

Group set-up for printed circuit board assembly

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The current practice in the assembly of electronic components on printed circuit boards (PCBs) is serial production, a process characterized by very long set-up times. However, with the advent of efficient on-line process information, new production control methods are now possible. This paper proposes a different production method, called the group set-up (GSU) method, which can significantly reduce set-up times. The traditional and the GSU production methods are compared, and it is shown that the GSU always performs better than the traditional method in terms of total production flow (throughput) and labour time. However, the traditional method performs better than the GSU in terms of work in process (WIP) inventory; and in some cases, in terms of makespan (lead time). A detailed analysis for a small number of PCBs is presented.

1. Introduction

The serial tradition production method used in the assembly of electronic components on printed circuit boards (PCBs) requires new set-ups of all components to be assembled on the machines, each time the PCB type is changed. This procedure results in extended set-up times, since even components that are common to the subsequent PCB will need to be set-up again. Its advantage, however, lies in the simplicity of both the production planning and the operational control of the production system.

Traditionally, two main approaches are employed for reducing the overall set-up time needed for production. The first approach simply enlarges the lot sizes and reduces the set-up frequency (Afentakis *et al.* 1984, Maxwell and Muckstadt 1985). However, in many instances, the lot size is prefixed and cannot be increased. Furthermore, enlarging the lot size also means enlarging the cost of the work in progress (WIP) inventory.

The second approach is essentially based on group technology (GT) concepts. The main idea underlying GT is that production and layout are product based. This approach uses the 'product-based families' concept, which can be defined as a 'classification of the products into groups, calling for the use of similar components, for which production sequences can be developed' (Boyle 1986). Thus, jobs (PCBs) should be sequenced such that job followers will require the same resources (tools, parts), eliminating much of the set-up between them. This method has been used by many authors (e.g. Tang 1986), with most applications being in the metal-processing industry. Another variation of this concept (Kusiak *et al.* 1985) scheduled products requiring the same limited resources (jigs, fixtures, etc.) separately from each other, so as to reduce the waiting periods for these resources. We refer to this as sequence-dependent scheduling.

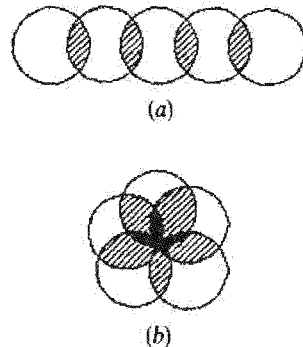


Figure 1. (a) Sequence-dependent scheduling. (b) The GSU production method.

A schematic presentation of sequence-dependent scheduling is shown in Fig. 1 (a). The marked spaces represent the set-up time savings using this method.

This approach, however, cannot be applied easily to the assembly of electronic components on PCBs. The sequence-dependent scheduling problem is shown to belong to the travelling salesman (TSP) type problem, which is NP-complete (Cunningham and Browne 1986, Lawler *et al.* 1985, Lin and Kernighan 1973, Rinnooy-Kan 1976). Its complexity is even greater for the electronic components assembly problem, since the production requirement is to sequence at least two machines, with the optimal schedule determined by solving a special TSP type problem for the total assembly system. There is no optimum seeking technique for this special TSP structure, and there is no heuristic method known to be able to tackle this problem efficiently, when the set-up times are not negligible.

In this paper, we propose the group set-up (GSU) method as a new approach to significantly reduce the overall set-up times and increase production flow in PCB assembly. The technical background on which this method is based is analysed in the next section.

1.1. Technical background

The special characteristic of the PCBs structure is that a large percentage of all the component types used may be regarded as highly common, often incorporating about 80% of each product (since most of them appear more than once in each PCB). This characteristic is especially frequent in digital PCBs (as against analogue PCBs, in which there are typically less components which are shared among different PCBs).

With larger production it is economically justified to dedicate one or more machines to the assembly of these components (C. H. Mangin, personal communication, 1986). This policy is referred to as a 'static operating policy' (Lofgren and McGinnis 1986) as against a 'dynamic operating policy', in which the components are switched to whatever is required by the subsequent product.

There are situations, however, in which the production volume may not justify the purchase of dedicated machines for the assembly of common components (a typical machine may cost up to U.S. \$0.7 million). A single machine should give a production volume of 50 000–75 000 PCBs per shift per year (computed for an average amount of 250 components per board, and an average machine rate of 3000–12 000 assembled components per hour (DynaPert-Precima Ltd. 1986, Universal Instruments Inc. 1986). With some production environments, when a small number of different PCBs is produced, it is possible to dedicate special locations on the machines for the assembly of

common components (Cunningham and Browne 1986). However, this cannot apply to situations whereby many different PCBs are to be produced, such as found in sub-contractors' plants, where they typically produce to the orders of many different customers. Such applications result in many types of electronic components, which are shared among several PCBs.

