such as a conveyor. The work elements are assigned to the work stations so that all stations have nearly an equal amount of work to do. The generally accepted definition of the assembly line balancing problem is to minimize the total amount of idle time i.e., to minimize the balance delay. Balance delay is defined as the amount of idle time for the entire assembly line resulting from unequal total task times assigned to the various work stations. If no idle time is created by the balance, a perfect balance is achieved.

Kilbridge and Wester(1962) concluded that the three predominant contributors to high balance delay for an assembly line system for a specific product were a wide range of work element times, a large amount of inflexible line mechanization, and indiscriminate choice of cycle times. It follows that proper choice of cycle time is a very important step in the design of flexible lines.

Steps involved in designing a balanced assembly line are (Moodie(1981)):

a) determine cycle time
b) compute minimum number of stations
c) prepare diagram of precedence relationships among elemental tasks.
d) assign tasks to workstations considering the restrictions on labor assignments

The restrictions for assignment of tasks to stations, other than precedence, has to include the following:

a.) The number of stations cannot be greater than the number of tasks. Also the minimum number of stations is one.
b.) No task time may be greater than the cycle time. Implicit in this restriction is that the accumulation of task times per station cannot exceed the cycle time.

But if we use n stations parallel to each other, the cycle time for the remaining stations could be t/n, where the cycle time for each of the stations in parallel is t.

Another measure of a balance is line efficiency which is the sum of all task times multiplied by 100, divided by (cycle time)(number of stations). If the line efficiency is plotted against cycle times, a sawtooth relationship occurs as shown in Figure 2.1. Peak efficiencies give the recommended cycle times for specific number of stations. It can be shown that if the balance delay is minimized, the number of stations will be minimized. The assignment of work elements to stations for a specific cycle time (determined by the desired production rate) will be complicated by the element ordering restrictions regarding when certain elements can be performed, i.e., precedence restrictions.

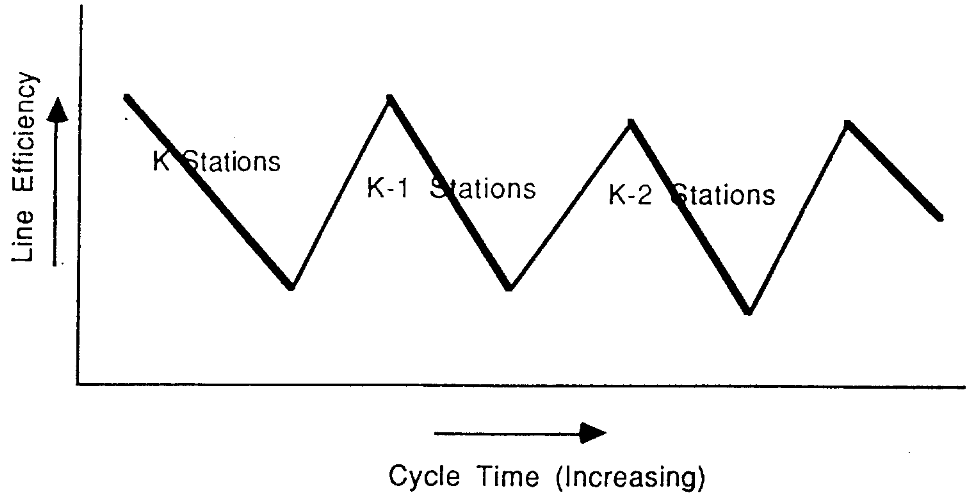

Figure 2.1 Line Efficiency as a Function of Cycle Time

Heuristics for assigning tasks to workstations have been proposed in the literature; some are of academic interest only, but others have found significant use in industrial applications. The ranked positional weight method by Helgeson and Birnie (1961) is a popular heuristic. This method uses positional weights of the elements represented by the sum of the element's time value and time values of all subsequent elements. The basic logic of this method is to assign elements to stations in order of decreasing values of positional weight when precedence restrictions and remaining unassigned idle time in the station permit. Even though the Helgeson and Birnie approach is logical and simple, it sometimes gives a poor solution. This is because an operation with a large associated time might take precedence over one with heavy dependence responsibilities if several of the dependent operations have small associated times. An improvement on the Helgeson and Birnie approach that guarantees optimality was suggested by Mansoor (1964). This approach involves interchanging tasks after an initial balance has been realized. Because the approach guarantees optimality, the combinations of tasks that qualify for interchange can become extremely cumbersome and thus impractical for large practical problems. A possible improvement developed by Bedworth (1973), named as region approach, builds on some of the ideas from Helgeson and Birnie, Mansoor, and Kilbridge and Wester (1961).

