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An Exact Exponential Branch-and-Merge Algorithm for the Single Machine Total Tardiness Problem

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Abstract

This paper proposes an exact exponential algorithm for the single machine total tardiness problem. It exploits the structure of a basic branch-and-reduce framework based on the well known Lawler's decomposition property that solves the problem with worst-case complexity in time $\mathcal{O}^*(3^n)$ and polynomial space. The proposed algorithm, called branch-and-merge, is an improvement of the branch-and-reduce technique with the embedding of a node merging operation. Its time complexity converges to $\mathcal{O}^*(2^n)$ keeping the space complexity polynomial. This improves upon the best-known complexity result for this problem provided by dynamic programming across the subsets with $\mathcal{O}^*(2^n)$ worst-case time and space complexity. The branch-and-merge technique is likely to be generalized to other sequencing problems with similar decomposition properties.

Keywords: Exact exponential algorithm, Single machine total tardiness, Branch and merge

1. Introduction

Since the beginning of this century, the design of exact exponential algorithms for NP-hard problems has been attracting more and more researchers. Although the research in this area dates back to early 60s, the discovery of new design and analysis techniques has led to many new developments. The main motivation behind the rise of interest in this area is the study of the intrinsic complexity of NP-hard problems. In fact, since the dawn of computer science, some of these problems appeared to be solvable with a lower exponential complexity than others belonging to the same complexity class. For a survey on the most effective techniques in designing exact exponential algorithms, readers are kindly referred to Woeginger's paper [24] and to the book by Fomin and Kratsch [6].

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In spite of the growing interest on exact exponential algorithms, few results are yet known on scheduling problems, see the survey of Lenté et al. [12]. Lenté et al. [11] introduced the so-called class of multiple constraint problems and showed that all problems fitting into that class could be tackled by means of the Sort & Search technique. Further, they showed that several known scheduling problems are part of that class. However, all these problems required assignment decisions only and none of them required the solution of a sequencing problem.

This paper focuses on a pure sequencing problem, the single machine total tardiness problem, denoted by $1||\sum T_j$. In this problem, a job set $N = \{1, 2, \dots, n\}$ of n jobs must be scheduled on a single machine. For each job j , a processing time p_j and a due date d_j are defined. The problem asks for arranging the job set into a sequence S so as to minimize $T(N, S) = \sum_{j=1}^n T_j = \sum_{j=1}^n \max\{C_j - d_j, 0\}$, where C_j is the completion time of job j . The $1||\sum T_j$ problem is NP-hard in the ordinary sense as shown by Du and Leung [3]. It has been extensively studied in the literature and many exact procedures [2, 10, 15, 20] have been proposed. The current state-of-the-art exact method of Szwarc et al. [20] dates back to 2001 and solves to optimality instances with up to 500 jobs. The complexity of this algorithm is analyzed by Shang et al. [18]. All these procedures are search tree approaches, but dynamic programming algorithms were also considered. On the one hand, a pseudo-polynomial dynamic programming algorithm was proposed by Lawler [10] running with complexity $\mathcal{O}(n^4 \sum p_i)$. On the other hand, the standard technique of doing dynamic programming across the subsets (see, for instance, Fomin and Kratsch [6]) applies and runs with complexity $\mathcal{O}(n^2 2^n)$ both in time and in space. Latest theoretical developments for the problem, including both exact and heuristic approaches can be found in the recent survey of Koulamas [9].

In the rest of the paper, the $\mathcal{O}^*(\cdot)$ notation [24], commonly used in the context of exact exponential algorithms, is used to measure worst-case complexities. Let $T(\cdot)$ be a super-polynomial and $p(\cdot)$ be a polynomial, both on integers. In what follows, for an integer n , we express running-time bounds of the form $\mathcal{O}(p(n) \cdot T(n))$ as $\mathcal{O}^*(T(n))$. We denote by $T(n)$ the time required in the worst-case to exactly solve the considered combinatorial optimization problem of size n , i.e., the number of jobs in our context. As an example, the complexity of dynamic programming across the subsets for the total tardiness problem can be expressed as $\mathcal{O}^*(2^n)$. By the way, the number of jobs n may not be the only possible measure of the instance size. Other parameters can be chosen, based on which different complexity analysis can be conducted. For scheduling problems, some results can be found in Mnich and Wiese [14], Mnich and van Bevern [13] and Hermelin et al. [8].

To the authors' knowledge, there is no available exact algorithm for this problem running in $\mathcal{O}^*(c^n)$ (c being a constant) time and polynomial space. Admittedly, one could possibly apply a divide-and-conquer approach [1, 7]. This would lead to an $\mathcal{O}^*(4^n)$ complexity in time requiring polynomial space. The aim of this work is to present an improved exact algorithm exploiting known decomposition properties of the problem. Different versions of the proposed approach are described in Section 2. A final version making use of a new technique called branch-and-merge that avoids the solution of several equivalent subinstances in the branching tree is presented in Section 3. We provide the algorithm for the worst-case

scenario for the simplicity of presentation and we prove that its complexity tends to $\mathcal{O}^*(2^n)$ in time and polynomial in space. Finally, Section 4 concludes the paper with final remarks.

2. A Branch-and-Reduce approach

We recall here some basic properties of the total tardiness problem and introduces the notation used along the paper. Given the job set $N = \{1, 2, \dots, n\}$, let $(1, 2, \dots, n)$ be a LPT (Longest Processing Time first) sequence, where $i < j$ whenever $p_i > p_j$ (or $p_i = p_j$ and $d_i \leq d_j$). Let also $([1], [2], \dots, [n])$ be an EDD (Earliest Due Date first) sequence, where $i < j$ whenever $d_{[i]} < d_{[j]}$ (or $d_{[i]} = d_{[j]}$ and $p_{[i]} \leq p_{[j]}$). As the cost function is a regular performance measure, we know that in an optimal solution, the jobs are processed with no interruption starting from time zero. Let B_j and A_j be the sets of jobs that precede and follow job j in an optimal sequence that is being searched. Correspondingly, $C_j = \sum_{k \in B_j} p_k + p_j$. Similarly, if job j is assigned to position k , we denote by $C_j(k)$ the corresponding completion time and by $B_j(k)$ and $A_j(k)$ the sets of predecessors and successors of j , respectively.

The main known theoretical properties are the following.

Property 1. (*Emmons [4]*) *Consider two jobs i and j with $p_i < p_j$. Then, i precedes j in an optimal schedule if $d_i \leq \max\{d_j, C_j\}$, else j precedes i in an optimal schedule if $d_i + p_i > C_j$.*

Property 2. (*Lawler [10]*) *Let job 1 in LPT order correspond to job $[k]$ in EDD order. Then, job 1 can be set only in positions $h \geq k$ and the jobs preceding and following job 1 are uniquely determined as $B_1(h) = \{[1], [2], \dots, [k-1], [k+1], \dots, [h]\}$ and $A_1(h) = \{[h+1], \dots, [n]\}$.*

Property 3. (*Szward and Mukhopadhyay [21]*) *For any pair of adjacent positions $(i, i+1)$ that can be assigned to job 1, at least one of them can be eliminated.*

In terms of complexity analysis, we recall (see, for instance, Eppstein [5]) that, if it is possible to bound above $T(n)$ by a recurrence expression of the type $T(n) \leq \sum_{i=1}^h T(n-r_i) + \mathcal{O}(p(n))$, then we have $\sum_{i=1}^h T(n-r_i) + \mathcal{O}(p(n)) = \mathcal{O}^*(\alpha(r_1, \dots, r_h)^n)$ where $\alpha(r_1, \dots, r_h)$ is the largest root of the function $f(x) = 1 - \sum_{i=1}^h x^{-r_i}$.

A basic branch-and-reduce algorithm TTBR1 (Total Tardiness Branch-and-Reduce version 1) can be designed by exploiting Property 2, which allows to decompose the problem instance into two smaller subinstances when the position of the longest job l is given. The basic idea is to iteratively branch by assigning job l to every eligible branching position and correspondingly decompose the instance. Each time job l is assigned to a certain position i , two different subinstances are generated, corresponding to schedule the jobs before l (inducing subinstance $B_l(i)$) or after l (inducing subinstance $A_l(i)$), respectively. The algorithm operates by applying to any given job set S starting at time t function $TTBR1(S, t)$ that computes the corresponding optimal solution. With this notation, the original instance is indicated by $N = \{1, \dots, n\}$ and the optimal solution is reached when function $TTBR1(N, 0)$ is computed.