The production plans in these environments are highly flexible. There are many combinations of PCBs that are possible to produce, whose common components vary from one combination to another. Their combined quantity usually exceeds the machine capacity (a typical machine can contain between 100 and 300 different component types), so that it is impossible to allocate a fixed location for each common component on the machine.

1.2. *Basic assumptions*

(1) The production environment that can benefit most from the implementation of the GSU method is a high-mix low-volume production environment. The basic production line consists of two machines: a DIP insertion machine and an axial/radial lead components insertion machine.

(2) There is an order constraint on the processing of the PCBs, which forces them to be processed first on machine 1 and afterwards on machine 2 (flowshop type assembly line). The reason is that larger components (ICs/DIPs—integrated circuits/dual in-line packages) should be assembled before the smaller ones (axial and radial-lead components), because their machine's head is larger and may hit the smaller components if they are inserted first. This constraint is not critical in the placement of SMCs (surface-mounted components—the future technology of electronic components), so that the production is more flexible (one lot can start being produced on machine 1, while the other can start on machine 2).

(3) The set-up time considered in this paper is only the set-up time required when the product type to be assembled is changed. Refilling components in the machines during the assembly of a lot of identical PCBs is not considered because the amount of components required for the assembly of each PCB does not depend on the production method used, and therefore the refilling operation does not affect the GSU method more than it affects the traditional production method. Also, the machine can continue assembling during the refilling operation, while during set-up for a new product, it must be idle.

(4) The GSU method was originally developed for the major technology currently used for electronics components—the 'thru-hole' technology. Although it is adaptable to the surface-mounted technology, this adoption is not a major concern of this paper.

(5) Due dates are not considered in this paper, except for the determination of the short-term production plan. The method described in this paper is implemented on the short-term production plan after being defined. This is the situation in most practical cases.

(6) This paper is not concerned with the routing of the machine's head on the PCB while assembling the components. The routing problem is a separate problem, dealt with extensively in the literature (Thorogood 1986, Magivou 1986, Gavish and Seidmann 1987).

2. The GSU method

The idea behind GSU is that the products are divided into groups, each of which is produced in two stages. In the first stage, the common components (i.e. components that are shared among product types in the group) are set up on the machines, once only for the whole group, and are assembled onto their respective PCBs. We refer to this stage as the common set-up and production. The next stage, referred to as the residual set-up and production, requires the separate set-up and assembly of the remaining components on each product. Therefore, 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; and
- (4) assembly of residual components on each PCB separately.

An algorithm for implementing the GSU method is presented in Appendix 1.

A schematic presentation of the GSU method is shown in Fig. 1(b). Again, the spaces marked represent the saving in set-up time. It should be clear that the savings under GSU should exceed that under sequence-dependent scheduling, in which some common components may need to be set-up more than once.

The grouping problem can be viewed as a clustering problem. There are several techniques that can be used in order to define groups (McCormick *et al.* 1972, Burbidge 1975, King 1980, Kusiak 1984), but it should be noted that the grouping problem should be solved by finding the right balance between the group size and the production time. As the group size is enlarged, the saving in set-up increases, since each product type added to the group typically contains some common components that are already set up on the machine. However, each PCB added also increases the production makespan and the lead-time of all the PCBs in the group. For this reason, while defining the groups of products, the due dates of all the product types should be considered. A simulation may be used to solve the problem more efficiently. Note, however, that in many practical cases the groups are pre-defined according to the demands of sales/customers.

3. Comparing the GSU with the traditional production method

In this section the GSU and the traditional production method are compared using the following three performance measures:

- production flow (throughput)
- labour time
- production makespan (lead time).

Figures 2(a) and 2(b) show the production flow of two PCB types assembled on two machines using the traditional method and the GSU method, respectively. With the traditional method, each PCB is first completed on machine 1 and then immediately transferred to machine 2; whereas with the GSU method, all PCBs are accumulated until all common components are inserted by machine 1. These PCBs are then reprocessed through machine 1 for the insertion of residual components. Processing in machine 2 follows an identical procedure as in machine 1.

