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Abstract: We investigate the computational complexity of scheduling multiprocessor tasks with prespecified processor allocations. We consider two criteria: minimizing schedule length and minimizing the sum of the task completion times. In addition, we investigate the complexity of problems when precedence constraints or release dates are involved.

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Key words & Phrases: Multiprocessor tasks, prespecified processor allocations, makespan, total completion time, release dates, precedence constraints.

1. Introduction
We address a class of multiprocessor scheduling problems. A collection of n tasks has to be executed by m processors. Task $J_j$ ($j = 1, \ldots, n$) requires processing during a given uninterrupted time $p_j$. Each task requires the simultaneous use of a set of prespecified processors for its execution; each processor can execute at most one task at a time. Such tasks are referred to as multiprocessor tasks. Sometimes, for each task $J_j$ a release date $r_j$ on which it becomes available for processing or precedence constraints, indicating the set of tasks that have to be completed before $J_j$ may start, are specified; we will state explicitly whether this is the case. We have to determine a schedule, that is, an allocation of each task $J_j$ to a time interval of length $p_j$ such that no two tasks on the same processor overlap. The completion time of task $J_j$ in schedule $\sigma$ is denoted by $C_j(\sigma)$ or shortly by $C_j$, if no confusion is possible as to the schedule we refer to. We are interested in two objectives. The first one is to find a schedule that minimizes the makespan $C_{\text{max}} = \max_j C_j$. The second objective concerns the minimization of the total completion time $\sum_j C_j$.

In this paper, scheduling problems are denoted using the three-field notation scheme that was proposed by Veltman, Lageweg, and Lenstra [1990] as an extension of the terminology of Graham, Lawler, Lenstra, and Rinnooy Kan [1979]. In the notation scheme $\alpha|\beta|\gamma$, $\alpha$ specifies the processor environment, $\beta$ the task characteristics, and $\gamma$ the objective function. Accordingly, the value of $\gamma$ of a schedule $\sigma$ and the minimal value with respect to $\gamma$ are denoted by $\gamma(\sigma)$ and $\gamma^*$, respectively. For
instance, $P_{j=1, P_2} | \text{fix}, r_j | C_{\text{max}}$ refers to the multiprocessor problem of minimizing the makespan, where for each task a fixed processor allocation and a release date are specified; $P_{m_j=1, P_2} | \Sigma_j$ denotes the multiprocessor problem of minimizing the total completion time, where all processing times are equal to 1, processor allocations are given, and the number $m$ of processors is specified as part of the problem type.

In the literature, little attention has been devoted to the complexity of scheduling multiprocessor tasks. Two branch and bound approaches for $P_{j=1, P_2} | \text{fix}, C_{\text{max}}$ have been proposed. Bozoki and Richard [1970] concentrate on incompatibility; two tasks are incompatible if they have at least one processor in common. Bianco, Dell’Olmo, and Speranza [1991] follow a graph-theoretical approach, and they determine a class of polynomially solvable instances that corresponds to the class of comparability graphs. We will investigate the complexity of a class of problems related to $P_{j=1, P_2} | \text{fix}, C_{\text{max}}$. The outline of the paper is as follows.

Section 2 deals with the makespan criterion. The general problem with a fixed number $m$ of processors is polynomially solvable if $m$ is equal to 2, but NP-hard in the strong sense for $m \geq 3$. There are two well-solvable cases. The first one concerns the case of unit processing times; the problem is then solvable in polynomial time through an integer programming formulation with a fixed number of variables. The second one concerns the three-processor problem in which all multiprocessor tasks of the same type are decreed to be executed consecutively, the so-called block-constraint; this problem is solvable in $O(n \Sigma_j)$ time. If the number of processors is part of the problem instance, then the problem with unit processing times is already NP-hard in the strong sense. In general, the introduction of precedence constraints or release dates leads to strong NP-hardness, with one exception: the problem with unit processing times in which both the number of processors and the number of distinct release dates are fixed is solvable in polynomial time through an integer programming formulation with a fixed number of variables. The computational complexity of the problem $P_{m_j=1, P_2} | \text{fix}, r_j, p_j=1 | C_{\text{max}}$ is still open.

Section 3 deals with the total completion time criterion. In general, this criterion leads to severe computational difficulties. The problem is NP-hard in the ordinary sense for $m=2$ and in the strong sense for $m=3$. The weighted version and the problem with precedence constraints are already NP-hard in the strong sense for $m=2$. The problem with unit time processing times is NP-hard in the strong sense if the number of processors is part of the problem instance, but still open in case of a fixed number of processors. Another open problem is $P_{m_j=1, P_2} | \Sigma_j$.

# 2. Makespan

In this section, we investigate the computational complexity of minimizing the makespan. If no precedence relation is specified, then we may discard the tasks that need all the processors for execution, since they can be scheduled ahead of the other ones. Hence, the two-processor problem without precedence constraints is simply solved by scheduling each single-processor task on its processor without causing idle time.