The algorithm proceeds by solving the subinstances along the branching tree according to a depth-first strategy and runs until all the leaves of the search tree have been reached. Finally, it provides the best solution found as an output. Algorithm 1 summarizes the structure of this approach, while Proposition 1 states its worst-case complexity.

Algorithm 1 Total Tardiness Branch-and-Reduce version 1 (TTBR1)

Input: $S = \{1, \dots, n\}$, the set of jobs to be scheduled; t , the starting time of jobs in S .

- 1: **function** TTBR1(S, t)
- 2: seqOpt \leftarrow the EDD sequence of jobs
- 3: $\ell \leftarrow$ the longest job in N
- 4: **for** $i = 1$ to n **do**
- 5: Branch by assigning job ℓ to position i
- 6: seqLeft \leftarrow TTBR1($B_\ell(i), t$)
- 7: seqRight \leftarrow TTBR1($A_\ell(i), t + \sum_{k \in B_\ell(i)} p_k + p_\ell$)
- 8: seqCurrent \leftarrow concatenation of seqLeft, ℓ and seqRight
- 9: seqOpt \leftarrow best solution between seqOpt and seqCurrent
- 10: **end for**
- 11: **return** seqOpt
- 12: **end function**

Proposition 1. *Algorithm TTBR1 runs in $\mathcal{O}^*(3^n)$ time and polynomial space in the worst case.*

Proof. Whenever the longest job 1 is assigned to the first and the last position of the sequence, two subinstances of size $(n - 1)$ are generated. For each $2 \leq i \leq n - 1$, two subinstances with size $(i - 1)$ and $(n - i)$ are generated. Hence, the total number of generated subinstances is $2n - 2$ and the time cost related to computing the best solution of size n starting from these subinstances is $\mathcal{O}(p(n))$. This induces the following recurrence for the running time $T(n)$ required by TTBR1:

$$T(n) = 2T(n - 1) + 2T(n - 2) + \dots + 2T(2) + 2T(1) + \mathcal{O}(p(n)) \quad (1)$$

By replacing n with $(n - 1)$, the following expression is derived:

$$T(n - 1) = 2T(n - 2) + \dots + 2T(2) + 2T(1) + \mathcal{O}(p(n - 1)) \quad (2)$$

Expression 2 can be used to simplify the right hand side of expression 1 leading to:

$$T(n) = 3T(n - 1) + \mathcal{O}(p(n)) \quad (3)$$

that induces as complexity $\mathcal{O}^*(3^n)$. The space requirement is polynomial since the branching tree is explored according to a depth-first strategy. \square

An improved version of the algorithm is defined by taking into account Property 3, which states that for each pair of adjacent positions $(i, i + 1)$, at least one of them can be discarded. The worst case occurs when the largest possible subinstances are kept, since otherwise the complexity is easy to be proved to be smaller. This corresponds to solving instances with size $n - 1, n - 3, n - 5, \dots$, that arise by branching on positions i and $n - i + 1$ with i odd. The resulting algorithm is referred to as TTBR2 (Total Tardiness Branch and Reduce version 2). Its structure is equal to the one of TTBR1 depicted in Algorithm 1, but lines 5-9 are executed only when l can be set on position i according to Property 3. The complexity of the algorithm is discussed in Proposition 2.

Proposition 2. *Algorithm TTBR2 runs in $\mathcal{O}^*((1 + \sqrt{2})^n) = \mathcal{O}^*(2.4143^n)$ time and polynomial space in the worst case.*

Proof. The proof is close to that of Proposition 1. We refer to instances where n is odd, but the analysis for n even is substantially the same. The algorithm induces a recursion of the type:

$$T(n) = 2T(n - 1) + 2T(n - 3) + \dots + 2T(4) + 2T(2) + \mathcal{O}(p(n)) \quad (4)$$

as the worst case occurs when we keep the branches that induce the largest possible subinstances. Analogously to Proposition 1, we replace n with $n - 2$ in the previous recurrence and we obtain:

$$T(n - 2) = 2T(n - 3) + 2T(n - 5) + \dots + 2T(4) + 2T(2) + \mathcal{O}(p(n - 2)) \quad (5)$$

Again, we plug the latter expression into the former one and obtain the recurrence:

$$T(n) = 2T(n - 1) + T(n - 2) + \mathcal{O}(p(n)) \quad (6)$$

that induces as complexity $\mathcal{O}^*((1 + \sqrt{2})^n) = \mathcal{O}^*(2.4143^n)$. The space complexity is still polynomial. \square

3. A Branch-and-Merge Algorithm

In this section, we describe how to get an algorithm running with complexity arbitrarily close to $\mathcal{O}^*(2^n)$ in time and polynomial space by integrating a node-merging procedure into TTBR1. We recall that in TTBR1 the branching scheme is defined by assigning the longest unscheduled job to each available position and accordingly divide the instance into two subinstances. To facilitate the description of the algorithm, we focus on the scenario where the LPT sequence $(1, \dots, n)$ coincides with the EDD sequence $([1], \dots, [n])$, for convenience we write $LPT = EDD$. We provide the algorithmic details of the node-merging procedure on this scenario to facilitate its understanding. The resulting branch-and-merge algorithm has its time complexity tend to $\mathcal{O}^*(2^n)$. We prove by Lemma 6 that the case where $LPT = EDD$ is the worst-case scenario, hence, it follows that the problem $1||\sum T_i$ can be solved in time

complexity tending to $\mathcal{O}^*(2^n)$. We leave to the reader the generalization of the node-merging procedure to the general case.

Figure 1 shows how an input instance $\{1, \dots, n\}$ is decomposed by the branching scheme of TTBR1. Each node is labelled by the corresponding subinstance P_j (P denotes the input instance). Notice that from now on $P_{j_1, j_2, \dots, j_k}, 1 \leq k \leq n$, denotes the instance (corresponding to a node in the search tree) induced by the branching scheme of TTBR1 when the largest processing time job 1 is in position j_1 , the second largest processing time job 2 is in position j_2 and so on till the k -th largest processing time job k being placed in position j_k .