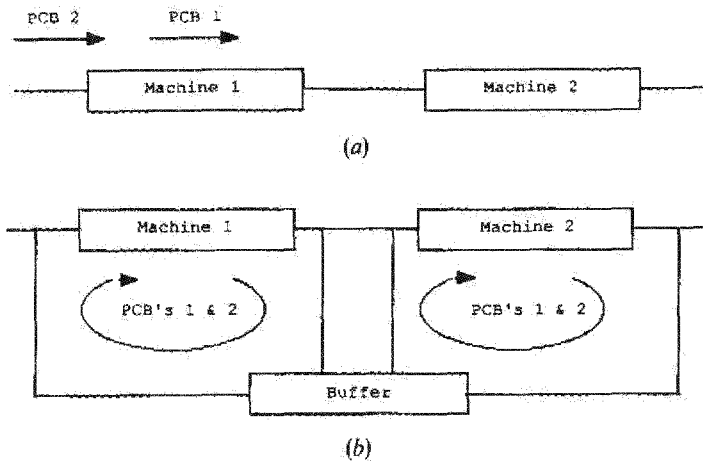


Figure 2. (a) The traditional production method. (b) The GSU production method.

Assumption

Orders for PCBs arrive in groups. Within each group, there are n different types of PCBs. Each PCB incorporates J_k component types ($k=1, 2, \dots, n$). J_k comprises J_{k_1} component types for machine 1 and J_{k_2} component types for machine 2 (i.e. $J_{k_1} + J_{k_2} = J_k$).

3.1. Comparing the production flow

The throughput is inversely proportional to the machines occupation time, so that

$$p \sim 1/\max\{T_1, T_2\}$$

where p is the line throughput and T_m is machine m occupation time.

In the electronics industry, as in many other industrial environments in which lots are produced in several stages on several machines, there are two practical approaches to production. In the first the stages are totally separated. The lot begins production on the second machine only after the last product is completed on the first machine. The advantage of this method is that machine 2 can operate continuously, with no idle time, since it does not depend on the production rate of machine 1. We refer to this approach as 'periodic production'. The second approach, called 'continuous production', applies to products individually transferred to the next stage immediately following completion in the previous one. As soon as the first product is completed on machine 1, it is transferred to machine 2 for processing. In this case, machine 2 may have idle times, but the overall production lead-time is reduced.

When the production is periodic, the occupation time of each machine is shorter for the GSU than for the traditional method, since some set-up time is saved for each group on each machine. Therefore, the throughput is higher for the GSU.

When the production is continuous it is always possible (through slippage) to ensure the continuation of production on machine 2. Therefore the occupation time for both machines is again shorter for the GSU and the throughput is higher.

A more detailed analysis of the production flow and a comparison between the GSU and the traditional production method in terms of throughput and WIP can be found in Carmon (1988) and in Carmon *et al.* (1988).

3.2. Comparing the labour time

The total set-up time needed to produce n PCB types using the traditional production method is

$$S_{\text{trad}} = s \times \sum_{k=1}^n J_k$$

where J_k represents the total number of component types required in PCB type k and s is the set-up time per component. This equation implies that a totally new set-up is needed whenever the PCB type produced is changed.

The GSU saves set-up time since each component type is set-up once only. In this case, the total set-up time is

$$S_{\text{gsu}} = s \times \left[\sum_{k=1}^n J_k - \sum_{i=2}^n (i-1) J_i \right]$$

where J_i represents the number of component types that are shared among i PCB types. Clearly, the advantage of the GSU method over the traditional method increases as the amount and the distribution of the common components are increased.

3.3. Comparing the production makespan for continuous production

Although the GSU decreases the machine's occupation time, it may increase the PCB's lead time because the method is characterized by an accumulation of the PCBs in the group. In case the lead time is critical, there is a need to formulate the makespan equations for both the GSU and the traditional production methods, in order to investigate the conditions under which each method is advantageous. In this section, we analyse the production networks and develop makespan equations for both methods.

3.3.1. Basic assumptions

In order to maintain simplicity, we constrain our analysis in three ways:

- (1) We take each component type as if it appears only once in the PCB.
- (2) Capacity limitations of the machines are ignored, i.e. the common set of components is less than or equal to machine capacity. This assumption is realistic because if extra capacity is needed, then extra component heads can be purchased. The method can also be modified to the performance of more than a single common set-up and production, but this modification is not a major concern of this paper.
- (3) There are two PCB types in the group.

