Theory and Methodology

Set-up saving schemes for printed circuit boards assembly

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Abstract: Focusing on a basic printed circuit board (PCB) assembly line configuration characterized by very long set-up times, we examine two scheduling methods that can significantly reduce the set-up. Both methods – the Grouped Set-Up (GSU) method that has been recently introduced in the literature and the Sequence Dependent Scheduling (SDS) method, which has not been studied in this context – are based on component commonality among PCB types. Using the typical traditional scheduling method as a benchmark, the GSU and the SDS methods are compared in terms of three performance measures: line throughput, average work-in-process (WIP) inventory level, and implementation complexity. Guidelines for selecting the most appropriate method for a given production environment are proposed. The analysis is illustrated using real data from a typical production line.

Keywords: Scheduling; Printed circuit boards; Grouped set-up; Sequence dependent scheduling

1. Introduction

The electronics industry today is a well-developed, world-wide industry, in which a large variety of products are produced. In the US alone the industry is valued at $200 billion-a-year. Printed circuit boards (PCBs) are the 'brains' of electronic products, and their cost plays a major role in determining the competitiveness of an electronics firm. This paper focuses on reduction of production costs via efficient scheduling methods.

A PCB consists of two major parts: the raw board and the electronic components assembled on it. Typically, the assembly line is a flowshop type line, in which the sequence of operations is predetermined by technological constraints. Batch production is common, and market pressures often require electronic manufacturers to produce a large variety of small-lot, customized PCBs. Searching for ways to reduce the cost and increase the throughput of small-lot PCB assembly lines, attention has focused on the time-consuming set-up operation (e.g., Carmon, Maimon and Dar-El, 1989; Lofgren and McGinnis, 1986; Cunningham and Browne, 1986).

The traditional serial production method used in the assembly of electronic components on PCBs requires that new set-up of all the components be done each time the PCB type is changed. This procedure results in extended set-up times, since components that are common to several PCB types are set-up several times. We examine two scheduling methods, the Grouped Set-up (GSU) method and the Sequence-Dependent Scheduling (SDS) method, which take advantage of component commonality and result in significant reductions in set-up times.

The GSU method was recently introduced in Carmon, Maimon and Dar-El (1989). It is reviewed here and an improved performance evaluation procedure is presented. In an attempt to overcome the disadvantages of the GSU method, the SDS method is suggested as an alternative scheduling method that sacrifices some of the reduction in set-up time but has some advantageous qualities for this type of a production system. Although the idea of sequence-dependent scheduling has been used in the past to reduce set-up time, the SDS concept is applied here in an inherently different manufacturing environment. Industrial data is used to illustrate the methods and a procedure is suggested for comparing their performance and selecting the most appropriate one.

The manufacturing environment

There are two main types of electronic components – thru-hole components (THC) and surface-mount components (SMC). The manufacturing environment considered in this paper is a flowshop-type assembly line which consists of two machines. These machines are typically a DIP insertion machine and an axial or axial + radial components insertion machine, or alternatively two SMC placement machines, for larger and smaller components, respectively. This configuration is very basic and popular among low-volume, high-mix electronics manufacturers. Extensions of this work to other configurations as well as to other industries (e.g., metal processing) are proposed as future research.

Modelling assumptions

1. The set-up time considered in this paper is the component set-up needed when the PCB type assembled is changed. Refilling components in the machines during assembly is not considered, since the quantity of each component required is independent of the scheduling method used. Furthermore, refilling operations do not cause stoppages, while for set-up changes machine stoppage is assumed to be necessary.
2. The set-up of a component type consists of loading and unloading the component bin or reel.
3. A mechanical set-up (i.e., changing the dimensions of the machine's table or changing the width of the conveyor carrying the PCBs to the machine) is not required between PCBs in the same production group. This is usually accomplished by 'panelling' – a method in which several PCBs are assembled as a single standard sized panel which is later cut to the correct dimensions.
4. PCB transfer times into and out of the machines are negligible.
5. This paper is not concerned with routing the machine's head in assembling the components on the PCB nor with component locations on the machines. These are viewed as separate problems, dealt with extensively in the literature (Thorogood, 1986; Magirou, 1986; Gavish and Seidmann, 1987, 1988; Chang and Terwilliger, 1987). Since the production environment described here is a low-volume high-mix environment, these problems are less significant as compared to a mass production environment.

6. Due-date and job importance considerations are used to determine the short-term production plans – i.e., the PCB types to be produced at each time period (e.g., one week) and their lot sizes. The short-term production plans are then used as input for the proposed methods.
7. All raw materials required for short-term production are available (a relaxation of this assumption is discussed in later sections).
8. For maximum efficiency, Machine 2 works in late start, i.e., the start of the assembly on Machine 2 is delayed in order for Machine 2 to work continuously.