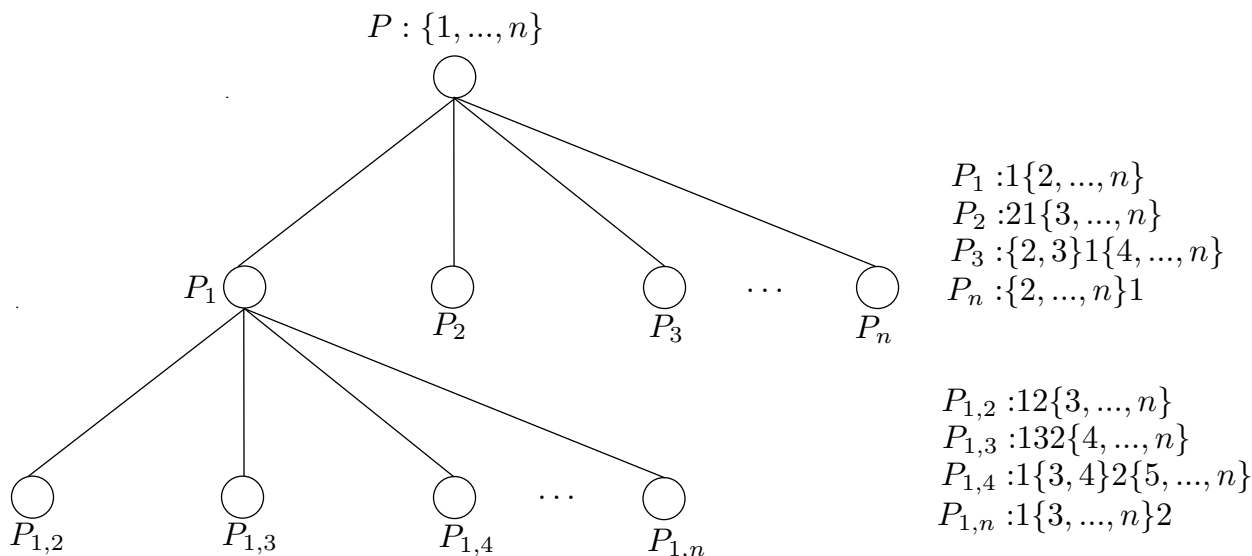


Figure 1: The branching scheme of TTBR1 at the root node

To roughly illustrate the guiding idea of the merging technique introduced in this section, consider Figure 1. Noteworthy, nodes P_2 and $P_{1,2}$ are identical except for the initial subsequence (21 vs 12). This fact implies, in this particular case, that the problem of scheduling job set $\{3, \dots, n\}$ at time $p_1 + p_2$ is solved twice. This kind of redundancy can however be eliminated by merging node P_2 with node $P_{1,2}$ and creating a single node in which the best sequence among 21 and 12 is scheduled at the beginning and the job set $\{3, \dots, n\}$, starting at time $p_1 + p_2$, remains to be branched on. Furthermore, the best subsequence (starting at time $t = 0$) between 21 and 12 can be computed in constant time. Hence, the node created after the merging operation involves a constant time preprocessing step plus the search for the optimal solution of job set $\{3, \dots, n\}$ to be processed starting at time $p_1 + p_2$. We remark that, in the branching scheme of TTBR1, for any constant $k \geq 3$, the branches corresponding to P_i and P_{n-i+1} , with $i = 2, \dots, k$, are decomposed into two subinstances where one subinstance has size $(n - i)$ and the other subinstance has size $(i - 1) \leq k$. Correspondingly, the merging technique presented on instances P_2 and $P_{1,2}$ can be generalized to all branches inducing instances of sizes less than k . Notice that, by means of algorithm TTBR2, any instance of size less than k requires $\mathcal{O}^*(2.4143^k)$ time (that is constant time

when k is fixed). In the remainder of the paper, for any constant $k \leq \frac{n}{2}$, we denote by left-side branches the search tree branches corresponding to instances P_1, \dots, P_k and by right-side branches the ones corresponding to instances P_{n-k+1}, \dots, P_n .

In the following subsections, we show how the node-merging procedure can be systematically performed to improve the time complexity of TTBR1. Basically, two different recurrent structures hold respectively for left-side and right-side branches and allow to generate fewer subinstances at each recursion level. The node-merging mechanism is described by means of two distinct procedures, called `LEFT_MERGE` (applied to left-side branches) and `RIGHT_MERGE` (applied to right-side branches), which are discussed in Sections 3.1 and 3.2, respectively. The final branch-and-merge algorithm is described in Section 3.3 and embeds both procedures in the structure of TTBR1. Notice that a numerical example of the algorithms introduced in the remainder is provided by Shang [17].

3.1. Merging left-side branches

The first part of the section aims at illustrating the merging operations on the root node. The following proposition highlights two properties of instances P_j and $P_{1,j}$ with $2 \leq j \leq k$.

Lemma 1. *For a pair of instances P_j and $P_{1,j}$ with $2 \leq j \leq k$, the following conditions hold:*

1. *The solution of instances P_j and $P_{1,j}$ involves the solution of a common subinstance which consists in scheduling job set $\{j+1, \dots, n\}$ starting at time $t = \sum_{i=1, \dots, j} p_i$.*
2. *Both in P_j and $P_{1,j}$, at most k jobs have to be scheduled before job set $\{j+1, \dots, n\}$.*

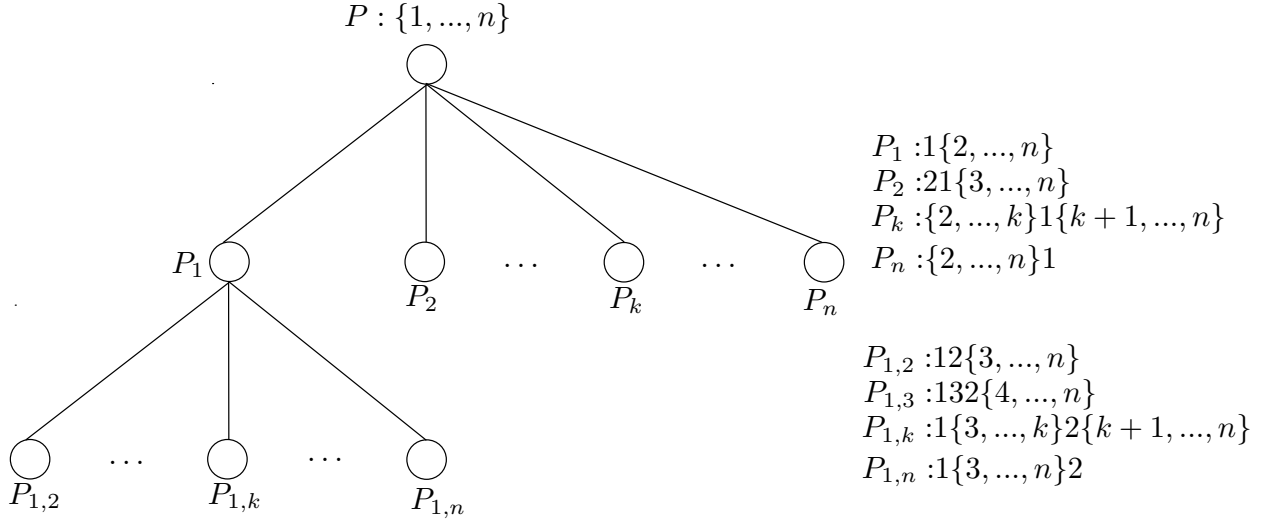
Proof. As instances P_j and $P_{1,j}$ are respectively defined by $\{2, \dots, j\}1\{j+1, \dots, n\}$ and $1\{3, \dots, j\}2\{j+1, \dots, n\}$, the first part of the property is straightforward.

The second part can be simply established by counting the number of jobs to be scheduled before job set $\{j+1, \dots, n\}$ when j is maximal, i.e., when $j = k$. In this case, job set $\{k+1, \dots, n\}$ has $(n-k)$ jobs which implies that k jobs remain to be scheduled before that job set. \square

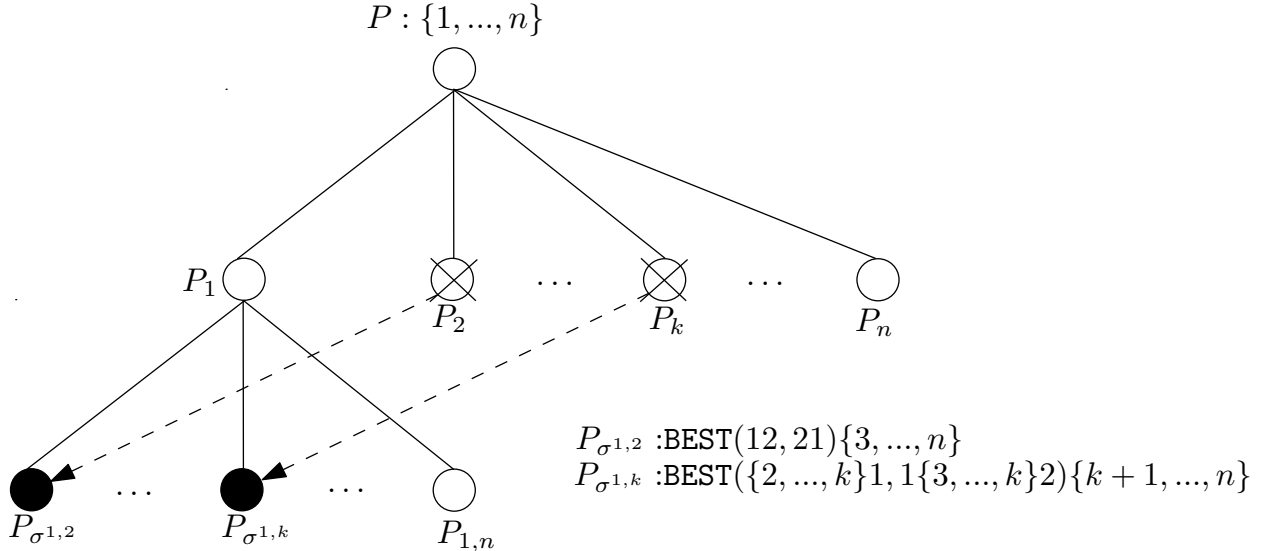
Each pair of instances indicated in Proposition 1 can be merged as soon as they share the same subinstance to be solved. More precisely, $(k-1)$ instances P_j (with $2 \leq j \leq k$) can be merged with the corresponding instances $P_{1,j}$.