3.3.2. Notation

- $i=1, 2$ PCB-type index variable
- $m=1, 2$ Machine-type index variable
- N_i PCB i batch size
- s Set-up time for a single component type on any machine
- R_m Processing rate of machine m (number of components per hour)
- $J_c(m)$ Number of components types to be assembled in the common production by machine m (GSU)
- $J_r(i, m)$ Number of components types to be assembled in the residual production of PCB type i by machine m (GSU)

- $J(i, m)$ Number of components types of PCB type i to be assembled by machine m (traditional) $J(i, m) = J_c(m) + J_r(i, m)$
 $S(i, m)$ Set-up time for PCB type i on machine m (traditional) $S(i, m) = s \times J(i, m)$
 $P(i, m)$ Processing time of PCB type i on machine m (traditional) $P(i, m) = J(i, m)/R_m$
 $T(i, m)$ Batch production time of PCB type i on machine m (traditional) $T(i, m) = P(i, m) \times N_i$
 $S_c(m)$ Common set-up time for both PCB types on machine m (GSU) $S_c(m) = s \times J_c(m)$
 $P_c(i, m)$ Common production time of PCB type i on machine m (GSU) $P_c(i, m) = J_c(m)/R_m$
 $T_c(i, m)$ Batch common production time of PCB type i on machine m (GSU) $T_c(i, m) = P_c(i, m) \times N_i$, $T_c(i, m) = T_r(i, m)$ in Fig. 3(b)
 $S_r(i, m)$ Residual set-up time for PCB type i on machine m (GSU) $S_r(i, m) = s \times J_r(i, m)$
 $P_r(i, m)$ Residual production time of PCB type i on machine m (GSU) $P_r(i, m) = J_r(i, m)/R_m$
 $T_r(i, m)$ Batch residual production time of PCB type i on machine m (GSU) $T_r(i, m) = P_r(i, m) \times N_i$

Note that

- (1) $2 \times S_c(m) + S_r(1, m) + S_r(2, m) = S(1, m) + S(2, m)$
- (2) $P_c(i, m) + P_r(i, m) = P(i, m)$

3.3.3. Makespan for the traditional case

The activity network for the traditional method may be represented as shown in fig. 3(a).

Since $T(1, 2)$ cannot start until both $T(1, 1)$ and $S(1, 2)$ are completed, and $T(2, 2)$ depends on the completion of $S(2, 2)$ and $T(2, 1)$, the makespan equation for this network consists of several 'maximum' conditions.

$$\begin{aligned}
 MS_{\text{trad}} &= \max \{ [S(1, 1) + T(1, 1) + S(2, 1) + T(2, 1) + P(2, 2)], \\
 &\quad [\max \{ [\max \{ [\max \{ [S(1, 2)], [S(1, 1) + P(1, 1)] \\
 &\quad + T(1, 2)], [S(1, 1) + T(1, 1) + P(1, 2)] \} + S(2, 2)], \\
 &\quad [S(1, 1) + T(1, 1) + S(2, 1) + P(2, 1)] \} + T(2, 2)] \} \\
 &= \max \{ [2S_c(1) + S_r(1, 1) + S_r(2, 1) + T_c(1, 1) + T_c(2, 1) \\
 &\quad + T_r(1, 1) + T_r(2, 1) + P_c(2, 2) + P_r(2, 2)], \\
 &\quad [\max \{ [\max \{ [\max \{ [S_c(1, 2) + S_r(1, 2)], [S_c(1) + S_r(1, 1) \\
 &\quad + P_c(1, 1) + P_r(1, 1)] \} \\
 &\quad + T_c(1, 2) + T_r(1, 2)], [S_c(1) + S_r(1, 1) + T_c(1, 1) + T_r(1, 1) \\
 &\quad + P_c(1, 2) + P_r(1, 2)] \} + S_c(2) + S_r(2, 2)], [2S_c(1) + S_r(1, 1) \\
 &\quad + S_r(2, 1) + T_c(1, 1) + T_r(1, 1) + P_c(2, 1) + P_r(2, 1)] \} + T_c(2, 2) + T_r(2, 2)] \}
 \end{aligned}$$

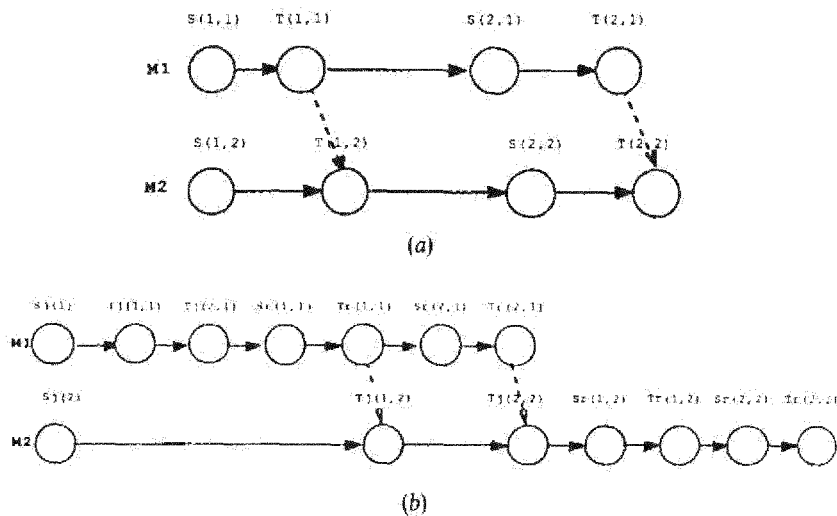


Figure 3. (a) The activity network for the traditional method. (b) The activity network for the GSU method.