3. Stochastic Line Balancing

We now explain how to adapt line balancing approach with deterministic times to one with stochastic times. If t_i represents the mean time for task i and $V(t_i)$ represent the associated operation-time variance, the value of the station time that is exceeded with a given probability can be obtained from the following equation, since we assume task times to be statistically independent:

$$t = \left[\sum_{i=1}^{n} t_i\right] + z_\alpha[V(t_i)]^{1/2}$$

where

n = the number of tasks in the station,

z_α = the value from the standardized normal distribution associated with required probability α

This fact allows confidence levels to be assigned for the completion of assigned tasks at each work station. If it is desired that at least 99.4 percent of all work assigned to an assembly line for a product be completed at standard working rates under the cycle time given, then a z_α value of 2.5 will define the necessary allowance. It may be noted that the number of stations will increase if we consider stochastic values for task times.

4. Mixed Model Line Balancing

Since many products produced in industry can have different variations that have simultaneous demand, it is often essential to produce more than one model simultaneously on an assembly line. Generally, since each model can have a different precedence diagram, the amount of work required for each of the models will be different. It creates an uneven flow of work along the line. Due to the complexity in assigning this work to the operators, there is a tendency to have an oversupply of operators to meet the the uneven flow of work. In this paper, we describe a procedure of adapting single-model line balancing technique to mixed-model line balancing. In a complex mixed-model case, we cannot derive the perfect solution. As Milaş (1990) pointed out, in mixed model case, the manufacturing planner usually tries to accommodate either an average work situation at each station or occasionally plans for the worst case. In the latter case, the amount of balance loss is obviously large. We select the average concept in which the line is balanced for an average condition. In this case, the calculation is done by summing each station's elemental times and weighting them in proportion to their value relative to each model (simply recognized as weighted average which considers production volume). Note that we are required to use average concept for the common precedence diagram developed for the entire set of products even though some products might have different precedence diagrams. Two major problems in mixed model line balancing are: determination of the sequence of the units flowing down the line and assignment of all the elements for all models to specific stations.

5. Sequencing Rules

We now discuss the sequencing rules for a flexible flow line. The basic flow line consists of m machines in series and n jobs that need m operations, each operation being performed on a different machine. The flow of work is unidirectional and thus each job must visit each machine in the prespecified order.

Even though the flow line problem is the simplest multi-stage scheduling problem, it is very difficult to solve due to inherent combinatorial aspects. Except for Johnson's (1954) optimizing procedure for the two-machine flow line with makespan criterion, no constructive algorithms exist for larger general flow lines or for other measures of performance. This difficulty is explained by Hax and Candea (1984). They show that nonpreemptive scheduling for the flow line problem is NP-complete when the makespan or the mean flow time is minimized, and preemptive scheduling for this flow line problem is NP-complete for the makespan criterion. Makespan is the time required to process all the jobs on hand. As Bitran and Tirupati (1988) point out, makespan is considered important because it represented unfinished work and surrogate measure of work-in-process. Makespan information is also a useful guide in setting due dates.

Because of the above reason, many heuristics have been developed with makespan criterion. Noteworthy heuristic among those is one by Campbell et al. (1970). Campbell et al. use Johnson's procedure to solve a series of two-machine approximations to the actual problem. The first two-machine problem considers only the first and the m-th machine of the original problem. The intervening (m-2) machines are ignored. Johnson's rule is applied to find the optimal permutation schedule. The second step of the heuristic puts together the first and second machine to form a virtual machine (say machine 1') on which job i requires a processing time $p_{i1'} = p_{i1} + p_{i2}$. The (m-1)-th and m-th machines are combined to form a second virtual machine (say machine 2') with processing time $p_{i2'} = p_{i(m-1)} + p_{im}$. Johnson's rule is applied to get the best permutation schedule for this two-virtual machine flow line problem. At step k the first virtual machine contains the original first through k-th machine and the second virtual machine includes the (m-k+1)-th through m-th machine. Johnson's rule is used again to find the optimal schedule. (m-1) total steps are required to generate (m-1) sequence. With each sequence, the makespan for the original problem is computed and the best sequence is chosen as the solution.