Figure 2 illustrates the merging operations performed at the root node on its left-side branches, by showing the branch tree before and after (Figure 2a and Figure 2b) such merging operations. For any given $2 \leq j \leq k$, instances P_j and $P_{1,j}$ share the same subinstance $\{j+1, \dots, n\}$ starting at time $t = \sum_{i=1}^j p_i$. Hence, by merging the left part of both instances which is constituted by job set $\{1, \dots, j\}$ having size $j \leq k$ we can delete node P_j and replace node $P_{1,j}$ in the search tree by the node $P_{\sigma^{1,j}}$ which is defined as follows (Figure 2b):

- $\{j+1, \dots, n\}$ is the set of jobs on which it remains to branch.
- Let $\sigma^{1,j}$ be the sequence of branching positions on which the j longest jobs $1, \dots, j$ are branched, that leads to the best jobs permutation between $\{2, \dots, j\}1$ and $1\{3, \dots, j\}2$.



(a) Left-side branches of P before performing the merging operations



(b) Left-side branches of P after performing the merging operations.

$\text{BEST}(\alpha, \beta)$ returns the better configuration between α and β .

Figure 2: Left-side branches merging at the root node

This involves the solution of two instances of size at most $k-1$ (in $\mathcal{O}^*(2.4143^k)$ time by TTBR2) and the comparison of the total tardiness value of the two sequences obtained.

In the following, we describe how to apply analogous merging operations on any node of the tree. With respect to the root node, the only additional consideration is that the children nodes of an arbitrary node may have already been affected by a previous merging.

In order to define the branching scheme used with the `LEFT_MERGE` procedure, a data structure \mathcal{L}_σ is associated to an instance P_σ . It represents a list of $k-1$ subinstances that

result from a previous merging and are now the first $k - 1$ children nodes of P_σ . When P_σ is created by branching, $\mathcal{L}_\sigma = \emptyset$. When a merging operation sets the first $k - 1$ children nodes of P_σ to $P_{\sigma_1}, \dots, P_{\sigma_{k-1}}$, we set $\mathcal{L}_\sigma = \{P_{\sigma_1}, \dots, P_{\sigma_{k-1}}\}$. As a conclusion, the following branching scheme for an arbitrary node of the tree holds.

Definition 1. *The branching scheme for an arbitrary node P_σ is defined as follows:*

- *If $\mathcal{L}_\sigma = \emptyset$, use the branching scheme of TTBR1;*
- *If $\mathcal{L}_\sigma \neq \emptyset$, extract instances from \mathcal{L}_σ as the first $k - 1$ branches, then branch on the longest job in the available positions from the k -th to the last according to Property 2.*

*This branching scheme, whenever necessary, will be referred to as **improved branching**.*

Before describing how merging operations can be applied on an arbitrary node P_σ , we highlight its structural properties by means of Proposition 3.

Proposition 3. *Let P_σ be an instance to branch on, and σ be the permutation of positions assigned to jobs $1, \dots, |\sigma|$, with σ empty if no positions are assigned. The following properties hold:*

1. $j^* = |\sigma| + 1$ is the job to branch on,
2. j^* can occupy in the branching process, positions $\{\ell_b, \ell_b + 1, \dots, \ell_e\}$, where

$$\ell_b = \begin{cases} |\sigma| + 1 & \text{if } \sigma \text{ is a permutation of } 1, \dots, |\sigma| \text{ or } \sigma \text{ is empty;} \\ \rho_1 + 1 & \text{otherwise} \end{cases}$$

with $\rho_1 = \max\{i : i > 0, \text{ positions } 1, \dots, i \text{ are in } \sigma\}$ and

$$\ell_e = \begin{cases} n & \text{if } \sigma \text{ is a permutation of } 1, \dots, |\sigma| \text{ or } \sigma \text{ is empty;} \\ \rho_2 - 1 & \text{otherwise} \end{cases}$$

with $\rho_2 = \min\{i : i > \rho_1, i \in \sigma\}$

Proof. According to the definition of the notation P_σ , σ is a sequence of positions that are assigned to the longest $|\sigma|$ jobs. Since we always branch on the longest unscheduled job, the first part of the proposition is straightforward. The second part aims at specifying the range of positions that job j^* can occupy. Two cases are considered depending on the content of σ :

- If σ is a permutation of $1, \dots, |\sigma|$, it means that the longest $|\sigma|$ jobs are set on the first $|\sigma|$ positions, which implies that the job j^* should be branched on positions $|\sigma| + 1$ to n .
- If σ is not a permutation of $\{1, \dots, |\sigma|\}$, it means that the longest $|\sigma|$ jobs are not set on consecutive positions. As a result, the current unassigned positions may be split into several ranges. As a consequence of the decomposition property, the longest job j^* should necessarily be branched on the first range of free positions,

that goes from ρ_1 to ρ_2 . Let us consider as an example $P_{1,9,2,8}$, whose structure is $13\{5, \dots, 9\}42\{10, \dots, n\}$ and the job to branch on is 5. In this case, we have: $\sigma = (1, 9, 2, 8)$, $\ell_b = 3$, $\ell_e = 7$. It is easy to verify that 5 can only be branched on positions $\{3, \dots, 7\}$ as a direct result of Property 2.

□

Corollary 1 emphasises the fact that even though a node may contain several ranges of free positions, only the first range is the current focus since we only branch on the longest job in eligible positions.

Corollary 1. *Instance P_σ has the following structure:*

$$\pi\{j^*, \dots, j^* + \ell_e - \ell_b\}\Omega$$

with π the subsequence of jobs on the first $\ell_b - 1$ positions in σ and Ω the remaining subset of jobs to be scheduled after position ℓ_e (some of them can have been already scheduled). The merging procedure is applied on job set $\{j^*, \dots, j^* + \ell_e - \ell_b\}$ starting at time $t_\pi = \sum_{i \in \Pi} p_i$ where Π is the job set of π .

The validity of merging on a general node still holds as indicated in Proposition 4, which extends the result stated in Proposition 1.

Proposition 4. *Let P_σ be an arbitrary instance and let $\pi, j^*, \ell_b, \ell_e, \Omega$ be computed relatively to P_σ according to Corollary 1. If $\mathcal{L}_\sigma = \emptyset$ the j -th child node P_{σ^j} is $P_{\sigma, \ell_b + j - 1}$ for $1 \leq j \leq k$. Otherwise, the j -th child node P_{σ^j} is extracted from \mathcal{L}_σ for $1 \leq j \leq k - 1$, while it is created as $P_{\sigma, \ell_b + k - 1}$ for $j = k$. For any pair of instances P_{σ^j} and $P_{\sigma^1, \ell_b + j - 1}$ with $2 \leq j \leq k$, the following conditions hold:*

1. *Instances P_{σ^j} and $P_{\sigma^1, \ell_b + j - 1}$ with $2 \leq j \leq k$ have the following structure:*

• P_{σ^j} :

$$\left\{ \begin{array}{ll} \pi^j\{j^* + j, \dots, j^* + \ell_e - \ell_b\}\Omega & 1 \leq j \leq k - 1 \text{ and } \mathcal{L}_\sigma \neq \emptyset \\ \pi\{j^* + 1, \dots, j^* + j - 1\}j^*\{j^* + j, \dots, j^* + \ell_e - \ell_b\}\Omega & (1 \leq j \leq k - 1; \mathcal{L}_\sigma = \emptyset) \\ & \text{or } j = k \end{array} \right.$$

• $P_{\sigma^1, \ell_b + j - 1}$:

$$\pi^1\{j^* + 2, \dots, j^* + j - 1\}(j^* + 1)\{j^* + j, \dots, j^* + \ell_e - \ell_b\}\Omega$$