2. The scheduling methods

The traditional method

The traditional scheduling method is the simplest scheduling method possible in terms of process control. The groups of PCBs (short term production plans) are produced sequentially, and so are the lots within each group. When a PCB type is changed, the machine is shut down, and all the components are unloaded from the machine. The components for the following PCB are then loaded. While it is technically possible to leave common components on the machines, this is not done in practice since it complicates the process control. It requires checking for component commonality among the PCBs and adapting the computer assembly program to the current components' locations on the machines (which may not be identical to the original locations programmed).

Since the set-ups in the traditional method are sequence independent it is possible to implement a simple scheduling rule like the Johnson rule (Johnson, 1954) for two machines to 'minimize' the makespan of the group. Note, though, that the set-up required for each PCB type in the traditional method is the full set-up of all the component types, and, therefore, the result may not be a minimal makespan.

The GSU method

The GSU approach has been recently introduced in Carmon (1988) and in Carmon, Maimon and Dar-El (1989). Its idea is that on each machine the groups of PCBs are produced in two stages. First, the common components (i.e., components that are shared among two or more PCB types in the group) are set-up on the machine only once for the whole group, and are assembled onto their respective PCBs. We refer to this stage as the common set-up and assembly. In the next stage, referred to as the residual set-up and assembly, separate set-up and assembly of the remaining components on each PCB type are sequentially performed. Further description of the GSU method is given in the Appendix. The method was shown to result in high throughput but also high work-in-process (WIP) inventory level. An analysis of its performance is presented in later sections.

The SDS method

The SDS approach applies the component commonality concept differently, maintaining a low WIP level. The idea is that PCB types should be sequenced such that a follower PCB will have a maximum of common components as the current PCB, thus eliminating much of the set-up between them. The ultimate goal is to minimize the number of component changes required during the sequence. Further details of the SDS method can be found in the Appendix.

Variations of the SDS method have been used in other applications, especially in the metal processing industry (e.g., Tang 1986), where the common resources are tools and parts. In other applications, similar parts requiring common resources such as pallets, are scheduled separately, in order to reduce idle times (Kusiak, Vanelli and Kumar, 1985). Focusing on the electronics industry, Cunningham and Browne

(1986) and Fathi and Taheri (1989) developed heuristic methods for sequencing reels of components for PCB assembly. As opposed to our model, however, previous work applied to single-machine processes.

The single machine sequence-dependent scheduling problem is essentially a Shortest Hamiltonian Path (SHP) problem, which is NP-complete (Garey and Johnson, 1979). The corresponding two machine problem complexity was investigated and was also proven to be NP-complete (Foo and Wager, 1983). The most appealing solution approach to the two machine problem is to reduce it to a single-machine problem, and then use heuristic or optimum seeking techniques (depending on the problem size) developed for the SHP problem. This reduction can be done in two ways. The first is by adding the set-up times for each PCB type on the two machines, while the second is by solving the problem for the dominant (bottleneck) machine, if its dominance is consistent. In any case, one has to make the assumption that the production sequence is the same on both machines (only permutational solutions allowed), since non-permutational solutions would most probably cause a large amount of WIP in the line – the phenomenon the SDS method is meant to avoid. Gnerally, the latter approach should be taken when one of the machines is substantially dominant (as in the following example). Otherwise, the first approach may yield better results. In most cases where no machine is substantially dominant it is probably worthwhile to compare the optimal sequence for the dominant machine to the optimal sequence for both machines (based on the sum of the set-ups) and select the one that yields a shorter machine occupation time T (since T determines the line throughput as defined and explained in Section 3).

The Shortest Hamiltonian Path problem is closely related to the Traveling Salesman Problem (TSP), which was the focus of a vast amount of research in the past decades. There are several techniques for solving these problems, such as explicit enumeration, integer programming, dynamic programming, branch and bound, and heuristic methods. Small problems (up to 15–20 PCB types in the group) can be solved optimally using techniques such as branch and bound. Computer processing time for larger problems is likely to be prohibitive, forcing the use of heuristic methods, such as discussed in Christofides (1976), Golden, Bodin, Doyle and Stewart (1980), Lin and Kernighan (1973), and others.

3. Comparing the three scheduling methods

The GSU and the SDS methods improve the performance of the PCB assembly line in different ways. In this section, we compare the three scheduling methods – the GSU, SDS, and traditional scheduling method, and define the conditions under which each method is superior to the others. There are three performance measures that are of most importance in a PCB assembly environment: the line throughput which determines the revenues, the average WIP inventory level which is the major production cost, and the implementation complexity which is a neglected factor in scheduling theory, but is crucial from the practical point of view. Other performance measures are of lesser importance in this environment.

