Schedule generation schemes for flexible manufacturing systems with additional resources

To cite this article: K Kalinowski et al 2018 IOP Conf. Ser.: Mater. Sci. Eng. 400 062016

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Abstract. The paper presents the problem of scheduling in flexible manufacturing systems with additional resources consideration. In the developed model, the basic resources e.g. and additional resources - staff, tools, etc. - are assigned to resource groups. The allocation of operations to particular resources is carried out through these groups - by indicating the number of resources needed from a given group. At the scheduling stage, depending on the expected values of beginning and ending of the operation, the most advantageous resource for allocation is selected. Forward and backward scheduling strategies and serial and parallel schedule generation schemes are discussed in this context.

1. Introduction

Efficiency of manufacturing systems is closely related to proper organisation of executed tasks. Therefore, over the years of the existence of production systems, effective methods that guarantee not only the achievement of acceptable schedules, but solutions as close as possible to the optimal - those that best meets the accepted criteria are still being sought [1,2]. These methods must also be implemented in well-organized information systems. An important role here is played by solutions used for obtaining and processing information from the production system and its environment [3]. Only permanent access to current data enables proper planning of tasks for subsequent planning periods. Due to the dynamic nature of the environment in which enterprises operate, decision-making often takes place in conditions of risk and uncertainty, and the data obtained require well-chosen methods of their processing [4,5,6]. The effectiveness of decision-making is closely related to the analysis stage, in which different variants can be simulated and discussed for selecting the most valuable acceptable solutions. Their quality strongly depends on the model, developed at the appropriate level of detail, and well-chosen methods. The issues raised in this work concern the extension of the classic model of flexible manufacturing system with the possibility of parallel planning of basic (machines) and other additional resources. In the area of methods for determining solutions, serial and parallel scheduling schemes were used.
2. Model of production system

The considered production system consists of \( m_b \) basic resources \( M_1, \ldots, M_{m_b} \), \( m_a \) additional resources denoted as \( W_1, \ldots, W_{m_a} \) and \( n \) tasks \( P_1, \ldots, P_n \) (indexed by \( j \)). Resources are discrete and renewable. In most cases, the basic resources are equivalent to machines and additional resources to workers, tools, or other equipment. All resources are grouped in \( p \) disjoint groups of parallel resources (competences groups) \( \text{PG}_1-\text{PG}_p \), a given resource belongs to exactly one of them. Each task \( P_j \) consists of \( k_j \) operations \( O_1, \ldots, O_{k_j} \), which must be done in order to complete the task. The resource requirements of an operation are indicated by relevant resources groups, one group for basic resources, and 0 or more for additional resources.

The condition allowing more than one resource to exist in a given resource group means that the implementation of a task can be done using one of many routes. In figure 1 a general concept for the implementation of the selected route in the task was presented.

\[
\begin{align*}
\text{min} & \quad v(u^t u^t + u^{st} u^{st} + u^{et} u^{et}) \\
\text{where:} & \\
u^t & \text{ is the partial score associated with the selected parameter, where } x \in \{t, st, et\}, \text{ respectively,} \\
w^x & \text{ is the weight of partial score associated with a parameter, where } x \in \{t, st, et\}, \text{ respectively.}
\end{align*}
\]

Figure 1. One of the possible routes for a task.

Determination of a solution in such a system requires the implementation of a multi-stage decision-making process. One of its stages is to make a decision about choosing the proper route variant for a given operation including the selection of the machine or specific additional resources from the group that can be used. This selection can be made arbitrarily before the scheduling process, or be carried out during scheduling, taking into account the current resource load.

In general, the selection of machines and additional resources from the sets of resources groups, taking into account the parameters of the operations adopted in the model, can be carried out according to the following:
The level of significance of parameters related to the start and end time of operations depends on the adopted task planning strategy. Table 1 presents the method of calculating the value of these assessments.

| Partial evaluations | Forward | Backward |
|---------------------|---------|----------|
| Processing time     | $u_v^t = \frac{t_v}{\max_v \{t_v^t\}}$ |  |
| Starting time       | $u_v^{st} = \frac{t_v^{st}}{\max_v \{t_v^{st}\}}$ | $u_v^{st} = \frac{\min_v(t_v^{st})}{t_v^{st}}$ |
| Ending time         | $u_v^{et} = \frac{t_v^{et}}{\max_v \{t_v^{et}\}}$ | $u_v^{et} = \frac{\min_v(t_v^{et})}{t_v^{et}}$ |

In the forward strategy, the most common goal is to perform the operation as soon as possible, hence it is important not only the potential time of its beginning, but first of all its ending - the shorter the better. In the case of backward strategy, both times are also important, but from the planning point of view, the beginning time of operations is more important - the closer to due date, the better. Because local optimisation does not guarantee a global optimal solution, it is recommended to use advanced algorithms for entire graph searching, based, for example, on artificial intelligence methods.