2. *By solving all the instances of size less than k , that consist in scheduling the job set $\{j^* + 1, \dots, j^* + j - 1\}$ between π and j^* and in scheduling $\{j^* + 2, \dots, j^* + j - 1\}$ between π^1 and $j^* + 1$, both P_{σ^j} and $P_{\sigma^1, \ell_b + j - 1}$ consist in scheduling $\{j^* + j, \dots, j^* + \ell_e - \ell_b\}\Omega$ starting at time $t_{\pi^j} = \sum_{i \in \Pi^j} p_i$ where Π^j is the job set of π^j .*

Proof. The first part of the statement follows directly from Definition 1 and simply defines the structure of the children nodes of P_σ . The instance P_{σ^j} is the result of a merging operation with the arbitrary instance P_{σ, ℓ_b+j-1} and it could possibly coincide with P_{σ, ℓ_b+j-1} , for each $j=1, \dots, k-1$. Furthermore, P_{σ^j} is exactly P_{σ, ℓ_b+j-1} for $j=k$. The structure of P_{σ, ℓ_b+j-1} is $\pi\{j^*+1, \dots, j^*+j-1\}j^*\{j^*+j, \dots, j^*+\ell_e-\ell_b\}\Omega$, and the merging operations preserve the job set to schedule after j^* . Thus, we have $\Pi^j = \Pi \cup \{j^*, \dots, j^*+j-1\}$ for each $j=1, \dots, k-1$, and this proves the first statement. Analogously, the structure of P_{σ^1, ℓ_b+j-1} is $\pi^1\{j^*+2, \dots, j^*+j-1\}(j^*+1)\{j^*+j, \dots, j^*+\ell_e-\ell_b\}\Omega$. Once the subinstance before j^*+1 of size less than k is solved, P_{σ^1, ℓ_b+j-1} consists in scheduling the job set $\{j^*+j, \dots, j^*+\ell_e-\ell_b\}$ at time $t_{\pi^j} = \sum_{i \in \Pi^j} p_i$. In fact, we have that $\Pi^j = \Pi^1 \cup \{j^*+2, \dots, j^*+j-1\} \cup \{j^*+1\} = \Pi \cup \{j^*, \dots, j^*+j-1\}$. \square

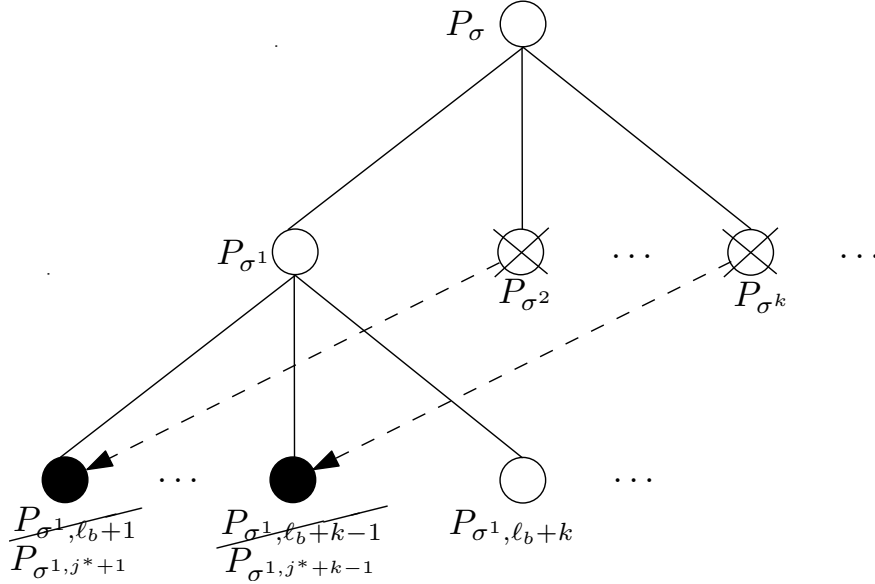


Figure 3: Merging for an arbitrary left-side branch

Analogously to the root node, each pair of instances indicated in Proposition 4 can be merged. Again, $(k-1)$ instances P_{σ^j} (with $2 \leq j \leq k$) can be merged with the corresponding instances P_{σ^1, ℓ_b+j-1} . P_{σ^j} is deleted and P_{σ^1, ℓ_b+j-1} is replaced by P_{σ^1, j^*+j-1} (Figure 3), defined as follows:

- $\{j^*+j, \dots, j^*+\ell_e-\ell_b\}\Omega$ is the set of jobs on which it remains to branch on.
- Let σ^{1, j^*+j-1} be the sequence of positions on which the j^*+j-1 longest jobs $1, \dots, j^*+j-1$ are branched, that leads to the best jobs permutation between π^j and $\pi^1\{j^*+2, \dots, j^*+j-1\}(j^*+1)$ for $2 \leq j \leq k-1$, and between $\pi\{j^*+1, \dots, j^*+j-1\}j^*$ and $\pi^1\{j^*+2, \dots, j^*+j-1\}(j^*+1)$ for $j=k$. This involves the solution of one or two instances of size at most $k-1$ (in $\mathcal{O}^*(2.4143^k)$ time by TTBR2) and the finding of the sequence that has the smallest total tardiness value knowing that both sequences start at time 0.

The `LEFT_MERGE` procedure is presented in Algorithm 2. Notice that, from a technical point of view, this algorithm takes as input one instance and produces as an output its first child node to branch on, which replaces all its k left-side children nodes.

Algorithm 2 `LEFT_MERGE` Procedure

Input: P_σ an input instance of size n , with ℓ_b, j^* accordingly computed

Output: Q : a list of instances to branch on after merging

```

1: function LEFT_MERGE( $P_\sigma$ )
2:    $Q \leftarrow \emptyset$ 
3:   for  $j=1$  to  $k$  do
4:     Create  $P_{\sigma_j}$  ( $j$ -th child of  $P_\sigma$ ) by the improved branching with the subinstance
     induced by the job set  $\{j^*+1, \dots, j^*+j-1\}$  solved if  $\mathcal{L}_\sigma = \emptyset$  or  $j=k$ 
5:   end for
6:   for  $j=1$  to  $k-1$  do
7:     Create  $P_{\sigma_{1j}}$  ( $j$ -th child of  $P_{\sigma_1}$ ) by the improved branching with the subinstance
     induced by the job set  $\{j^*+2, \dots, j^*+j-1\}$  solved if  $\mathcal{L}_{\sigma_1} = \emptyset$  or  $j=k$ 
8:      $\mathcal{L}_{\sigma^1} \leftarrow \mathcal{L}_{\sigma^1} \cup \text{BEST}(P_{\sigma_{j+1}}, P_{\sigma_{1j}})$ 
9:   end for
10:   $Q \leftarrow Q \cup P_{\sigma^1}$ 
11:  return  $Q$ 
12: end function

```

Lemma 2. *The `LEFT_MERGE` procedure returns one node to branch on in $\mathcal{O}(n)$ time and polynomial space. The corresponding instance is of size $(n-1)$.*

Proof. The creation of instances P_{σ^1, ℓ_b+j-1} , for all $j = 2, \dots, k$, can be done in $\mathcal{O}(n)$ time. The call of `TTBR2` costs constant time. The `BEST` function called at line 8 consists in computing then comparing the total tardiness value of two known sequence of jobs starting at the same time instant: it runs in $\mathcal{O}(n)$ time. The overall time complexity of `LEFT_MERGE` procedure is then bounded by $\mathcal{O}(n)$ time as k is a constant. Finally, as only node P_{σ^1} is returned, its size is clearly $(n-1)$ when P_σ has size n . \square

In the final part of this section, we discuss the extension of the algorithm in the case where $LPT \neq EDD$. In this case, Property 2 allows to discard subinstances associated to branching in some positions. Notice that if an instance P can be discarded according to this property, then we say that P does not exist and its associated node is empty.