The line throughput

When the machines work continuously (see Assumption 8) the assembly line throughput (D) is inversely proportional to the machine occupation time (T), as follows:

$$D = 1/T. \tag{1}$$

When the line consists of two machines,

$$T = \max(T_1, T_2), \tag{2}$$

i.e., the throughput is inversely proportional to the dominant machine's occupation time.

The machine occupation time consists of the set-up time and the assembly time. Since the assembly time is constant for all scheduling methods, the only variable affecting the machine occupation time is the total set-up required.

Denote by

m : The machine index, $m = 1, 2$.

i : The PCB type index, $i = 1, 2, \ldots, n$.

s : The average set-up time (including loading and unloading) required for a single component type.

$C_{i,m}$: The number of component types assembled by Machine m on PCB type i.

$C^*_{k,m}$: The number of component types shared among k PCB types in the group assembled by Machine m according to the GSU method.

$C'_{h,m}$: The number of component types shared among h PCB types, which are sequentially assembled by Machine m according to the SDS method.

The set-up time for the traditional method is calculated as follows:

$$S_{\text{trad}} = s \sum_{m=1}^{2} \sum_{i=1}^{n} C_{i,m}. \tag{3}$$

The set-up time for the GSU method is

$$S_{\text{GSU}} = s \sum_{m=1}^{2} \sum_{i=1}^{n} C_{i,m} - s \sum_{m=1}^{2} \sum_{k=2}^{n} (k-1) C^*_{k,m}, \tag{4}$$

and the set-up time for the SDS method is

$$S_{\text{SDS}} = s \sum_{m=1}^{2} \sum_{i=1}^{n} C_{i,m} - s \sum_{m=1}^{2} \sum_{h=2}^{n} (h-1) C'_{h,m}. \tag{5}$$

The set-up time for the GSU method depends on the number of common component types in the group. The set-up time for the SDS method depends on the distribution of common components among the PCB types. The saving in set-up time in the SDS method must be less than or equal to that of the GSU method, since in the latter method, each component is set-up *only* once, whereas in the SDS method, each component is set-up *at least* once – depending on the PCB sequence.

To calculate the line throughput let us denote by

T_m : The occupation time of machine m, which is the sum of the set-up and the assembly times of all the PCBs in the group on Machine m.

$\text{Ct}_{i,m}$: The total number of components assembled on PCB type i by Machine m (allowing for multiple components of the same type).

p : The assembly time of a single component on each machine

N_i : The lot size of PCB type i.

$P_{i,m}$: The assembly time of a lot of PCBs type i on Machine m, as follows:

$$P_{i,m} = p N_i \text{Ct}_{i,m}. \tag{6}$$

The occupation time of machine m is given by

$$T_m^{\text{trad}} = p \sum_{i=1}^{n} N_i \text{Ct}_{i,m} + s \sum_{i=1}^{n} C_{i,m}, \tag{7}$$

$$T_m^{\text{GSU}} = p \sum_{i=1}^{n} N_i \text{Ct}_{i,m} + s \sum_{i=1}^{n} C_{i,m} - s \sum_{k=2}^{n} (k-1) C^*_{k,m}, \tag{8}$$

$$T_m^{\text{SDS}} = p \sum_{i=1}^{n} N_i \text{Ct}_{i,m} + s \sum_{i=1}^{n} C_{i,m} - s \sum_{h=2}^{n} (h-1) C'_{h,m}. \tag{9}$$

The average WIP level

Under the GSU method, the WIP of each group is constant until the assembly of the residuals on Machine 2 begins, and then it reduces in steps until the last lot of PCBs in the group is completed. The introduction of a new group to Machine 1 while Machine 2 is still completing the assembly of the previous one radically increases the average WIP level for the GSU method. With both the traditional and SDS methods, the WIP function is a reducing step function – each step representing the completion of a lot of PCBs on Machine 2. In both methods a new group in introduced to Machine 1 only when Machine 2 is completing the last lot in the previous group (the time in which two groups are in the line concurrently is assumed to be negligible for these methods hereafter). With only one group at a time in the assembly line, the average WIP level for both the SDS and the traditional methods is much lower than the average WIP level for the GSU method.

Calculating the average WIP level for all methods and particularly for the GSU method can be markedly simplified by approximating the WIP reducing step function by a straight line representing the average rate of completed PCBs leaving the line. Thus the WIP functions for the traditional and the SDS methods reduce to jigsaw functions.

Denote by

I : The average WIP in the line.
W_i : The average WIP of PCB type i.
WG_t : The average WIP of a group.