## 2.1. The block-constraint and pseudopolynomiality on three processors

The block-constraint decrees that all bipercessor tasks of the same type are scheduled consecutively. As this boils down to the case that there is at most one bipercessor task of each type, we replace all bipercessor tasks of the same type by one task of this type with processing time equal to the sum of the individual processing times. The bipercessor task that requires $M_2$ and $M_3$ is named a task of
type A and its processing time is denoted by $p_A$. Correspondingly, the biprocessor task that requires $M_1$ and $M_3$ and the biprocessor task that requires $M_1$ and $M_2$ are said to be of type B and C, respectively; their processing times are denoted by $p_B$ and $p_C$.

**Figure 1.** A schedule satisfying the block-constraint.

**Theorem 1.** The problem $P_{\text{3|fix}|C_{\text{max}}}$ subject to the block-constraint is NP-hard in the ordinary sense.

**Proof.** We will show that $P_{\text{3|fix}|C_{\text{max}}}$ subject to the block-constraint is NP-hard by a reduction from the NP-complete problem Partition.

**Partition**

Given a multiset $N = \{a_1, \ldots, a_n\}$ of $n$ integers, is it possible to partition $N$ into two disjoint subsets that have equal sum $b=\sum_{j \in N} a_j/2$?

Given an instance of Partition, define for each $j \in N$ a task $J_j$ that requires $M_1$ for execution and has processing time $p_j=a_j$. In addition, we introduce five separation tasks that create two time slots of length $b$ on $M_1$. The tasks $J_A$, $J_B$, and $J_C$, each with processing time $b$, are of the type A, B, and C, respectively. The two single-processor tasks $J_{n+1}$ and $J_{n+2}$, each with processing time $2b$, have to be executed by $M_2$ and $M_3$, respectively.

Note that each processor has a load of $4b$, which implies that $4b$ is a lower bound on the makespan of any feasible schedule. We will show that Partition has a solution if and only if there exists a schedule for the corresponding instance of $P_{\text{3|fix}|C_{\text{max}}}$ with $C_{\text{max}} \leq 4b$.

Suppose that there exists a subset $S \subseteq N$ such that $\sum_{j \in S} a_j = \sum_{j \in N-S} a_j = b$. A schedule of length $C_{\text{max}} = 4b$ then exists, as is illustrated in Figure 2.

Conversely, notice that only four possibilities exist to schedule the tasks $J_{n+1}, J_{n+2}, J_A, J_B$, and $J_C$ in a time interval of length $4b$. Each of these possibilities leaves two separated idle periods of length $b$ on processor $M_1$, in which the tasks $J_j$ with $j \in N$ must be processed. Thus, if there exists a schedule of length $C_{\text{max}} = 4b$, then there is a subset $S \subseteq N$ such that $\sum_{j \in S} a_j = \sum_{j \in N-S} a_j$.

We conclude that $P_{\text{3|fix}|C_{\text{max}}}$ is NP-hard in the ordinary sense. □

**Theorem 2.** The problem $P_{\text{3|fix}|C_{\text{max}}}$ subject to the block-constraint is solvable in pseudopolynomial time.

**Proof.** We propose an algorithm for this problem that requires $O(n \sum_{j \in N} p_j)$ time and space. For $i = 1, 2, 3$, let $T_i$ denote the set of indices of tasks that require only $M_i$ for processing, and $n_i = |T_i|$. In addition, we define $p(S) = \sum_{j \in S} p_j$.

Using an interchange argument, we can transform any optimal schedule into an optimal schedule
with some biprocessor task scheduled first and some other biprocessor task scheduled last. Suppose for the moment that these tasks are of type A and C, respectively; a B-type task is then scheduled somewhere in between. Any feasible schedule of this type, referred to as an ABC-schedule, is completely specified by the subsets \( Q_1 \subseteq T_1 \) and \( Q_3 \subseteq T_3 \) scheduled before the B-type task; see Figure 3.

![Figure 3. Structure of an ABC schedule.](image)

For an ABC-schedule with given subsets \( Q_1 \) and \( Q_3 \), the earliest start time of the task of type \( B \) is

\[
S_B(Q_1,Q_3) = \max\{p(Q_1), p_A + p(Q_3)\}.
\]

The earliest start time of the task of type \( C \) is then

\[
S_C(Q_1,Q_3) = \max\{S_B(Q_1,Q_3) + p_B + p(T_1 - Q_1), p_A + p(T_2)\}.
\]

The minimal length of such a schedule is therefore

\[
C_{\text{max}}(Q_1,Q_3) = \max\{S_C(Q_1,Q_3) + p_C, S_B(Q_1,Q_3) + p_B + p(T_3 - Q_3)\}.
\]

Hence, the minimal length of an ABC-schedule is determined by \( p(Q_1) \) and \( p(Q_3) \). In other words, the length of an optimal ABC-schedule is equal to the minimum of \( C_{\text{max}}(Q_1,Q_3) \) over all possible values of \( p(Q_1) \) and \( p(Q_3) \). Due to symmetry, we can transform any ABC-schedule into an CBA-schedule of the same length. The only other types of schedules of interest to us are therefore the BAC and ACB-schedules. Similar arguments show that the length of an optimal BAC-schedule is equal to the minimum of \( C_{\text{max}}(Q_2,Q_3) \) over all possible values of \( p(Q_2) \) and \( p(Q_3) \), and that the length of an optimal ACB-schedule is equal to the minimum of \( C_{\text{max}}(Q_1,Q_2) \) over all possible values of \( p(Q_1) \) and \( p(Q_2) \).