Lemma 3. *Consider a version of algorithm `TTBR` which uses the left merging mechanism to prune nodes. Instances such that $LPT = EDD$ correspond to worst-case instances for this algorithm.*

Proof. We prove the result by showing that the time reduction obtained from left merging and Property 2 in the case $LPT=EDD$ is not greater than that of any other cases. Notice that the time reduction is measured as the decrease in the worst-case time complexity implied by

not exploring pruned nodes. Let us consider the improved branching scheme. The following exhaustive cases hold:

1. $1 = [1]$ and $2 = [2]$;
2. $1 = [j]$ with $j \geq 2$;
3. $1 = [1]$ and $2 = [j]$ with $j \geq 3$.

We first sketch the idea of the proof. For each of the 3 cases above, we analyse the time reduction that can be obtained on one single branching and merging and we show that the reduction corresponding to case 1, which covers the case $LPT=EDD$, is the smallest among all the 3 cases. In fact, for case 2 and case 3, some nodes are not created due to Property 2, and the resulting time reduction is not less than that of case 1.

Let $T(n)$ be the time needed to solve an instance of size n in general. From Lemma 2, we can deduce that $T(n) > 2T(n - 1)$ because for instances with $LPT = EDD$, on each branching, a node of size $(n - 1)$ is returned by left merging and another node of size $(n - 1)$ exists due to the last child node of P_σ . This statement is also valid in the worst case if no merging is done, due to the branching scheme. The inequality $T(n) > 2T(n - 1)$ induces that $T(n) = \omega(2^n)$, which will be used below to prove the lemma.

In order to be general, consider the current node as P_σ , as shown in Figure 3. The time reduction of the 3 cases are denoted respectively by $TR1$, $TR2$ and $TR3$. We also note $TR_{LPT=EDD}$ the time reduction corresponding to the case $LPT = EDD$.

In case 1, no nodes are eliminated by Property 2, hence, the merging can be done as described for the case $LPT=EDD$ (Figure 3). Therefore, $TR1 = TR_{LPT=EDD} = T(n - 2) + T(n - 3) + \dots + T(n - k)$ according to Lemma 2 when **LEFT_MERGE** is executed.

In case 2, the subinstance of P_σ corresponding to branching the longest job on the first position, is eliminated directly by Property 2. Therefore, $TR2 \geq T(n - 1)$.

In case 3, let ℓ_b be the first free position in P_σ , as defined in Proposition 3. Some child nodes of P_{σ^1} , as in Figure 3, corresponding to branch job 2 on positions $\{\ell_b + 1, \dots, \ell_b + j - 1\}$, are eliminated due to Property 2. For these nodes, the time reduction that could have been achieved by merging is already ensured, while the nodes that are not eliminated, notably those corresponding to branch job 2 in positions $\{\ell_b + j, \dots, \ell_b + k - 1\}$ can still be merged pairwise with nodes $\{P_{\sigma^{j+1}}, \dots, P_{\sigma^k}\}$. More reduction can be gained if $j > k$. Therefore, $TR3 \geq T(n - 2) + T(n - 3) + \dots + T(n - k)$.

Since $TR1 \leq TR3$, this brings us to compare $TR1$ and $TR2$. Suppose $TR1 > TR2$, i.e., $T(n - 1) < T(n - 2) + T(n - 3) + \dots + T(n - k)$, then we have $T(n - 1) < T(n - 2) + T(n - 3) + \dots + T(1)$. By solving this recurrence relation we get $T(n) = o(2^n)$ which is in contradiction with the fact that $T(n) = \omega(2^n)$, as proved above. Therefore, $TR1 < TR2$, i.e., on each recursion of the algorithm, the time reduction obtained in case 1 is not greater than any other cases. Since $TR_1 = TR_{LPT=EDD}$, this proves that $LPT = EDD$ is the worst-case scenario, in which the **LEFT_MERGE** procedure returns one node of size $n - 1$ to branch on. \square

3.2. Merging right-side branches

Due to the branching scheme, the merging of right-side branches involves a more complicated procedure than the merging of left-side branches. In the merging of left-side branches, it is possible to merge some nodes associated to instances P_ℓ with children nodes of P_1 , while for the right-side branches, it is not possible to merge some nodes P_ℓ with children nodes of P_n . We can only merge children nodes of P_ℓ with children nodes of P_n . Let us more formally introduce the right merging procedure and, again, let $k < \frac{n}{2}$ be the same constant parameter as used in the left merging.

Figure 4 shows an example on the structure of merging for the k right-side branches with $k = 3$. The root instance P consists in scheduling job set $\{1, \dots, n\}$. As for left-side merging, we always focus on the worst case where $LPT = EDD$. Unlike left-side merging, the right-side merging is done horizontally for each level. Nodes that are involved in merging are colored. For instance, the black square nodes at level 1 can be merged. Similarly, the black circle nodes at level 1 can be merged, the grey square nodes at level 2 can be merged and the grey circle nodes at level 2 can be merged. Notice that each right-side branch of P is expanded to a different depth which is actually an arbitrary decision: the expansion stops when the first child node has size $(n - k - 1)$ as indicated in the figure. This eases the computation of the final complexity.

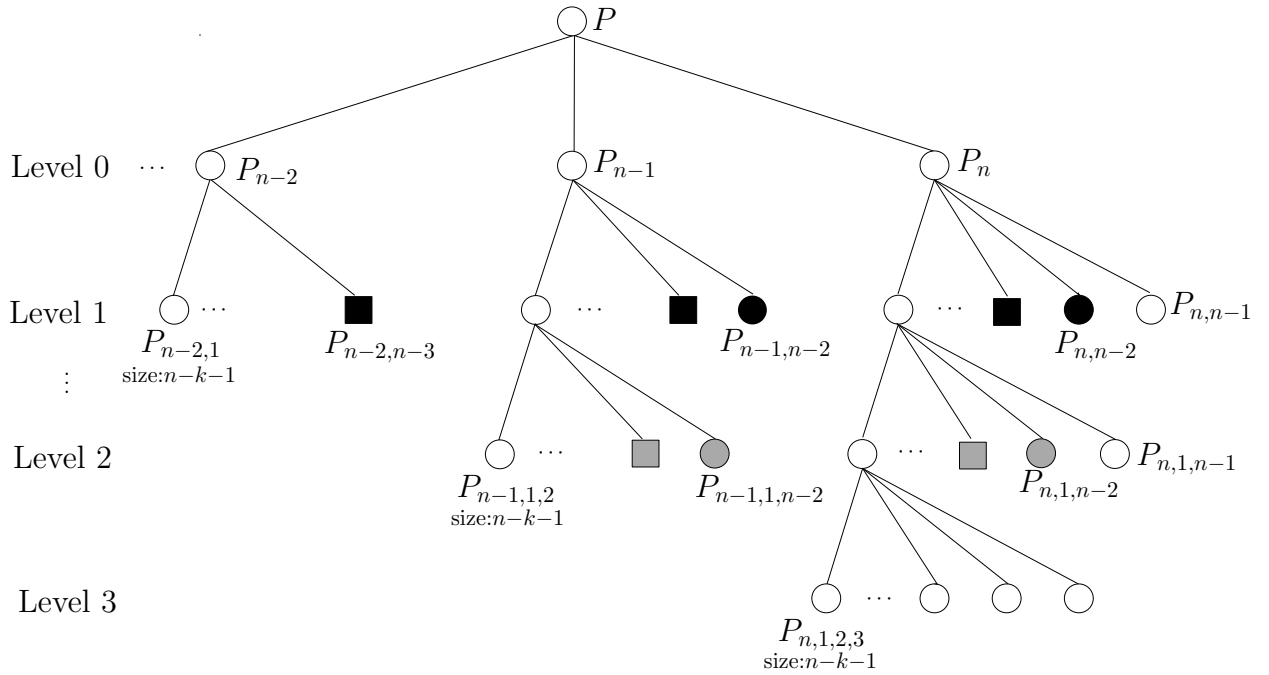
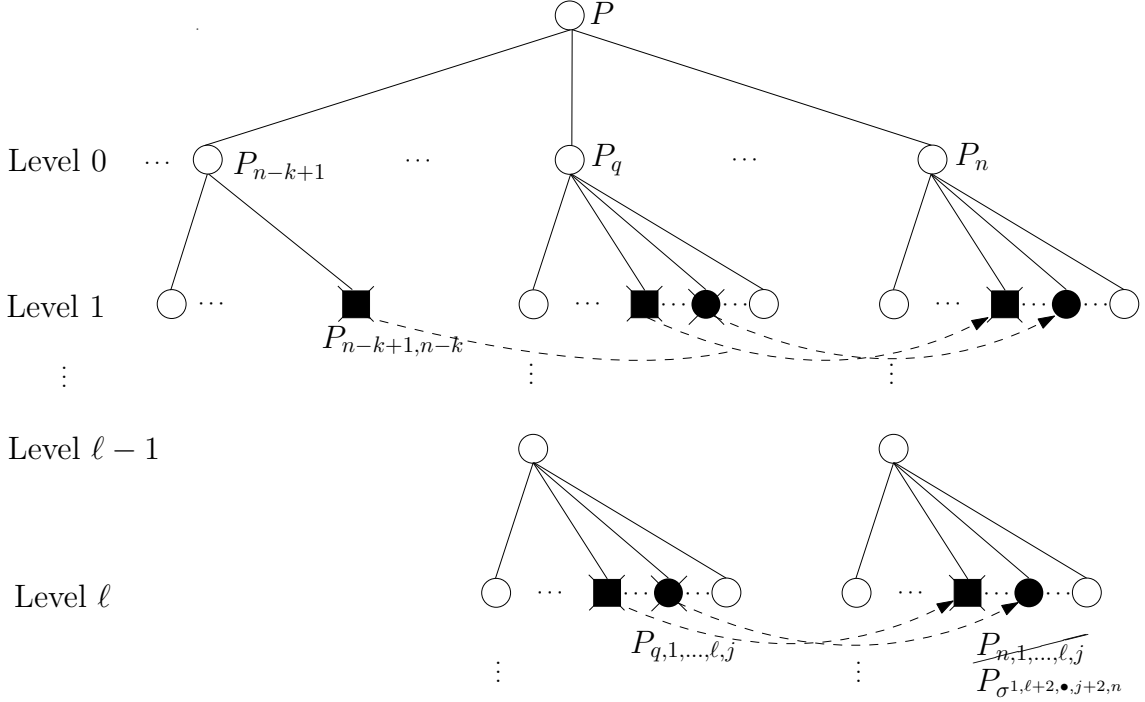