3.3.4. Makespan for the GSU case

The activity network for the GSU method is presented in fig. 3(b).

The makespan for this network is

$$\begin{aligned}
 MS_{gsu} = \max \{ & [S_c(1) + T_c(1, 1) + T_c(2, 1) + S_r(1, 1) + T_r(1, 1) \\
 & + S_r(2, 1) + T_r(2, 1) + P_c(2, 2)], \\
 & [\max \{ [\max \{ [\max \{ [S_c(2)], [S_c(1) + T_c(1, 1) + T_c(2, 1) \\
 & + S_r(1, 1) + P_r(1, 1)] \} + T_c(1, 2)], \\
 & [S_c(1) + T_c(1, 1) + T_c(2, 1) + S_r(1, 1) + T_r(1, 1) + P_c(1, 2)] \}, \\
 & [S_c(1) + T_c(1, 1) + T_c(2, 1) + S_r(1, 1) + T_r(1, 1) + S_r(2, 1) + P_r(2, 1)] \\
 & + T_c(2, 2) \} + S_r(1, 2) + T_r(1, 2) + S_r(2, 2) + T_r(2, 2)
 \end{aligned}$$

3.3.5. Effects of the various production factors on the production makespan

The analysis of the networks shows that when machine 1 is dominant (the process bottleneck—because of lower rate or greater amount of components to assemble), the condition for shorter makespan for the GSU is that the time to assemble the residuals on the second machine is smaller than the time to set up the common components on the first machine. This is true since the makespan in this case is equal to the machine 1 occupation time plus the time required for the residual production on machine 2. Such a situation is unlikely to happen, but could happen if the amount of the residual components to be assembled on machine 2 for both PCBs is very small and/or the amount of common components on machine 1 is very large.

When machine 2 is the bottleneck, the probability that the GSU performs better than the traditional method is increased, depending on the waiting periods on machine 2 for the PCBs produced on machine 1 (this is true, of course, only when the production on machine 2 is not delayed so that waiting times are eliminated). These waiting periods are lengthened if the common production on machine 1 is longer than the common set-

up of machine 2, and if the residuals' production on machine 1 is longer than the common production on machine 2.

When the amounts of the common components required on both machines are large, the GSU typically results in a reduced makespan.

The GSU performs better than the traditional method for all cases where no restriction exists on the order of the production (e.g. it is possible to start assembling components of machine 2 before machine 1 is completed).

The makespan of both production methods under various production conditions is illustrated in Appendix 2.

4. A simple example

In an attempt to study the properties of the GSU method, and to compare its performance with that of the traditional method, we use a simple numerical example of two PCB types produced on two different machines. Examples of such machines are Universal Instruments Inc. (1986) and DynaPert-Precima Ltd. (1986) thru-hole assembly machines. We assume that there is only one machine available of each type, i.e. one machine 1 and one machine 2.

Technical data and constraints

(1) From data collected in several electronic manufacturers' plants, we take the loading time of one component type on each machine to be 1 minute of operator's work. This time is the set-up time.

(2) We assume that the set-up time needed to reload the machines when they run out of components is negligible. This assumption is correct when using most of the insertion machines (i.e. machines which assemble thru-hole components—the current practice in industry), because their construction enables the operator to reload components while the machines are working. Note, however, that with surface-mounted component (SMC) placement machines, the batch size and the amount of each type of component to be placed on the boards are of importance, since it takes some set-up time to reload the machines.

(3) The machines' rates (including loading the PCBs) are

Machine 1: 4000 components per hour;

Machine 2: 10 000 components per hour.

(4) The difference between transfer times of components which are closer to the machine's head and components which are further from it is negligible (0.1–0.3 s). For this reason, there is no point in splitting set-up and production in order to shorten the transfer times of farther-located components.

The PCBs specifications are as follows:

PCB type	Machine type	Total number of components	Number of common components	Batch size
1	1	100	60	100
	2	100	90	
2	1	100	60	100
	2	100	90	

Table.