For \( i = 1,2,3 \), we compute all possible values that \( p(Q_i) \) can assume in \( O(n_ip(T_i)) \) time and space by a standard dynamic programming algorithm of the type also used for the knapsack and the subset-sum problems; see e.g. Martello and Toth [1990]. If these values are put in sorted lists, then all possible values that \( S_B(Q_1,Q_3) \) can assume are computed in \( O(p(Q_1)+p(Q_3)) \) time and space. The minimum of \( C_{\text{max}}(Q_1,Q_3) \) over \( p(Q_1) \) and \( p(Q_3) \) is then determined by evaluating expression (1)
for each possible combination of \( p(Q_1) \) and \( p(Q_3) \); this takes \( O(p(T_1)+p(T_3)) \) time.

The lengths of the optimal \( BAC \) and \( ACB \)-schedules are determined similarly. The overall minimum then follows immediately, and an optimal schedule is determined by backtracing. Since \( n_i \leq n \) and \( p(T_i) \leq \Sigma_{j \in N} p_j \) for each \( i \), it takes \( O(n \Sigma_{j \in N} p_j) \) time and space to find an optimal schedule.

<table>
<thead>
<tr>
<th>number</th>
<th>allocation</th>
<th>processing time</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n )</td>
<td>( M_2 \ &amp; M_3 ) (type A)</td>
<td>( p_A )</td>
</tr>
<tr>
<td>( n ) &amp; ( M_1 \ &amp; M_3 ) (type B)</td>
<td>( p_B )</td>
<td></td>
</tr>
<tr>
<td>( n ) &amp; ( M_1 \ &amp; M_2 ) (type C)</td>
<td>( p_C )</td>
<td></td>
</tr>
<tr>
<td>( 1 )</td>
<td>( M_1 )</td>
<td>( p_A+b )</td>
</tr>
<tr>
<td>( n-1 )</td>
<td>( M_1 )</td>
<td>( p_A+b+p_z )</td>
</tr>
<tr>
<td>( 1 )</td>
<td>( M_1 )</td>
<td>( p_y )</td>
</tr>
<tr>
<td>( n )</td>
<td>( M_1 )</td>
<td>( p_B+p_y )</td>
</tr>
<tr>
<td>( n ) &amp; ( M_1 )</td>
<td>( p_z )</td>
<td></td>
</tr>
<tr>
<td>( n-1 )</td>
<td>( M_1 )</td>
<td>( p_B+p_y )</td>
</tr>
<tr>
<td>( n )</td>
<td>( M_2 )</td>
<td>( p_B+p_y )</td>
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<td>( M_2 )</td>
<td>( p_y )</td>
</tr>
<tr>
<td>( 1 )</td>
<td>( M_3 )</td>
<td>( p_C+p_y )</td>
</tr>
<tr>
<td>( n-1 )</td>
<td>( M_3 )</td>
<td>( p_C+p_y+p_z )</td>
</tr>
</tbody>
</table>

Table 1. Separation tasks for \( P_3 | \text{fix}_j | C_{\text{max}} \).

### 2.2. Strong NP-hardness for the general 3-processor problem

Theorem 3. The problem \( P_3 | \text{fix}_j | C_{\text{max}} \) is NP-hard in the strong sense.

Proof. The proof is based upon a reduction from the strongly NP-complete problem 3-Partition.

3-Partition
Given an integer \( b \) and a multiset \( N = \{a_1, \ldots, a_{3n}\} \) of \( 3n \) positive integers with \( b/4 < a_j < b/2 \) and \( \Sigma_{j=1}^{n} a_j = nb \), is there a partition of \( N \) into \( n \) mutually disjoint subsets \( N_1, \ldots, N_n \) such that the elements in \( N_j \) add up to \( b \), for \( j = 1, \ldots, n \)?

Given an instance of 3-Partition, we construct the following instance of \( P_3 | \text{fix}_j | C_{\text{max}} \). There are \( 3n \) single-processor tasks \( J_j \) that correspond to the elements of 3-Partition; these tasks have to be executed by \( M_3 \) and their processing time is equal to \( a_j \), for \( j = 1, \ldots, 3n \). In addition, there are \( 3n \) biprocessor separation tasks and \( 5n-1 \) single-processor separation tasks; there processing times and processing requirements are defined in Table 1. Here we define

\[
\begin{align*}
p_B &= (n+1)b, \\
p_y &= (n+1)(b+p_B), \\
p_z &= (n+1)(b+p_B+p_y), \\
p_C &= (n+1)(b+p_B+p_y+p_z), \\
p_A &= (n+1)(b+p_B+p_y+p_z+p_C).
\end{align*}
\]
Note that each processor has a processing load equal to
\[
\gamma = n (p_A + p_B + p_C + p_y + p_z + b) - p_z,
\]
which implies that \( \gamma \) is a lower bound on the makespan of any schedule. We will show that 3-Partition has an affirmative answer if and only if there exists a schedule with makespan at most \( \gamma \) for the corresponding instance of \( P_{3| fix_j} | C_{\text{max}} \).