Figure 4: An example of right-side branches merging for $k = 3$

More generally, Figure 5 shows the right-side search tree and the content of the nodes involved in the merging in a generic way.

The rest of this section intends to describe the merging by following the same lines as for left merging. We first extend the notation P_σ in the sense that σ may now contain



$$\begin{aligned}
P_{q, 1, \dots, l, j} &: (2, \dots, \ell+1)\{\ell+3, \dots, j+1\}(\ell+2)\{j+2, \dots, q\}1\{q+1, \dots, n\} \\
P_{\sigma^{1, \ell+2, \bullet, j+2, n}} &: (2, \dots, \ell+1)\{\ell+3, \dots, j+1\} \underset{\max\{j+1, n-k+\ell+1\} \leq q \leq n}{\text{BEST}} ((\ell+2)\{j+2, \dots, q\}1\{q+1, \dots, n\})
\end{aligned}$$

Figure 5: Generic right-side merging at the root node

placeholders. The i -th element of σ is either the position assigned to job i if i is fixed, or \bullet if job i is not yet fixed. The \bullet sign is used as placeholder, with its cardinality below indicating the number of consecutive \bullet . As an example, the instance $\{2, \dots, n-1\}1n$ can now be denoted by $P_{n-1, \bullet_{n-2}, n}$. The cardinality of \bullet may be omitted whenever it is not important for the presentation or it can be easily deduced as in the above example. Note that this adapted notation eases the presentation of right merge while it has no impact on the validity of the results stated in the previous section.

Proposition 5. *Let P_σ be an instance to branch on. Let $j^*, \ell_b, \ell_e, \rho_1$ and ρ_2 be defined as in Proposition 3. Extending Corollary 1, instance P_σ has the following structure:*

$$\pi\{j^*, \dots, j^* + \ell_e - \ell_b\}\gamma\Omega'$$

where π is defined as in Corollary 1 and γ is the sequence of jobs on positions ρ_2, \dots, ρ_3 with $\rho_3 = \max\{i : i \geq \rho_2, \text{positions } \rho_2, \dots, i \text{ are in } \sigma\}$ and Ω' the remaining subset of jobs to be scheduled after position ρ_3 (some of them can have been already scheduled). The merging procedure is applied on job set $\{j^*, \dots, j^* + \ell_e - \ell_b\}$ preceded by a sequence of jobs π and followed by $\gamma\Omega'$.

Proof. The instance structure stated in Corollary 1 is refined on the part of Ω . Ω is split

into two parts: γ and Ω' . The motivation is that γ will be involved in the right merging, just like the role of π in left merging. \square

Proposition 6 shed lights on how to merge the right side branches originated from the root node.

Proposition 6. *For each instance in the set*

$$\mathcal{S}_{\ell,j} = \left\{ P_\sigma: \begin{array}{l} |\sigma| = \ell + 2, \\ \max\{j+1, n-k+\ell+1\} \leq \sigma_1 \leq \\ n, \\ \sigma_i = i-1, \forall i \in \{2, \dots, \ell+1\}, \\ \sigma_{\ell+2} = j \end{array} \right\}^1$$

with $0 \leq \ell \leq k-1$, $n-k \leq j \leq n-1$, and with σ_i referring to the position of job i in σ , we have the two following properties:

1. *The solution of instances in $\mathcal{S}_{\ell,j}$ involves the solution of a common subinstance which consists in scheduling job set $\{\ell+3, \dots, j+1\}$ starting at time $t_\ell = \sum_{i=2}^{\ell+1} p_i$.*
2. *For any instance in $\mathcal{S}_{\ell,j}$, at most $k+1$ jobs have to be scheduled after job set $\{\ell+3, \dots, j+1\}$.*

Proof. As each instance P_σ is defined by $(2, \dots, \ell+1)\{\ell+3, \dots, j+1\}(\ell+2)\{j+2, \dots, \sigma_1\}1\{\sigma_1+1, \dots, n\}$, the first part of the property is straightforward.

Besides, the second part can be simply established by counting the number of jobs to be scheduled after job set $\{\ell+3, \dots, j+1\}$ when j is minimal, i.e., when $j = n-k$. In this case, $(\ell+2)\{j+2, \dots, \sigma_1\}1\{\sigma_1+1, \dots, n\}$ contains $k+1$ jobs. \square

The above proposition highlights the fact that some nodes can be merged as soon as they share the same initial subinstance to be solved. More precisely, at most $k - \ell - 1$ nodes associated to instances $P_{q,1.. \ell, j}$, $\max\{j+1, n-k+\ell+1\} \leq q \leq (n-1)$, can be merged with the node associated to instance $P_{n,1.. \ell, j}$, for all $j = (n-k), \dots, (n-1)$. The node $P_{n,1.. \ell, j}$ is replaced in the search tree by the node $P_{\sigma^{1, \ell+2, \bullet, j+2, n}}$ defined as follows (Figure 5):

- $\{\ell+3, \dots, j+1\}$ is the set of jobs on which it remains to branch.
- Let $\sigma^{1, \ell+2, \bullet, j+2, n}$ be the sequence containing positions of jobs $\{1, \dots, \ell+2, j+2, \dots, n\}$ and placeholders for the other jobs, that leads to the best jobs permutation among $(\ell+2)\{j+2, \dots, q\}1\{q+1, \dots, n\}$, $\max\{j+1, n-k+\ell+1\} \leq q \leq n$. This involves the solution of at most k instances of size at most $k+1$ (in $\mathcal{O}^*(k \times 2.4143^{k+1})$ time by TTBR2) and the determination of the best of the computed sequences knowing that all of them start at time t , namely the sum of the jobs processing times in $(2, \dots, \ell+1)\{\ell+3, \dots, j+1\}$.

¹Placeholders do not count in the cardinality of σ

The merging process described above is applied at the root node, while an analogous merging can be applied at any node of the tree. With respect to the root node, the only additional consideration is that the right-side branches of a general node may have already been modified by previous mergings. As an example, let us consider Figure 6. It shows that, subsequently to the merging operations performed from P , the right-side branches of P_n may not be the subinstances induced by the branching scheme. However, it can be shown in a similar way as per left-merge, that the merging can still be applied.