We get

$$I_{trad} = I_{SDS} = 0.5 \sum_{i=1}^{n} W_i = 0.5\mathrm{WG}_t. \tag{10}$$

Calculating the average WIP level for the GSU method is more complicated. A crude approximation for its value would be

$$I_{GSU} = 1.5 \sum_{i=1}^{n} W_i = 1.5\mathrm{WG}_t. \tag{11}$$

A more accurate approximation could be obtained through a deeper analysis of the process: Let G_1 and G_2 be two consecutively assembled groups. Let T_1 and T_2 be the occupation times of machines 1 and 2 respectively. Let T_{c1} and T_{c2} be the common components' set-up and assembly times on machines 1 and 2 respectively. Let T_{r1} and T_{r2} be the residual components' set-up and assembly times on machines 1 and 2 respectively.

Assume that these times are identical for G_1 and G_2, i.e.,

$$T_1(G_1) = T_1(G_2), \quad T_2(G_1) = T_2(G_2), \quad T_{c1}(G_1) = T_{c1}(G_2),$$
$$T_{c2}(G_1) = T_{c2}(G_2), \quad T_{r1}(G_1) = T_{r1}(G_2), \quad T_{r2}(G_1) = T_{r2}(G_2).$$

If $T_1 = T_2$, then G_2 starts processing on Machine 1 as soon as G_1 starts processing on Machine 2. During the common components assembly of G_1 on Machine 2 both groups are in the line. Then G_1 starts the residual components' assembly on Machine 2 and gradually leaves the line. In this case the average WIP level is

$$I_{GSU} = \frac{2T_{c2} + 1.5T_{r2}}{T_1}\mathrm{WG}_t. \tag{12}$$

If $T_1 > T_2$, then G_2 starts processing on Machine 1 as soon as G_1 starts processing on Machine 2, and G_1 leaves the line $T_1 - T_2$ time units before G_2 completes its processing on Machine 2. The average WIP level is

$$I_{GSU} = \frac{2T_{c2} + 1.5T_{r2} + (T_1 - T_2)}{T_1}\mathrm{WG}_t. \tag{13}$$

If $T_2 > T_1$, then G_2 starts processing on Machine 1 only $T_2 - T_1$ time units after G_1 starts processing on Machine 2 (late start). Therefore during this time there is only one group in line. Then, if $T_1 > T_{r2}$, then during $T_1 - T_{r_2}$ there are two groups in the line and during T_{r2} there are 1.5 groups. The average WIP level in this case is

$$I_{\mathrm{GSU}} = \frac{(T_2 - T_1) + 2(T_1 - T_{r2}) + 1.5T_{r2}}{T_2} \mathrm{WG}_t. \tag{14}$$

Otherwise, if $T_1 < T_2$, then the average WIP level is

$$I_{\mathrm{GSU}} = \frac{T_{c2} + 0.5T_{r2} + T_1}{T_2} \mathrm{WG}_t. \tag{15}$$

The more accurate calculation procedure requires that the term $1.5\mathrm{WG}_t T_{r2}$ in the first and the second cases and the term $0.5\mathrm{WG}_t T_{r2}$ in the third case are replaced by the precise expression for the WIP during the residual production stage on Machine 2 (i.e., during the residual production of the first PCB in the group on Machine 2 all PCBs are in the line, and therefore the WIP is WG_t; during the production of the second PCB, all PCBs but the first are in the line, etc). In this case it may be worthwhile to complete the PCBs with higher WIP values first.

The above analysis was based on the assumptions that all raw material are available in the line (as WIP) at the beginning of the short term production plan, and that as soon as a PCB is completed it leaves the line and is not considered as WIP anymore. However, these assumptions may not hold in reality. In production environments where the vendors supply the materials just in time (JIT) the WIP in the traditional or the SDS methods is drastically decreased since there is only one lot of PCBs in the line at each time instant. The WIP in the GSU is decreased too, but the decrease is not as drastic because the PCBs flow time is much longer.

The assumption that the PCBs are no longer considered as WIP as soon as their assembly is complete is violated if, for example, all the PCBs in the short term production plan have to be transferred together to the next production stage or their consumer. In this case (assuming all materials are available at the beginning of production) the average WIP level for the traditional and the SDS methods is doubled, while for the GSU method, the only increase in WIP occurs at the residual assembly stage on Machine 2. Thus the effect of relaxing this assumption is much smaller on the average WIP level of the GSU method.

The process control

The main advantage of the traditional production method over the GSU and the SDS methods is the simplicity of its process control. This derives from two characteristics of the method: the complete separation of different PCB types, and the fixed location of each PCB type in the queue to the machines.