If 3-Partition has an affirmative answer, then a schedule with makespan \( C_{\text{max}} \leq \gamma \) exists, as is illustrated in Figure 4.

- The sum \( \sum_{j \in TP_j} \) is a multiple of \( b \), since \( p_A, p_B, p_C, p_y, \) and \( p_z \) are multiples of \( b \),
- \( \sum_{j \in TP_j} = k_4 b \), since all other terms are multiples of \( (n+1)b \),
- \( k_1 = k_5 \), since \( p_A > n(p_C + p_y + p_B + b) \),
- \( k_2 = k_7 + k_8 \), since \( p_C > n(p_z + p_B + b) \),
- \( k_3 = k_7 \), since \( p_z > n(p_B + b) \),
- \( k_4 = k_7 + k_8 \), since \( p_y > n(p_B + b) \), and
- \( k_4 = k_6 \), since \( \sum_{j \in TP_j} = k_4 b \).

It follows that
\[
k_1 = k_5, \quad k_2 = k_4 = k_6 = k_7 + k_8, \quad k_3 = k_7, \quad k_4 b = \sum_{j \in TP_j}.
\] (3)

Analogous computations lead to similar relations that should hold at the start of a task of type \( B \) and \( C \), respectively.

We will make extensive use of these relations in our analysis of the form that a schedule with makespan \( \gamma \) should have. Using an interchange argument, we see that there exists an optimal schedule in which a biprocessor task starts at time 0. We analyze the case that the first biprocessor task is of type \( B \) and that the next biprocessor task of another type is of type \( A \); this case will be denoted as case \( BA \).

Hence, we have that no tasks of type \( A \) and \( C \) and at least one task of type \( B \) have been executed at the start of the first task of type \( A \): \( k_1 = k_2 = k_3 = 0 \) and \( k_5 \geq 1 \). Expression (3), however, decrees that \( k_2 = k_5 \), which yields a contradiction. Therefore, case \( BA \) cannot occur. A continued application of this argument shows that any schedule with makespan \( \gamma \) should have the form as displayed in Figure 4, or its mirror image. A schedule with this structure determines \( n \) separate periods of length \( b \) on
processor $M_3$, in which the remaining single-processor tasks have to be scheduled. These tasks correspond to the $3n$ elements of 3-Partition. We conclude that, if a schedule of length $\gamma$ exists, then a solution to 3-Partition is obtained by taking the partition of $N$ as defined by the schedule. We conclude that $P^3 | \text{fix} | C_{\text{max}}$ is NP-hard in the strong sense. □

2.3. Unit execution times, release dates, and precedence constraints

In this section, we show that the $P_m | \text{fix} | P_j=1 | C_{\text{max}}$ problem is solvable in polynomial time by providing an integer linear programming formulation with a fixed number of variables; a problem that allows such a formulation is solvable in polynomial time [H.W. Lenstra, Jr., 1983]. A similar approach is given by Blazewicz, Drabowski and Weglarz [1986].

Consider an arbitrary instance of the problem. There are at most $M = 2^m - 1$ tasks of a different type; let these types be numbered $1, \ldots, M$. We can denote the instance by a vector $b = (b_1, \ldots, b_M)$ in which component $b_j$ indicates the number of tasks of type $j$. A collection of tasks is called compatible if all these tasks can be executed in parallel; hence, a compatible collection of tasks contains at most one task of each type. A compatible collection is denoted by a $(0,1)$-vector $c$ of length $M$ with $c_j = 1$ if the collection contains a task of type $j$ and zero otherwise. There are at most $K = 2^M - 1$ different compatible collections; this number is fixed, as $M$ is fixed. Let the collections be numbered $1, \ldots, K$; let the vectors indicating the collections be denoted by $c_1, \ldots, c_K$. The problem of finding a schedule of minimal length is then equivalent to the problem of finding a decomposition of this instance into a minimum number of compatible collections. Formally, we wish to minimize $\sum_{j=1}^{K} x_j$ subject to $\sum_{j=1}^{K} c_j x_j = b$, $x_j$ integer and nonnegative. As the number of variables in this integer linear programming formulation is fixed, we have proven the following theorem.

Theorem 4. The $P_m | \text{fix} | P_j=1 | C_{\text{max}}$ problem is solvable in polynomial time. □

If the number of processors is specified as part of the problem type, implying that this number is no longer fixed, then things get worse from a complexity point of view. This is stated in the following theorem.