4.1. The labour time

Using the serial traditional production method, the time taken for set-ups is

$$\text{For PCB type 1: } (100 + 100) \times 1 = 200$$

$$\text{For PCB type 2: } (100 + 100) \times 1 = 200$$

The total set-up time in the process is 400 min = 6.66 hours.

The net processing time of the batches is

$$[(100 + 100)/4000 + (100 + 100)/10\,000] \times 100 = 7 \text{ hours}$$

i.e.

$$\frac{\text{set-up}}{\text{production}}$$

is about 49%, meaning that the set-up time is about $\frac{1}{2}$ of the total production time.

Using the GSU method, the set-up time for the production is

$$\text{Common set-up time: } (60 + 90) \times 1 = 150$$

Residual set-up times:

$$\text{For PCB type 1: } (40 + 10) \times 1 = 50$$

$$\text{For PCB type 2: } (40 + 10) \times 1 = 50$$

$$\text{Total set-up time: } 250 \text{ min} = 4.17 \text{ hours}$$

Using the GSU method, the labour time consumed by set-up in the process is reduced by 37.5%, and the ratio

$$\frac{\text{set-up}}{\text{production}}$$

is about 37%, i.e. the set-up time is now about $\frac{1}{3}$ of the production time.

4.2. The production flow

The production flow is inversely proportional to the machines' occupation time.

Using the traditional production method, the machines' occupation times are

$$\text{For PCB type 1 on machine 1 } 4.17 \text{ hours}$$

$$\text{For PCB type 2 on machine 1 } 4.17 \text{ hours}$$

$$\text{For PCB type 1 on machine 2 } 2.67 \text{ hours}$$

$$\text{For PCB type 2 on machine 2 } 2.67 \text{ hours}$$

Machine 1 total occupation time is 8.34 hours.

Machine 2 total occupation time is 5.34 hours.

Using the GSU production method, the machines' occupation times are

$$\text{For PCB types 1 and 2 on machine 1 } 7.33 \text{ hours}$$

$$\text{For PCB types 1 and 2 on machine 2 } 3.83 \text{ hours.}$$

4.3. The production makespan

Computation of the makespan yields the following results:

The makespan using the traditional method is $MS_{\text{trad}} = 8.35$ hours.

The makespan using the GSU method is $MS_{\text{gsu}} = 7.89$ hours.

For the particular case, the GSU performs better than the traditional production method in terms of the production makespan.

5. Complexity

The complexity of implementing the GSU method involves four factors:

- (1) the complexity of the 'grouping' method;
- (2) the complexity of the production management and the information control;
- (3) the complexity of the practical production environment;
and in the case of continuous production,
- (4) the complexity of the makespan calculation.

(1) Clearly, the grouping problem is very complicated. However, in many practical cases, the group, which is actually the short-term production plan, is pre-defined by the sales/customers demands (the PCB's due-dates).

(2) While reducing the overall set-up times, this new approach also complicates production management and information control. The information system must now be able to control simultaneously all data related to the production and in-process inventory of different PCB types. However, the current accelerated development of information systems should be able to control large amounts of production and process data, enabling the implementation of this more complicated but more efficient production method.

(3) The complexity of the production environment depends on many factors which affect the assembly process and the scheduling methods used. Among them are PCB variety, component variety, fluctuations in demand, machine downtime and lot size. The impact of these factors is not discussed here, but they should be considered when a scheduling method for the assembly of PCBs is selected.

(4) It can be shown that the makespan calculation can be done in $O(nm)$ time, where n is the number of PCB types in the group and m is the number of machines. The number of 'max' expressions in the equation is $2n(m-1)$, and the number of figures summed is also a function of n and m . This results in a calculation that grows polynomially with the problem size and a reasonable computer time consumed.

6. Conclusions and further research

The GSU was shown to perform better than the traditional (serial) production method in terms of

- labour time
- total production flow (throughput)

and in some cases also in terms of

- the production makespan (lead time).

The GSU complicates the WIP inventory control, but such advanced information and production control system are currently available.

The advantage of the CSU method is especially important for production environments in which there are many types of products sharing 'common' components, and where the production volume justifies the purchase of only one machine of each type.

The GSU approach needs to be further developed for more PCB types and more machines. An efficient grouping method needs to be defined. The effect of lot size on the

production makespan also needs to be further analysed. There are other possibilities of sequence-dependent scheduling for the cases of less common components or less PCB types, and a comparison between these other possibilities and the GSU needs to be developed. One such method and a comparison between this method and the GSU method is described in Carmon (1988) and Carmon *et al.* (1988).

Appendix 1: The major set-up algorithm

(The algorithm is implemented for each machine separately.)