We adapt the heuristic of Campbell et al. to flexible flow lines. This heuristic implies that different jobs (corresponds to part number in Amdahl company case) use different flow lines with the first and last machines in common. Determination of the order (sequence) in which the different models are to be assembled as they progress down the assembly line is a major part of the mixed model assembly line balancing problem. We propose to collapse all lines into a single common flow line that includes all the machines for different flow lines in series. Note that this single common flow line preserves the prespecified order or precedence constraints for individual flow lines. If a job does not use the machine of the single common line, we substitute 0 (zero) for the value of processing time for this machine for this job. We eventually apply Campbell's heuristic to this single common flow line. When we consider mixed model with different individual demand rates, we use processing time multiplied by the volume as the processing time for the single common flow line.

III. Proposed Approach

We propose to design the line as follows:

a. Determine cycle time.

b. Perform mixed model line balancing using the above cycle time (see section 2.4).

c. Do sequencing (see section 2.5) at each workstation and run simulation to establish a new cycle time.

d. Repeat step a to step c until no more improvement is possible.

IV. An example application

In this section, we discuss an application of the above approach, with emphasis on the application of line balancing and sequencing heuristics in Amdahl Corporation.

Amdahl Corporation is a manufacturer of high-performance mainframe computer systems comprising processors, peripherals and software products in Sunnyvale, California. Of the four manufacturing plants of Amdahl, Plant 2 manufactures and tests PCBs for the whole company. Hence, any demands for PCBs throughout the company would be reviewed by the plant's staff, who in turn, will decide whether those demands will be satisfied in house or subcontracted out. Plant 2 must have a very flexible manufacturing system that can support multiple generations of main frame products to fulfill this role properly. The two products for which boards are currently being made in plant 2 are "A" and "M" products. The latter is a new product currently leaving the engineering model stage and entering a steep production ramp. Since it will comprise most of the output in the future, we will focus on it in this paper.

In addition to meeting different types of demand, plant 2 must support two production technologies, Surface Mount Technology (SMT) and Plated Through Hole (PTH) since "M" product requires boards that need only SMT, only PTH, and mixed possessing both characteristics. The 321 "M" boards consist of 47 distinct part numbers (different boards) representing both PTH and SMT production technologies.

Since WIP levels are currently high, the company wants to concentrate on minimizing it. We can reduce the WIP level by minimizing the cycle time. To maintain flexibility to respond to changes in available resources and demand fluctuations the manufacturing process must have a short cycle time. To become a world-class manufacturer the plant needs to focus on quality, operating costs, inventory turns, employer involvement and total customer satisfaction.

V. Discussion and Results

The basic steps involved are:

a) Commence analysis by setting the initial cycle time = maximum element processing time (by assumption, cycle time must be equal to or greater than the maximum element processing time).

b) Perform line balancing to identify workstation assignments.

c) Determine sequence of work at each workstation by using the sequencing heuristic. Next, compute the new cycle time by running a simulation of the line with the proposed sequencing rules.

d) Repeat steps a), b) and c) until no more improvement is possible.

As explained in section 2.4, we first derived the general common precedence diagram common for all 47 part types. This is shown in Figure 5.1. The element besides nodes indicate the element processing time which is obtained by summing each station's element time for each model multiplied by weight proportional to each production volume relative to whole volume.

For the convenience of analysis, we partition the line into two section. i.e., the work from BIRTH to WAVE can be considered as one section- front section, and the rest (i.e., after the WAVE) named rear section. This partitioning is justified as none of the tasks after WAVE can be combined with any task that occurs prior to WAVE. This allows us to have two independent line balancing problems, one before and one after Wave station (See Bedworth and Bailey (1982)). Thus the rear section from Wash2 to Final is not considered in this report. The inclusion is easily obtained by applying the same technique. In sequencing we consider the rear section as black box and use total processing time from Wash2 to Final as a single elemental processing time.