Theorem 5. The $P | \text{fix} | P_j=1 | C_{\text{max}}$ problem is NP-hard in the strong sense.

Proof. The proof is based upon a reduction from the strongly NP-complete problem Graph 3-Colorability. A similar approach is used by Blazewicz, Lenstra, and Rinnooy Kan [1983].

Graph 3-Colorability

Given a graph $G = (V, E)$, does there exist a 3-coloring, that is, a function $f : V \rightarrow \{1, 2, 3\}$ such that $f(u) \neq f(v)$ whenever $(u,v) \in E$?

Given an arbitrary instance $G = (V, E)$ of Graph 3-Colorability, we construct the following instance of $P | \text{fix} | P_j=1 | C_{\text{max}}$. There are $|V|$ tasks $J_1, \ldots, J_{|V|}$ and $|E|$ processors $M_1, \ldots, M_{|E|}$. A task $J_u$ has to be processed by $M_e$ if $u \in e$. We claim that there exists a 3-coloring for $G$ if and only if there exists a schedule of length at most 3. Suppose that a 3-coloring of $G$ exists. Since no two nodes $u$ and $v$ with the same color are adjacent, the corresponding tasks $J_u$ and $J_v$ require different processors. Hence, all tasks that correspond to identically colored nodes can be executed in parallel. This
generates a schedule with length no more than 3. Conversely, in a schedule with length at most 3 we have that the nodes corresponding to tasks scheduled in time period $t$ ($t = 1, 2, 3$) are independent; therefore, these nodes can be given the same color. This leads to a 3-coloring of $G$. Thus, $P |\text{fix}_j, p_j = 1 | C_{\text{max}}$ is NP-hard in the strong sense. □

**Corollary 1.** For $P |\text{fix}_j, p_j = 1 | C_{\text{max}}$, there exists no polynomial approximation algorithm with performance ratio smaller than $4/3$, unless $P=NP$. □

The introduction of precedence constraints leaves little hope of finding polynomial-time optimization algorithms. Even the two-processor problem with unit execution times and the simplest possible precedence relation structure, a collection of vertex-disjoint chains, is already NP-hard in the strong sense.

**Theorem 6.** The $P_{2|\text{chain}, \text{fix}_j, p_j = 1 | C_{\text{max}}}$ problem is NP-hard in the strong sense.

**Proof.** The proof is based upon a reduction from 3-Partition and follows an approach of Blazewicz, Lenstra, and Rinnooy Kan [1983]. Given an arbitrary instance of 3-Partition, we construct the following instance of $P_{2|\text{chain}, \text{fix}_j, p_j = 1 | C_{\text{max}}}$. Each element $a_j$ corresponds to a chain $K_j$ of $2a_j$ tasks; the first part consists of $a_j$ tasks that have to be executed by $M_1$ and the second part also consists of $a_j$ tasks that have to be executed by $M_2$. In addition, there is a chain $L$ of $2nb$ tasks; groups of $b$ tasks have to be alternately executed by $M_2$ and $M_1$.

Suppose that there exists a partition of $N$ into $N_1, \ldots, N_n$ that yields an affirmative answer to 3-Partition. A feasible schedule with makespan no more than $2nb$ is then obtained as follows. The chain $L$ is scheduled according to its requirements; the execution of $L$ is completed at time $2nb$. Now $M_1$ and $M_2$ are idle in the intervals $[2(i-1)b, (2i-1)b]$ and $[(2i-1)b, 2ib]$ ($i = 1, \ldots, n$), respectively. For each $i \in \{1, \ldots, n\}$ it is now possible to schedule the three chains corresponding to the elements of $N_i$ in $[2(i-1)b, (2i-1)b]$ and $[(2i-1)b, 2ib]$.

Conversely, suppose that there exists a feasible schedule with makespan no more than $2nb$. It is clear that this schedule contains no idle time. Let $N_i$ be the index set of the chains $K_j$ that are completed in the interval $[(2i-1)b, 2ib]$. It is impossible that $\sum_{j \in N} a_j > b$ due to the definition of $N_1$. The case $\sum_{j \in N} a_j < b$ cannot occur either, since this would lead to idle time in $[b, 2b]$. Therefore, we must have that $\sum_{j \in N} a_j = b$. Through a repetition of this argument, it can be easily proven that $N_1, \ldots, N_n$ constitutes a solution to 3-Partition. □

The introduction of release dates has a similar inconvenient effect on the computational complexity.