The SDS method is similar to the traditional method in terms of the latter characteristic. Its complexity stems mainly from the requirements to calculate the sequence-dependent set-up time between each pair of PCB types and to solve the SHP problem. However, when the group size is not too large this can be easily performed by accessible computer software.

The GSU method is more complicated than the other two methods. There are several activities that must be performed prior to and during the implementation of this method. The common components should be separated from the residual components, each component should be assigned a specific location on each machine, and the assembly programs should be modified accordingly. Two optimal assembly routes are needed for each PCB type, one for the common components, and the other for the residual components. Each PCB must be loaded twice onto each machine. All information concerning the WIP inventory (production stage, location in the buffer, etc.) must be under control. For these reasons, a high level of information control is a preliminary condition for implementing the GSU method.

4. A numerical example

An industrial example is used to illustrate the differences among the three methods. Note that the results of applying the scheduling methods to this example should not be interpreted as being generally true for every situation in the PCB assembly industry, as they are merely intended to illustrate the comparative advantages and drawbacks of the scheduling methods.

The data was taken from a particular electonics firm, located in Israel. The eight PCB types are the most frequently assembled PCBs in this company. 20 PCBs of each type are assembled every week, on average. Assembly rate is taken as 3600 components per hour and assembly times are given in minutes. The average set-up time is 1 minute per component type. Other relevant data is given in Tables 1, 2 and 3. A Gantt chart demonstrating the three scheduling methods is shown in Figure 1.

There are 131 component types assembled on Machine 1, out of which 28 are considered common components. On Machine 1, there are 2 component types shared among 4 PCB types, 8 components types shared among 3 PCB types, and 18 component types which are shared among 2 PCB types.

There are 53 component types assembled on Machine 2, out of which 10 are considered common components. On Machine 2, there is 1 component type shared among 8 PCB types, 1 component type shared among 5 PCB types, 2 component types shared among 4 PCB types, 2 component types shared among 3 PCB types, and 4 component types which are shared among 2 PCB types.

Since Machine 1 is substantially dominant in this case (see the machine occupation times, (17)–(22), the optimal schedule for Machine 1 is chosen as the SDS sequence. This sequence, 1-3-5-2-7-8-6-4, is the optimal solution to the SHP problem as determined by a B & B method (Little, Murty, Sweeny and Karel, 1963) developed originally for the TSP. With this schedule, there are 18 component types shared among 2 consecutive PCB types, 4 component types shared among 3 consecutive PCB types, 3 component types shared among 4 consecutive PCB types and 1 component type which is shared among all 8 PCB types.

The set up times for the three scheduling methods are:

$$S_{\text{trad}} = 250 \text{ minutes}, \tag{16}$$

$$S_{\text{GSU}} = 185 \text{ minutes}, \tag{17}$$

$$S_{\text{SDS}} = 208 \text{ minutes}. \tag{18}$$

In this example, using the traditional method as the base, the saving in set-up time using the GSU method is $65/250 = 26\%$, while for the SDS method it is $42/250 = 16.8\%$.

Table 1
PCB general data

PCB type i	1	2	3	4	5	6	7	8	total
No. of comp. types assembled by M1	29	20	41	19	19	19	17	13	177
Total no. of comp. assembled by M1	63	40	198	190	42	41	29	13	616
No. of comp. types assembled by M2	14	10	6	9	8	9	10	12	78
Total no. of comp. assembled by M2	86	62	111	187	43	42	41	30	602
Assembly time of PCB i in M1	1.05	0.7	3.3	3.17	0.7	0.68	0.48	0.22	
Assembly time of lot i in M1	21	13.3	66	63.3	14	13.7	9.7	4.3	205.3
Assembly time of PCB i in M2	1.43	1.03	1.85	3.12	0.72	0.7	0.68	0.5	
Assembly time of lot i in M2	28.7	20.7	37	62.3	14.3	14	13.7	10	200.7

Table 2
Component sharing among PCB types

Common components on Machine 1	Shared Among PCB Types	Common components on Machine 2	Shared Among PCB Types
1	1, 2, 3, 5	1	1, 2, 3, 4, 5, 6, 7, 8
2	1, 2, 3, 5	2	7, 8
3	1, 3, 5	3	4, 6, 7
4	2, 3, 7	4	3, 4
5	3, 7	5	2, 3, 7, 8
6	2, 3	6	1, 8
7	2, 5, 8	7	5, 7
8	7, 8	8	4, 5, 6, 7
9	2, 7	9	3, 4, 5
10	3, 7	10	4, 5, 6, 7, 8
11	2, 3, 5		
12	4, 5		
13	2, 3, 6		
14	2, 3		
15	2, 5		
16	7, 8		
17	3, 5		
18	1, 3		
19	3, 8		
20	3, 5		
21	3, 5		
22	4, 5		
23	3, 4		
24	3, 4, 5		
25	3, 4, 6		
26	2, 5, 7		
27	2, 5		
28	7, 8		