Since element time at PLACE has maximum value of 34.40 and company doesn't have realistic current cycle time yet , we proceed with mixed model line balancing with cycle time 35 by applying Ranked Positional Weight Method of Helgeson-Birnie (1961) and Region Approach of Bedworth sequentially. The results are shown in Figure 5.2 and Figure 5.3. Figure 5.2 shows network from Figure 5.1 redrawn into regions and Figure 5.3 shows the final result. We obtained a line efficiency of 83% with this mixed line balance.

We end this section on a note of caution. We should be careful in selecting a cycle time for Amdahl since cycle time is inversely proportional to number of products to be produced and is proportional to the amount of time available. The current design of the line is based on current estimates of times and production quantities. If the estimates of production change as a result of the ramping up process, the current cycle time may turn out to be unrealistically small. The procedures described in this report will still be valid when that happens as they have been developed for the new mixed line. We have made an assumption that set up times are too small based on an analysis of actual data. Thus compensation was made in processing times to accommodate set up. If this assumption is not true, different sequencing rules are to be used.

We recommend building a decision support system which allows the company to evaluate trade-offs among cycle time, workstation capacities and production volumes.

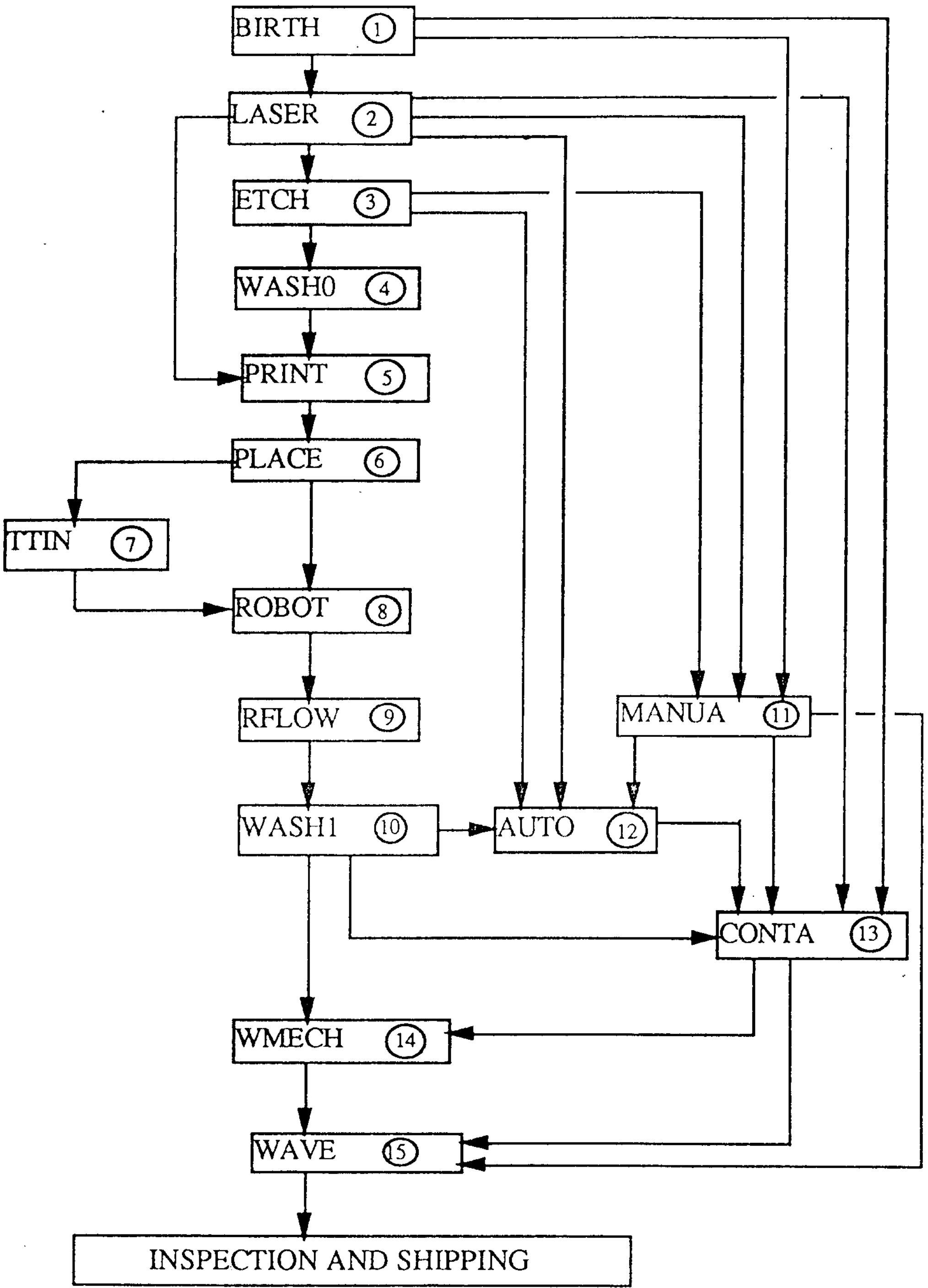

Figure 5.1 Common Precedence Diagram for Amdahl - plant 2

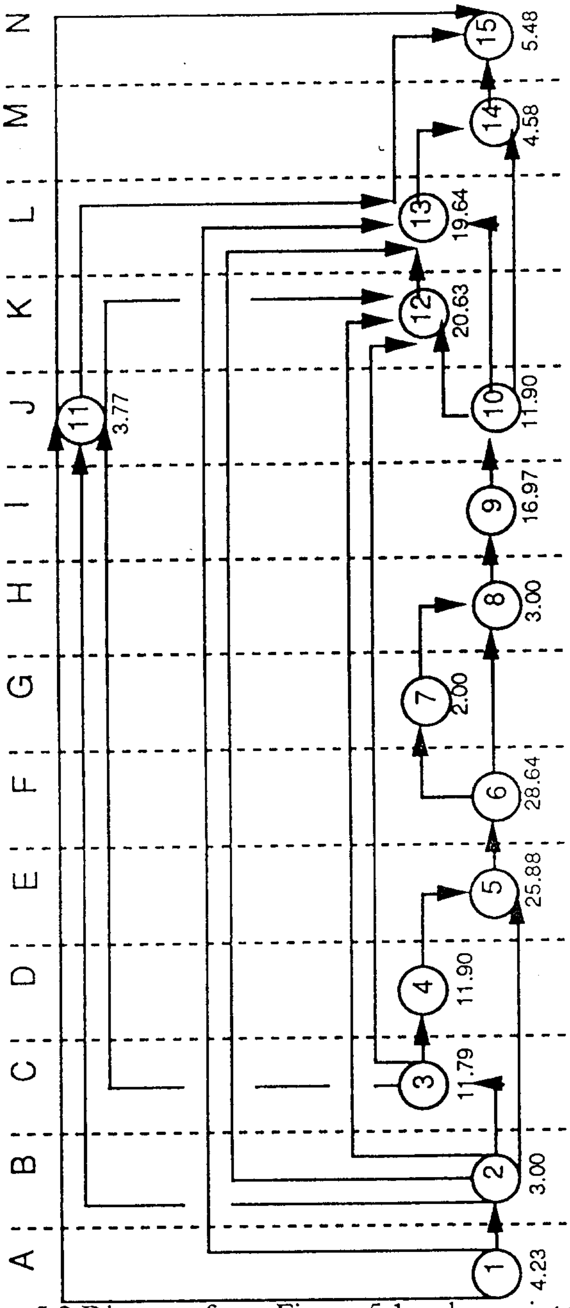

Figure 5.2 Diagram from Figure 5.1 redrawn into regions

Station	Tasks (In Order of Assignment)
1	1, 2, 3, 4, 11
2	5
3	6, 7, 8
4	9, 10
5	12
6	13, 14, 15

Figure 5.3 Balancing according to Bedworth's Region Method

VI. Conclusion

By combining a mixed model line balancing procedure with good sequencing rules we have come up with very general model which can be applied to any kind of assembly problem. Here we suggest an approach for mixed model line balancing for products with different routes and demands. We also suggest extensions to handle stochastic element processing times and present a sequencing heuristic for the mixed model. Both approaches involve extensions to previously developed heuristics.

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