**Theorem 7.** The $P_{2|\text{fix}_j, r_j | C_{\text{max}}}$ problem is NP-hard in the strong sense.

**Proof.** The proof is again based upon a reduction from 3-Partition. Given an arbitrary instance of 3-Partition, we construct the following instance of $P_{2|\text{fix}_j, r_j | C_{\text{max}}}$. For each element $a_j$, we define a task $J_j$ with $p_j = a_j$ and $r_j = 0$ that has to be executed by $M_1$. Furthermore, there are $n$ tasks $K_j$ with processing time $b$ and release date $r_j = (j-1)(b+\varepsilon)$, for $j = 1, \ldots, n$ and $\varepsilon$ sufficiently small; these tasks have to be executed by $M_2$. Finally, there are $n-1$ biprocessor tasks $L_j$ with processing time $\varepsilon$ and release date $r_j = jb + (j-1)\varepsilon$, for $l = 1, \ldots, n-1$. It is easy to see that 3-Partition has an affirmative
answer if and only if there exists a feasible schedule for \( P2 | \text{fix}_j, r_j | C_{\text{max}} \) with \( C_{\text{max}} \leq nb + (n-1)e. \) 

Consider the case \( Pm | \text{fix}_j, r_j, p_j = 1 | C_{\text{max}} \) where the number \( s \) of distinct release dates is fixed. Analogously to our analysis of \( Pm | \text{fix}_j, p_j = 1 | C_{\text{max}} \), we can transform any instance of \( Pm | \text{fix}_j, r_j, p_j = 1 | C_{\text{max}} \) into an integer linear programming problem with a fixed number of variables. We have proven the following theorem.

**Theorem 8.** The \( Pm | \text{fix}_j, r_j, p_j = 1 | C_{\text{max}} \) problem with a fixed number of distinct release dates is solvable in polynomial time. □

3. Sum of completion times
In this section, we investigate the computational complexity of our type of scheduling problems when we wish to minimize total completion time. Our main result is establishing NP-hardness in the ordinary sense for \( P2 | \text{fix}_j | \Sigma C_j \). The question whether this problem is solvable in pseudopolynomial time or NP-hard in the strong sense still has to be resolved. The weighted version, however, is NP-hard in the strong sense. We start with an easy observation. Given an instance, let the maximal processing time be denoted by \( p_{\text{max}} = \max_j p_j \).

**Proposition 1.** There is an optimal schedule for \( P | \text{fix}_j | \Sigma C_j \) in which the tasks that require all processors for execution during \( p_{\text{max}} \) time are scheduled last, if they exist. □

**Proof.** Consider a schedule \( \sigma' \) for \( P | \text{fix}_j | \Sigma C_j \) in which the task \( J \) that needs all processors for execution during time \( p_{\text{max}} \) is not scheduled last. The interchange illustrated in Figure 5 generates a schedule \( \sigma^* \) with \( \Sigma C_j(\sigma^*) \leq \Sigma C_j(\sigma) + p(\sigma) - p_{\text{max}} \leq \Sigma C_j(\sigma) \), where \( p(\sigma) = \sum_{j \in B} p_j \).

**Figure 5.** The interchange.

3.1. NP-hardness for the 2-processor problem.

**Theorem 9.** The \( P2 | \text{fix}_j | \Sigma C_j \) problem is NP-hard.

**Proof.** Our proof is based upon a reduction from the NP-complete problem Even-Odd Partition.

**Even-Odd Partition**
Given a multiset of \( 2n \) positive integers \( A = \{a_1, \ldots, a_{2n}\} \) such that \( a_i < a_{i+1} \) (\( i = 1, \ldots, 2n-1 \)), is there a partition of \( N \) into two disjoint subsets \( A_1 \) and \( A_2 \) with equal sum \( b = \sum_{i=1}^{2n} a_i / 2 \) and such that \( A_1 \) contains exactly one of \( \{a_{2i-1}, a_{2i}\} \), for each \( i = 1, \ldots, n \)?

Given an instance of Even-Odd Partition, define \( p = (n^2+1)b, \) \( q = n^2(n^2+1)(n+1)p, \) and \( r = \sum_{j=1}^{n} (n+j-1)(a_{2j-1}+a_{2j}) + n^2(n+1)b. \) We construct the following instance of \( P2 | \text{fix}_j | \Sigma C_j \). Each
element \( a_j \) corresponds to a partition task \( J_j \) with processing time \( p_j = nb + a_j \) that has to be executed by \( M_1 \). In addition, we define \( n^2 + 3 \) extra tasks. There are \( n^2 \) identical tasks \( Q_i \) (\( i = 1, \ldots, n^2 \)) with processing time \( 2p(n+1) \) that have to be executed by \( M_2 \), a task \( K \) with processing time \( p \) that has to be executed by \( M_2 \), a biprocessor task \( L \) with processing time \( p \), and a task \( P \) with processing time \( 2p(n+1) \) that has to be executed by \( M_1 \). We will show that Even-Odd Partition is answered affirmatively if and only if there exists a schedule for the corresponding instance of \( P|fixj|\Sigma C_j \) with total completion time no more than the threshold

\[ y = (2n^2 + 4n + 8)p + q + r. \]

Suppose that there exist subsets \( A_1 \) and \( A_2 \) that lead to an affirmative answer to Even-Odd Partition. Then there exists a schedule \( \sigma^* \) with total completion time no more than \( y \), as is illustrated in Figure 6: the completion times of the extra tasks add up to \( (2n^2 + 2n + 8)p + q \), the sum of the completion times of the partition tasks is equal to \( 2np + r \).

\[
\begin{array}{cccccc}
A_1 & L & A_2 & P & Q_1 & Q_2 \\
K & & & & \\
0 & p & 2p & 3p & (2n+4)p & \\
\end{array}
\]

Figure 6. The schedule \( \sigma^* \) with partition sets \( A_1 \) and \( A_2 \).