The following factors of tasks flow are used in evaluation process:
- completion time $C_j$, indicating the end of the last operation of a given $j$-th task,
- flow time $F_j$, $F_j = C_j - r_j$, where $r_j$ is a ready time of a $j$-th task,
- residence time $Fse_j$, $Fse_j = C_j - b_j$, where $b_j$ is the start time of $j$-th task.

The used performance measures based on these factors are as follow:
- maximum values: $C_{\max} = \max_j(C_j)$, $F_{\max} = \max_j(F_j)$, $Fse_{\max} = \max_j(Fse_j)$,
- average values $\bar{C} = \frac{1}{n} \sum_{j=1}^{n} C_j$, $\bar{F} = \frac{1}{n} \sum_{j=1}^{n} F_j$, $\bar{Fse} = \frac{1}{n} \sum_{j=1}^{n} Fse$.

### 3. Schedule generation schemes

The schedule is created by inserting subsequent operations. During this process, all accepted constraints should be taken into account, e.g. precedence and resource constraints. It means that the operations should be inserted not in any order but in a specific order. Operations that are possible to schedule are inserted into a partially created schedule, which allows further setting of subsequent operations related to them. The methods of selecting the operations for inserting into the schedule, possible to set in the schedule, are defined by the so-called Schedule Generation Schemes (SGS). The basic division distinguishes serial and parallel scheme. On this basis, many methods have been developed using SGS schemes [9-12].

In figure 2 shows the adopted scheduling procedures using forward and backward strategies. In both strategies there are three common blocks:
- creating/updating the list of eligible operations - represents the stage of creating or editing a set of operations, all operations for which all predecessors have been set in the schedule are searched (indicated by the precedence relations),
- selection of operation - the operation to scheduling is selected. Depending on the method adopted - the list of operations is previously sorted or not,
• scheduling - in the discussed method, a monolithic approach was adopted, in which the allocation of tasks to resources (selection from alternatives) is at the same stage as setting the start times of operations. In the hierarchical approach, the stages of allocating all operations to resources and setting them in the schedule are implemented separately.

Figure 2. Scheduling procedure by SSGS and PSGS.

The serial SGS (SSGS) uses activity incrementation and consists in choosing operations sequentially from a ranked list and inserting into a schedule according to a given strategy, e.g. at the earliest possible date in case of forward scheduling. Each decision step is related to the planning of one operation. Depending on the rules used, the position of operations on the ranking list may change in subsequent decision stages.

The Parallel SGS (PSGS) scheme applies the so-called time incrementation. Each of the decision steps in the parallel scheme is an independent decision problem, related to the designated moment of time, in which all the operations that are allowed for planning are scheduled. The time point of the next decision stage is determined on the basis of the operations setting times from the previous stage, e.g. earliest finish time of operations in case of forward scheduling.
4. Example

Considered system consists of 5 basic resources M1-M5 grouped in 3 resource groups RG1-RG3, 4 additional resources grouped in 2 resource groups RG4-RG5 and 5 tasks P1-P5. Each process consists of 3 operations. All operations require one basic resource (from groups RG1-RG3) and some additional resources from groups RG4-RG5. Operation times and resource requirements are presented in Table 2. A forward strategy ad ready time $r_j = 0$ was adopted for all tasks.

| RG1(M1,M2) | RG2(M3) | RG3(M4,M5) | RG4(W1,W2) | RG5(W3,W4) |
|------------|---------|------------|------------|------------|
| P1 | P2 | P3 | P4 | P5 |
| O1 | O2 | O3 | O1 | O2 | O3 | O1 | O2 | O3 | O1 | O2 | O3 | O1 | O2 | O3 | O1 | O2 | O3 |
| 2 | 1 | 2 | 1 | 2 |
| 2 | 3 | 2 | 2 | 2 |
| 2 | 1 | 3 | 2 | 3 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