Table 3
The PCBs' data for use in the GSU method

PCB type *i*	1	2	3	4	5	6	7	8	Total
No. of c.c. in PCB *i* on M1	4	12	18	5	14	2	8	5	–
No. of residual comp. in PCB *i* on M1	25	8	23	14	5	17	9	8	109
Total no. of c.c. in PCB *i* on M1	5	23	57	88	31	3	13	5	225
Total no. of residual comp. in PCB *i* on M1	58	17	141	102	11	38	16	8	391
Assembly time of c.c. in lot *i* on M1	1.7	7.7	19	29.3	10.3	1	4.3	1.7	75
Assembly time of residual comp. in lot *i* on M1	19.3	5.7	47	34	3.7	12.7	5.3	2.7	130.4
No. of c.c. in PCB *i* on M2	2	2	4	6	5	4	7	5	–
No. of residual comp. in PCB *i* on M2	12	8	2	3	3	5	3	7	43
Total no. of c.c. in PCB *i* on M2	36	47	108	184	39	34	33	17	498
Total no. of residual comp. in PCB *i* on M2	50	15	3	3	4	8	8	13	104
Assembly time of c.c. in lot *i* on M2	12	15.7	36	61.3	13	11.3	11	5.7	166
Assembly time of residual comp. in lot *i* on M2	16.7	5	1	1	1.3	2.7	2.7	4.3	34.7

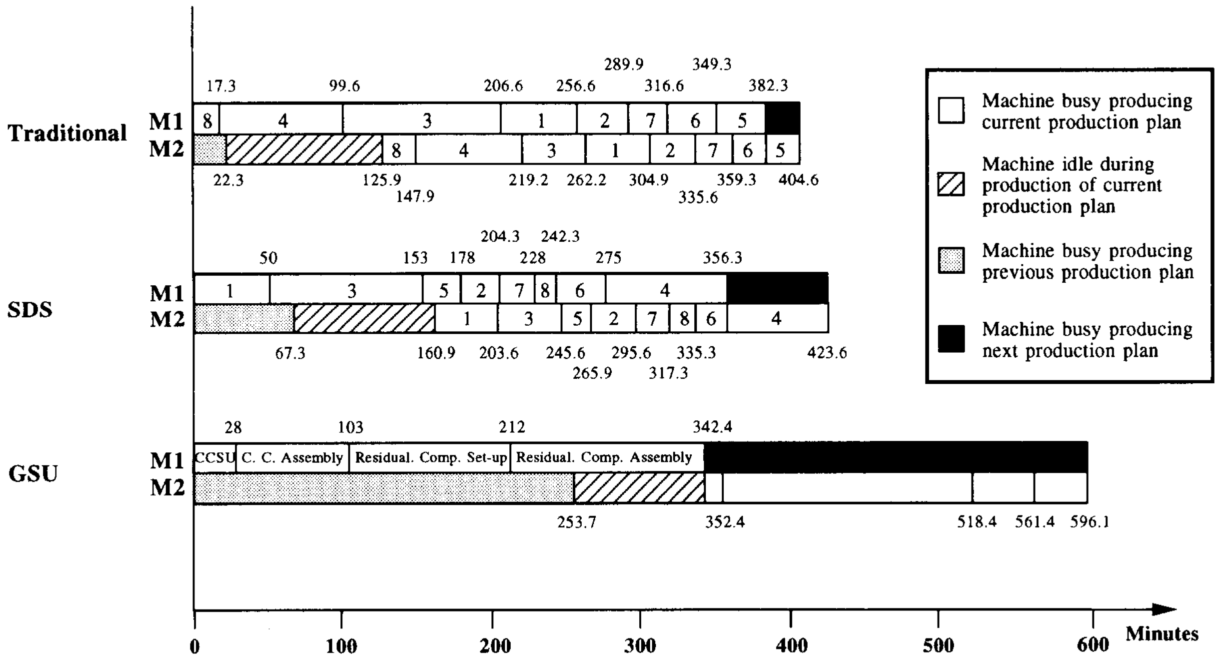

Figure 1. A Gantt chart of the three scheduling methods

The methods result in the following machine occupation times for machine 1:

$$T_1^{\text{trad}} = 382.3 \text{ minutes}, \tag{19}$$

$$T_1^{\text{GSU}} = 342.4 \text{ minutes}, \tag{20}$$

$$T_1^{\text{SDS}} = 356.3 \text{ minutes}. \tag{21}$$

Machine 2 occupation times are:

$$T_2^{\text{trad}} = 278.7 \text{ minutes}, \tag{22}$$

$$T_2^{\text{GSU}} = 253.7 \text{ minutes}, \tag{23}$$

$$T_2^{\text{SDS}} = 262.7 \text{ minutes}. \tag{24}$$

Machine 1 dominates the assembly line performance. Using the GSU method, it is possible to save $(382.3 - 342.4)/382.3 = 10.4\%$ in Machine 1 occupation time, and therefore, increase the line throughput from the base throughput obtained by the traditional method by 10.4%. Using the SDS method, it is possible to increase the throughput by 6.8%.