Conversely, suppose that there exists a schedule \( \sigma \) with total completion time no more than \( y \). We first show that the extra tasks in \( \sigma \) must be scheduled according to the pattern of Figure 6.

A straightforward computation shows that task \( P \) and the \( Q \)-tasks must be completed after all other tasks in \( \sigma \). Suppose that task \( L \) precedes task \( K \), and that \( m \) partition tasks are completed before \( L \) starts. Note that \( m \leq n \); otherwise, task \( K \) could be scheduled parallel to the \( m \) partition tasks, without increasing the completion time of any other job. If we compare this schedule with \( \sigma^* \), then task \( L \) turns out to be the only task with smaller completion time; this gain is more than offset by the increase of completion time of task \( K \). Hence, in order to satisfy the threshold, the extra jobs must be scheduled according to the pattern of Figure 6.

We now show that, if \( \Sigma C_j (\sigma) \leq y \), then the partition tasks must constitute an affirmative answer to Even-Odd Partition. First, suppose that the partition tasks before \( L \) in \( \sigma \) have total processing time smaller than \( p \), implying that at most \( n \) partition tasks are scheduled before \( L \). Then the total completion time of the partition jobs amounts to at least \( r + 2np \), the total completion time of the \( Q \)-tasks, task \( K \), and task \( L \) is equal to the total completion time of these tasks in \( \sigma^* \), and the completion time of task \( P \) is greater than \( 3p + (2n+2)p \), implying that the threshold is exceeded. Hence, the total processing time of the partition tasks before task \( L \) amounts to at least \( p \).

Now suppose that \( m \) partition tasks with total processing time \( p + x \) precede task \( L \). Comparing \( \sigma \) with \( \sigma^* \) shows that the total completion time of the extra jobs in \( \sigma \) is \( x(n^2 + 1) \) greater and that the difference in total completion time of the partition tasks is no more than \( 2p(n-m) + x(2n-m) \) in favor of \( \sigma \). If \( m = n \), then the difference in total completion time between \( \sigma^* \) and \( \sigma \) is at least equal to \( x(n^2 + 1) - xn \) in favor of \( \sigma^* \); \( x > 0 \) then clearly implies that the threshold will be exceeded. In case \( m > n \), we wish to show that \( x(n^2 + 1) > 2p(n-m) + x(2n-m) \), which boils down to showing that \( x(n^2 + 1 - 2n + m) > 2p(n-m) \). As the left-hand-side of the inequality is positive and the right-hand-
side negative, we have that the case \( m > n \) leads to an excess of the threshold. Hence, exactly \( n \) partition tasks with total processing time equal to \( p \) must precede task \( L \) in \( \sigma \). The total completion time of the partition tasks is equal to \( 2np + n(p_{[1]} + p_{[2]} + \cdots + p_{[n-1]} + p_{[n]}) \), where \( p_{[i]} \) and \( p_{[i+1]} \) denote the processing time of the \( i \)th partition task before \( L \) and after \( L \), respectively. It is easy to see that the threshold can only be met if \( \{ p_{[i]} , p_{[i+1]} \} = \{ p_{[1]} , p_{[2]} \} \), for \( i = 1, \ldots , n \). Define \( A_1 \) and \( A_2 \) as the set of partition tasks before \( L \) and after \( L \), respectively. As the total processing time of the tasks in \( A_1 \) amounts to \( n^2b + \sum_{i=1}^{n} a_i = (n^2+1)b \), we have that the corresponding subset of partition elements has sum equal to \( b \). Furthermore, \( A_1 \) contains exactly one element from every pair \( \{ a_{2i-1} , a_{2i} \} \); hence, the subsets \( A_1 \) and \( A_2 \) lead an affirmative answer to Even-Odd Partition. 

**Theorem 10.** The \( P_2 | \text{fix}_j | \sum w_j c_j \) problem is NP-hard in the strong sense.

**Proof.** The proof is based upon a reduction from 3-Partition. Given an arbitrary instance of 3-Partition, we construct the following instance of \( P_2 | \text{fix}_j | \sum w_j c_j \). Each element \( a_j \) corresponds to a task \( J_j \) with processing time \( a_j \) and unit weight that has to be executed by \( M_1 \). In addition, there are \( n \) tasks \( K_j \) with processing time \( b \) and weight \( 2(j+\alpha-1)\beta \) that have to be executed by \( M_2 \), and \( n_L \) biprocessor tasks \( L_j \) with processing time \( b \) and weight \( 2(j-1)\beta \), where \( \alpha = 3n(2n-1) \), \( \beta = \alpha b \), and \( n_L = \alpha + n - 1 \).