Case 1. In figure 3 the reference schedules are presented, created by SSGS and PSGS, without additional resources. In the SSGS scheme, the order in which the operations are inserted corresponds to the order of tasks according to the assigned numbers (from P1 to P5). The order of inserting its operations according to the forward strategy, in order: O1, O2, O3. This is one of many possible sequences by SSGS. In the PSGS scheme, operations were inserted in accordance with the time incrementation.

| Table 3. Case 1. Characteristics of production tasks. |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Schedule by     | $C_{\text{max}}$ | $\bar{C}$    | $F_{\text{max}}$ | $\bar{F}$    |
| SSGS (a)        | 12               | 8,8            | 12               | 8,8            | 44             | 37             |
| PSGS (b)        | 11               | 8,8            | 11               | 8,8            | 44             | 42             |

Figure 3. Schedule by SSGS (a) and PSGS (b) using forward strategy without additional resources consideration.
PSGS has completed a set of tasks faster than SSGS - by one unit of time. Parameters based on C and F are the same due to the assumed \( r_j = 0 \) (\( C_{\text{max}} = F_{\text{max}} \) and \( \bar{C} = \bar{F} \)). Despite the differences in the flows times \( F_j \) of individual tasks, both schedules have the same \( F_{\text{sum}} = 44 \). A significant difference appears with the \( F_{\text{se}} \) parameter, in the case of SSGS it is significantly shorter (42 vs 37). This difference is caused by task P1 - as can be seen in the Gantt chart (figure 3), its residence time by PSGS is longer by 5 units of time. In some practical applications this situation may not be beneficial, so the choice between the two solutions is not obvious. There are also negligible differences in the selection of alternative resources in particular groups: operations P3.O3 and P4.O3.

**Case 2.** In figure 4 the schedules including all given resource groups are presented. The order in which the operations are inserted to schedules is the same as in the previous case.

![Figure 4](image.png)

**Figure 4.** Schedule by SSGS (a) and PSGS (b) using forward strategy and all given resources groups.

In the presented Gantt charts (figure 4), each operation is displayed many times, adequately to the number of additional resources used (table X). Table 4 presents selected performance measures of obtained solutions. Because of \( r_j = 0 \) parameters \( C_{\text{max}} = F_{\text{max}} \) and \( \bar{C} = \bar{F} \), so \( F_{\text{max}} \) and \( \bar{F} \) are omitted.

| Schedule by  | \( C_{\text{max}} \) | \( \bar{C} \) | \( F_{\text{sum}} \) | \( F_{\text{se}} \) |
|-------------|-----------------|---------|----------------|-------------|
| SSGS (a)    | 16              | 10,2    | 51             | 35          |
| PSGS (b)    | 12              | 10,6    | 53             | 49          |

Also in this case PSGS has completed a set of tasks faster than SSGS - by 4 unit of time. On the other hand. the schedule generated by SSGS has better other performance measures: \( \bar{C} \), \( F_{\text{sum}} \) and \( F_{\text{se}} \).
Looking at the differences in individual tasks, the case is already ambiguous, e.g. the task P1 has residence time \( F_{se} = 6 \) in SSGS and \( F_{se} = 11 \) in PSGS while for the task P3 SSGS has longer \( F_{se} = 9 \) vs 8 in PSGS. In this case there are also negligible differences in the selection of alternative resources in particular groups can be noticed.

In general, on the basis of the above examples, it can be seen that SSGS creates longer schedules \((C_{\text{max}})\) than PSGS, but residence time \( F_{se} \) of particular tasks is rather shorter in them. This is partly due to the way in which the operations are inserted into the schedule, but also from the specification of tasks and accepted parameters of operations (eg processing times).

5. Conclusions
The main aim of the work was to present serial and parallel schedule generation schemes in applications to flexible manufacturing systems with additional resources. The model of the system in which resource requirements of operations are directed to resources by resource groups is presented. This is a situation often encountered in practice - if planning involves not only the machines but also people who participate in the operation. The method also refers to two basic scheduling strategies - forward and backward - for these strategies formulas allowing selection of the best route variant due to the processing time and well as the starting and ending times of an operation were described. In the schedule evaluation process, apart from the basic parameters of the schedule evaluation, an additional performance measure based on residence time was defined. It describes the duration of the task from the moment it is started until its completion and indicates, often desirable, the ‘compactness’ of the task realization. It can be also used in the planning of input materials supplies – for determining the value of the parameter \( r_j \). The example presented showed the main advantages and disadvantages of using individual schedule generation schemes.

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