Using the data from Table 3, we get the WIP vector

$$W = (W_1, W_2, W_3, W_4, W_5, W_6, W_7, W_8) = (149, 102, 309, 377, 85, 83, 70, 43), \tag{25}$$

with

$$\text{WG}_t = 1218 \text{ components}, \tag{26}$$

$$I_{\text{trad}} = I_{\text{SDS}} = 609 \text{ components}. \tag{27}$$

Since $T_1 > T_2$ in this case, the average WIP level using the GSU method is approximately

$$I_{\text{GSU}} = \frac{2T_{c2} + 1.5T_{r2} + (T_1 - T_2)}{T_1}\text{WG}_t = 1993.8 \text{ components}, \tag{28}$$

i.e., the avarage WIP level for the GSU method is more than three times higher than the average WIP level for the SDS and the traditional methods.

5. A scheme for selecting a scheduling method

The choice of a scheduling method should be based on the relative performance of the methods in terms of the selected performance measures: throughput, average WIP level, and implementation complexity. The revenues from throughput and the WIP costs are quantifiable and their calculation was presented earlier. A numeric measure for the implementation complexity, however, is difficult to determine. It is possible to estimate the cost of the computer planning and control system required for each scheduling method, but it is almost impossible to consider all the different effects of a complex production system on the overall performance. Nevertheless, the most natural basis for comparing the overall performance is the resulting cash flow (other utility measures/multi-criteria methodologies could be used). Therefore, the comparison procedure, using the traditional method as the base, is to calculate the throughput of the three scheduling methods and evaluate the marginal increase in profitability resulting from the increased throughput using the GSU and the SDS methods. The average WIP level and the resulting holding costs are calculated for all methods, and the differences between the marginal increase in profitability and the marginal increase in WIP holding cost for the GSU and for the SDS methods are calculated. If the GSU and/or the SDS methods show a positive difference then the marginal additional production complexity cost should be estimated and subtraced. The final result determines the most appropriate scheduling method for the specific production environment.

Lacking data on profitability, holding costs, and implementation costs we do not show an example of a complete selection process here. However, this calculation is straightforward given the required data.

6. Discussion and conclusions

In this paper we compared scheduling methods for the assembly of a set of product types. The production line we studied consisted of two sequential assembly machines, and was characterized by medium production volume, limited production capacity, component commonality, limited number of component feeders, negligible product transfer time and a given weekly or daily production plan.

Two scheduling methods for the assembly of PCBs were presented, that outperform the traditional production in terms of reduced set-up times and higher throughput. The GSU scheduling method was shown to perform better than the SDS method in terms of throughput, whereas the SDS scheduling method was better than the GSU method in terms of the average WIP level.

The decision as to which method to use for a specific production environment depends on several considerations. Generally, the traditional method should be used when the number of common components is small, since there is no point in complicating the process control for a small saving in set-up time. The GSU should be chosen when the PCB assembly line is a bottleneck operation in the production process, and any increase in its throughput is significant to the whole plant. The necessary conditions for implementing the GSU method are a large number of common components and a high level of process control. The SDS method is superior to the others when the common components are distributed among the PCB types such that the difference in set-up time between the GSU and SDS methods is small. The operational simplicity and the reduced WIP levels of the SDS method over the GSU method are typically significant.

Future research can be conducted in several directions. The methods could be extended to larger assembly lines consisting of more than two machines; combinations of the methods could be developed to yield improved performances; efficient clustering methods which determine the group size and the group elements should be developed; and the methods can be modified for use in other industrial environments.

Appendix. The GSU and the SDS scheduling methods

A schematic presentation of the production using the GSU method is shown in Figure 2. The shaded spaces represent common components, which result in set-up time savings.

When the GSU method is used, the production stages on each machine are as follows:

1. Set-up of common components;
2. Assembly of common components on all the PCBs in the group;
3. Set-up of residual components;
4. Assembly of residual components on each PCB type separately.

Figures 3a and 3b show the production flow of two PCB types assembled on two machines using the traditional method and the GSU method, respectively.