Suppose that there exists a partition of \( N \) into \( N_1 , \ldots , N_n \) that yields an affirmative answer to 3-Partition. A feasible schedule with sum of weighted completion times no more than \( y = \beta + \sum_{k=1}^{n} w_k (2(n-k)+1) + \sum_{i=1}^{n} w_i (2n+\alpha-1) + \sum_{i=\alpha+1}^{n} w_i (2n-2(\alpha-i)) \) is then obtained by scheduling the tasks as illustrated in Figure 7.

Conversely, suppose that there exists a schedule \( \sigma \) with sum of weighted completion times no more than \( y \). Straightforward computations show that the \( K \)-tasks and the \( L \)-tasks have to be scheduled as indicated in Figure 7 and that the tasks \( J_j \) have to be scheduled in the time slots parallel to the \( K \)-tasks. Let \( N_j \) denote the set of \( J \)-tasks that are scheduled parallel to \( K_j \); the sets \( N_1 , \ldots , N_n \) constitute a solution to 3-Partition. 

**3.2. Strong NP-hardness for the general 3-processor problem**

**Theorem 11.** The \( P_3 | \text{fix}_j | \sum c_j \) problem is NP-hard in the strong sense.

**Proof.** The proof is based upon a reduction from the decision version of the \( P_3 | \text{fix}_j | C_{\max} \) problem, which was shown to be NP-complete in Section 2.2. The decision version of \( P_3 | \text{fix}_j | C_{\max} \) is defined as the following question: given an instance of \( P_3 | \text{fix}_j | C_{\max} \) and a threshold \( b \), does there exist a schedule \( \sigma \) with makespan no more than \( b \)?

Given an arbitrary instance of \( P_3 | \text{fix}_j | C_{\max} \) and a threshold \( b \), we construct the decision instance
of $P_3|\text{fix}_j|\sum C_j$ by adding $nb+1$ identical triprocessor tasks $K_j$ with processing time $p_{\text{max}}$. The corresponding threshold is equal to $y=nb+\sum_{k=n}^{n+1}(b+kp_{\text{max}})$.

Application of Proposition 1 shows that there is an optimal schedule with the $K$-tasks executed last. The number of $K$-tasks is such that the threshold will be exceeded if the first $K$-task starts later than $b$. Hence, the decision variant of $P_3|\text{fix}_j|\sum C_j$ has an affirmative answer if and only if the decision variant of $P_3|\text{fix}_j|C_{\text{max}}$ has an affirmative answer.

Note that, the number of tasks needed in our reduction is pseudopolynomially bounded. We conclude that $P_3|\text{fix}_j|\sum C_j$ is NP-hard in the strong sense.

3.2. Unit execution times and precedence constraints

In this section, we address the complexity of minimizing total completion time in case of unit processing times. We show that $P|\text{fix}_j,p_j=1|\sum C_j$ is NP-hard in the strong sense; the complexity of this problem with a fixed number of processors is still open.

Theorem 12. The $P|\text{fix}_j,p_j=1|\sum C_j$ problem is NP-hard in the strong sense.

Proof. The proof of this theorem is based upon a reduction from $P|\text{fix}_j,p_j=1|C_{\text{max}}$; it proceeds along the same lines as the proof of the previous theorem. Given an instance of $P|\text{fix}_j,p_j=1|C_{\text{max}}$, we add $w$ tasks that require all processors for execution; application of Proposition 1 shows that these tasks can be assumed to be executed after all other tasks. By choosing $w$ suitably large, we obtain the situation that the threshold of $P|\text{fix}_j,p_j=1|\sum C_j$ is exceeded if and only if the threshold of $P|\text{fix}_j,p_j=1|C_{\text{max}}$ is exceeded. As the decision variant of $P|\text{fix}_j,p_j=1|C_{\text{max}}$ is NP-complete in the strong sense and as $w$ is polynomially bounded, we conclude that $P|\text{fix}_j,p_j=1|\sum C_j$ is NP-hard in the strong sense.

As could be expected, the addition of precedence constraints does not have a positive effect on the computational complexity. We show that even the mildest non-trivial problem of this type, with two processors and chain-type precedence constraints, is NP-hard in the strong sense.

Theorem 13. The $P_2|\text{chain},\text{fix}_j,p_j=1|\sum C_j$ problem is NP-hard in the strong sense.

Proof. The proof is based upon the same reduction as used in the proof of Theorem 6, only the threshold differs. As the number of tasks is equal to $2nb$, and as each task has unit processing time, an obvious lower bound on the total completion time is equal to $y=2nb(2nb+1)$; this bound can only be attained by a schedule without idle time in which both processors execute $nb$ tasks. Hence, there exists a schedule with total completion time no more than $y$ if and only if there exists a schedule with makespan no more than $b$. We conclude that $P_2|\text{chain},\text{fix}_j,p_j=1|\sum C_j$ is NP-hard in the strong sense.

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References


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