Notation

- $i=1,2$ Product type index variable
- $j=1,\dots,n$ Component type index variable
- $m=1,2$ Machine type index variable
- N_i Product i batch size
- A_{ij} Amount of component j needed to produce one unit of product i
- $E_{ij}=0,1$ Binary variable which is 1 if product type i contains a j component and is 0 otherwise
- V_j Amount of various product types each component is shared among

$$V_j = \sum_i E_{ij}$$

- W_j Total amount of component j needed for the production of all the products in the production plan

$$W_j = \sum_i A_{ij} N_i$$

- C_m Machine capacity (components feeders)

Preliminary step

Define the groups of boards to be produced according to their size. All the boards in the group should have at least one equal dimension. This dimension will define the conveyer's width, so that no mechanical set-up (i.e. changing the width of the conveyers which carry the boards) will have to be made between the assembly of two different boards within the same group, since the mechanical set-up is time-consuming (a typical mechanical set-up for one machine can take up to 30 min) and must be avoided (Mangin 1985).

The PCBs dimensions can be controlled by using 'panelling', a production method in which the boards are assembled as 'panels', each panel containing several boards, and cut at the end of the production process into their desired dimensions.

- (1) Compute

$$V_j = \sum_i E_{ij}$$

for each component j in the next group of PCBs to be produced.

- (2) Define j^* , the component with the maximal V_j .

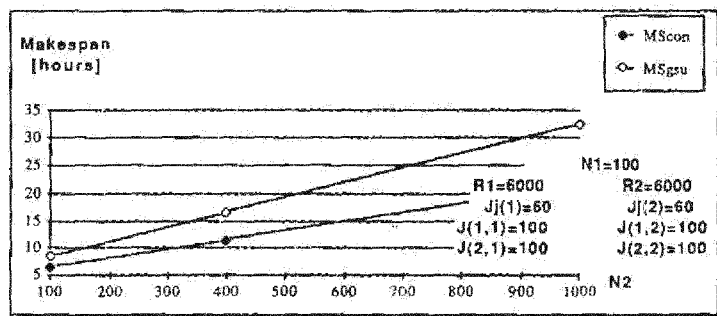
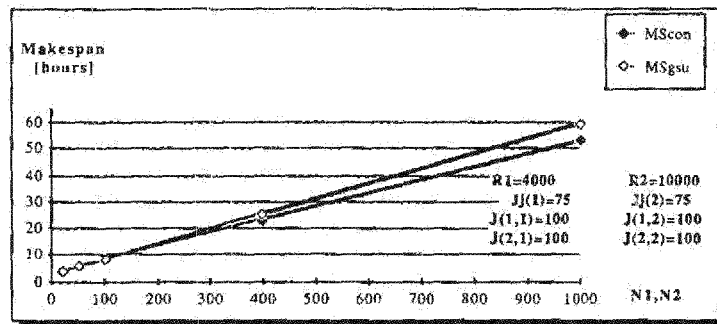
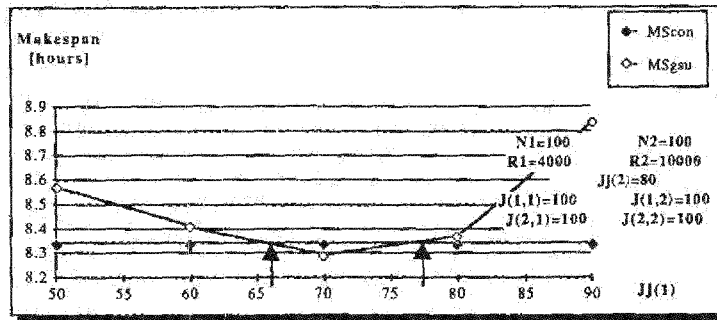
- (3) If j^* is not a singleton then choose the component with the minimal W_j where