Figure 3b clearly demonstrates the reason for a higher WIP in the GSU method. Each PCB in a group has to be loaded on each machine twice, for the common component assembly and for the residual component assembly. Two groups of PCBs can be produced concurrently (on separate machines), thus increasing the average WIP level.

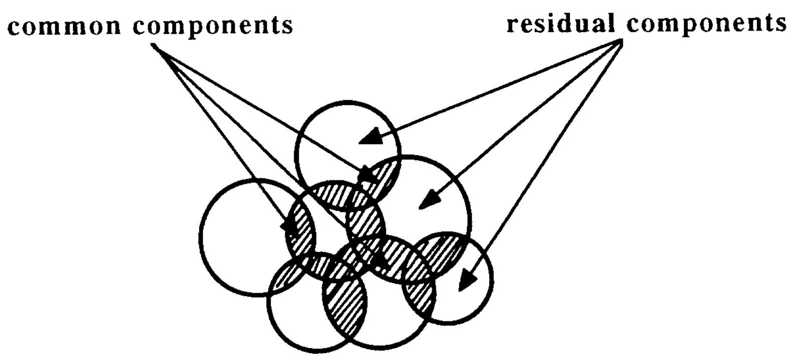

Figure 2. The savings in set-up time in the GSU method

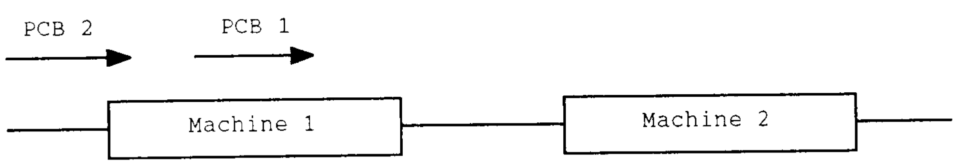

Figure 3a. The traditional production method

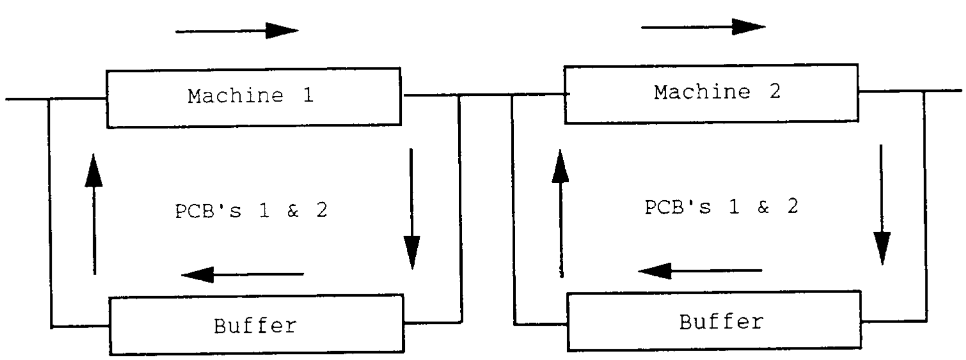

Figure 3b. The GSU production method

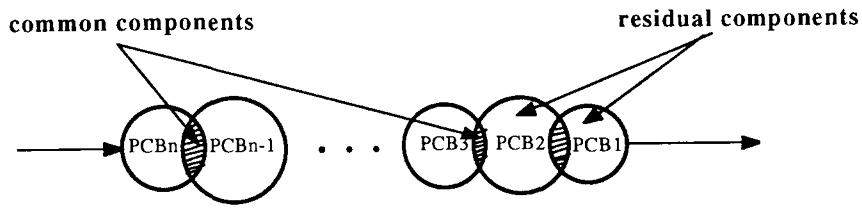

Figure 4. The savings in set-up time in the SDS method

The SDS method

In the SDS approach the ultimate goal is to minimize the number of component changes required during the sequence – in other words, to maximize the total commonality between adjacent PCBs. A schematic presentation of sequence-dependent scheduling in PCB assembly is shown in Figure 4, where the shaded spaces represent the set-up time saved when using this method.

The production steps using the SDS method are as follows:

Step 1. Determine the production sequence for the PCBs using a TSP-based strategy.

Step 2. Set up the components for the first PCB type on both Machines 1 and 2.

Step 3. Assemble all the components of this PCB type, first on Machine 1 and then on Machine 2.

Step 4. Set up the components for the next PCB type on both Machine 1 and 2, changing only the components that are not shared between the first and the second PCB types; adjust the computer assembly program accordingly.

Step 5. Assemble all the components on the second PCB type, first on Machine 1, then on Machine 2.

Step 6. Continue the set-up and assembly of all remaining PCB types according to the sequence determined in Step 1, unloading all the components not required for the next PCB type every time the PCB type is changed.

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