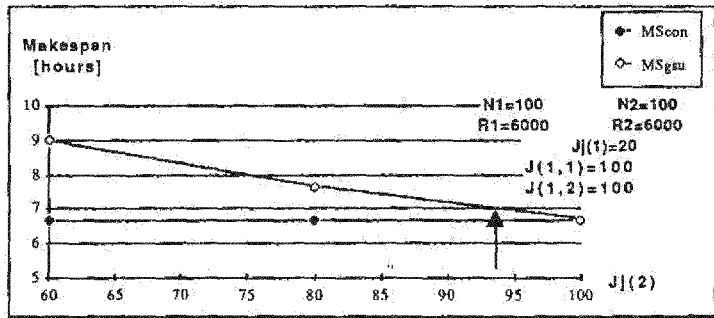
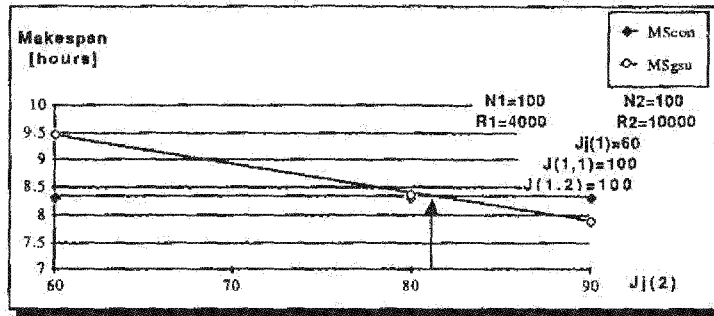
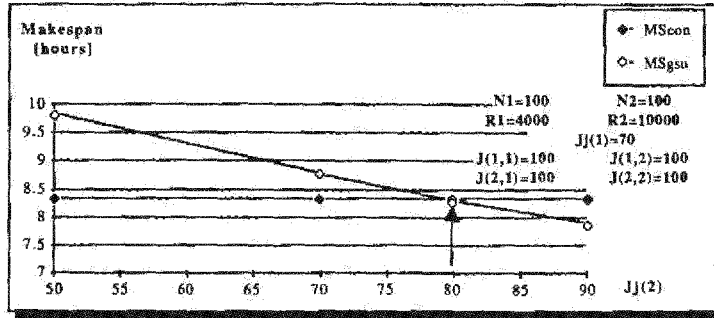
$$W_j = \sum_i A_{ij} N_i$$

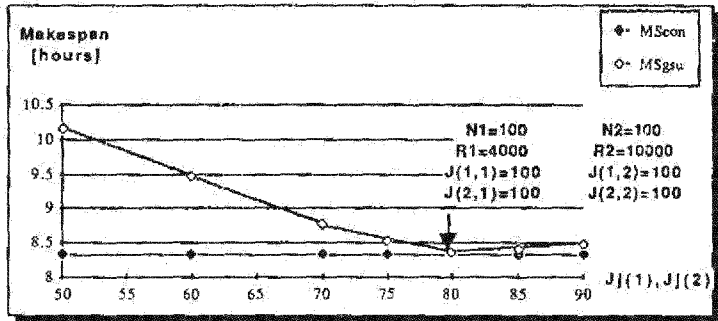
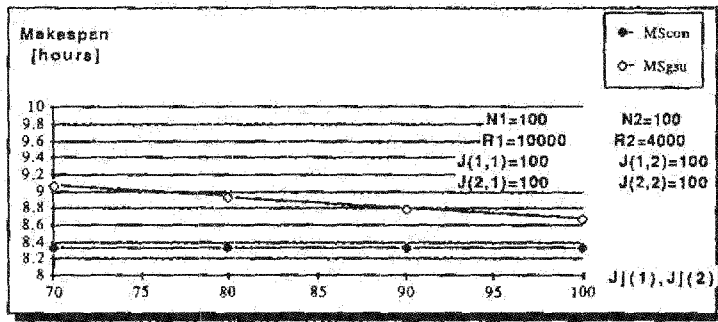
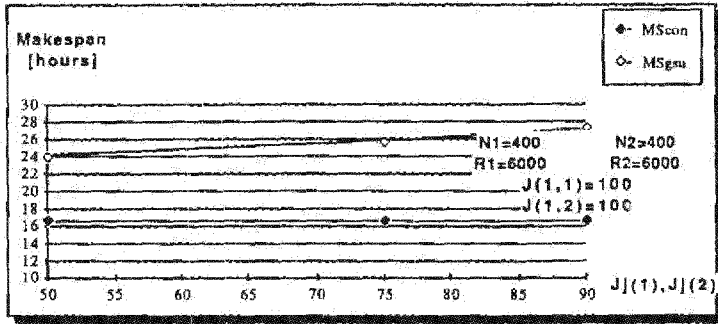
For equal W_j 's, choose arbitrarily.

- (4) Delete j^* from the list of components to be assigned.
- (5) Repeat steps 2-5 until the amount of components assigned equals the machine capacity, C_m or until $V_j < 2$.
- (6) Sort the components chosen according to their W_j value, and assign them to the machine's feeders so that components with larger W_j will be assigned closer to the machine's head (although the time difference is almost negligible).
- (7) If the next V_j on the list satisfies $V_j \geq 2$ then at least one more major set-up should be performed.

Appendix 2: Makespan using GSU versus traditional method







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