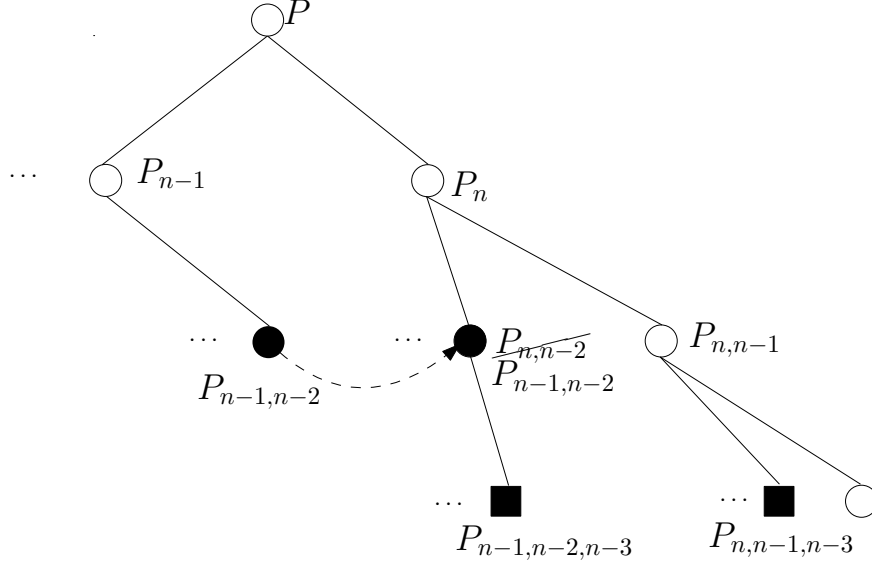


Figure 6: The right branches of P_n have been modified when performing right-merging from P

In order to define the branching scheme used with the `RIGHT_MERGE` procedure, a data structure \mathcal{R}_σ is associated to an instance P_σ . It represents a list of subinstances that result from a previous merging and are now the k right-side children nodes of P_σ . When a merging operation sets the k right-side children nodes of P_σ to $P_{\sigma^{n-k+1}}, \dots, P_{\sigma^n}$, we set $\mathcal{R}_\sigma = \{P_{\sigma^{n-k+1}}, \dots, P_{\sigma^n}\}$, otherwise we have $\mathcal{R}_\sigma = \emptyset$. As a conclusion, the following branching scheme for an arbitrary node of the tree is defined. It is an extension of the branching scheme defined in Definition 1.

Definition 2. *The branching scheme for an arbitrary node P_σ is defined as follows:*

- If $\mathcal{R}_\sigma = \emptyset$, use the branching scheme defined in Definition 1;
- If $\mathcal{L}_\sigma = \emptyset$ and $\mathcal{R}_\sigma \neq \emptyset$, branch on the longest job in the available positions from the 1st to the $(n - k)$ -th, then extract instances from \mathcal{R}_σ as the last k branches.
- If $\mathcal{L}_\sigma \neq \emptyset$ and $\mathcal{R}_\sigma \neq \emptyset$, extract instances from \mathcal{L}_σ as the first $k - 1$ branches, then branch on the longest job in the available positions from the k -th to the $n - k$ -th, finally extract instances from \mathcal{R}_σ as the last k branches.

This branching scheme, whenever necessary, will be referred to as improved branching. It generalizes, also replaces, the one introduced in Definition 1

Proposition 7 states the validity of merging a general node, which extends the result in Proposition 6.

Proposition 7. *Let P_σ be an arbitrary instance and let $\pi, j^*, \ell_b, \ell_e, \gamma, \Omega'$ be computed relatively to P_σ according to Proposition 5. If $\mathcal{R}_\sigma = \emptyset$, the right merging on P_σ can be easily performed by considering P_σ as a new root instance. Suppose $\mathcal{R}_\sigma \neq \emptyset$, the q -th child node P_{σ^q} is extracted from \mathcal{R}_σ , for all $n' - k + 1 \leq q \leq n'$, where $n' = \ell_e - \ell_b + 1$ is the number of children nodes of P_σ . The structure of P_{σ^q} is $\pi\{j^*+1, \dots, j^*+q-1\}\gamma^q\Omega'$.*

For $0 \leq \ell \leq k-1$ and $n' - k \leq j \leq n' - 1$, the following conditions hold:

1. Instances in $\mathcal{S}_{\ell,j}^\sigma$ have the following structure:
 $\pi(j^*+1, \dots, j^*+\ell)\{j^*+\ell+2, \dots, j^*+j\}(j^*+\ell+1)\{j^*+j+1, \dots, j^*+q-1\}\gamma^q\Omega'$ with q varies from $\max\{j+1, n-k+\ell+1\}$ to n' .
2. The solution of all instances in $\mathcal{S}_{\ell,j}^\sigma$ involves the scheduling of a job set $\{j^*+j+1, \dots, j^*+q-1\}$, $\max\{j+1, n-k+\ell+1\} \leq q \leq n'$, which is of size less than k . Besides, for all instances in $\mathcal{S}_{\ell,j}^\sigma$ it is required to solve a common subinstance made of job set $\{j^*+\ell+2, \dots, j^*+j\}$ starting after $\pi(j^*+1, \dots, j^*+\ell)$ and before $(j^*+\ell+1)\{j^*+j+1, \dots, j^*+q-1\}\gamma^q\Omega'$.

Proof. The proof is similar to the one of Proposition 4. The first part of the statement follows directly from Definition 2 and simply defines the structure of the children nodes of P_σ . For the second part, it is necessary to prove that $\{j^*+j+1, \dots, j^*+q-1\}\gamma^q$ consists of the same jobs for any valid value of q . Actually, since right-merging only merges nodes that have common jobs fixed after the unscheduled jobs, the jobs present in $\{j^*+j+1, \dots, j^*+q-1\}\gamma^q$ and the jobs present in $\{j^*+j+1, \dots, j^*+q-1\}j^*\{j^*+q, \dots, j^*+n'-1\}\gamma$, $\max\{j+1, n-k+\ell+1\} \leq q \leq n'$, must be the same, which proves the statement. \square

Analogously to the root node, given the values of ℓ and j , all the instances in $\mathcal{S}_{\ell,j}^\sigma$ can be merged. More precisely, we rewrite σ as $\alpha \bullet_{n'} \beta$ where α is the sequence of positions assigned to jobs $\{1, \dots, j^*-1\}$, $\bullet_{n'}$ refers to the job set to branch on and β contains the positions assigned to the rest of jobs. At most $k - \ell - 1$ nodes associated to instances $P_{\alpha, \ell_b + q - 1, \ell_b \dots \ell_b + \ell - 1, \ell_b + j - 1, \bullet, \beta}$, with $\max\{j+1, n' - k + \ell + 1\} \leq q \leq n' - 1$, can be merged with the node associated to instance $P_{\alpha, \ell_e, \ell_b \dots \ell_b + \ell - 1, \ell_b + j - 1, \bullet, \beta}$.

Node $P_{\alpha, \ell_e, \ell_b \dots \ell_b + \ell - 1, \ell_b + j - 1, \bullet, \beta}$ is replaced in the search tree by node $P_{\alpha, \sigma^{\ell, \ell_b, j}, \bullet, \beta}$ defined as follows:

- $\{j^*+\ell+2, \dots, j^*+j\}$ is the set of jobs on which it remains to branch.
- Let $\sigma^{\ell, \ell_b, j}$ be the sequence of positions among

$$\{(\ell_b + q - 1, \ell_b \dots \ell_b + \ell - 1, \ell_b + j - 1) : \max\{j+1, n' - k + \ell + 1\} \leq q \leq n' - 1\}$$

associated to the best job permutation on $(j^*+\ell+1)\{j^*+j+1, \dots, j^*+q-1\}\gamma^q$, for all $\max\{j+1, n' - k + \ell + 1\} \leq q \leq n'$. This involves the solution of k instances of size at most

$k+1$ (in $\mathcal{O}^*(k \times 2.4143^{k+1})$ time by TTBR2) and the determination of the best of the computed sequences knowing that all of them start at time t , namely the sum of the jobs processing times in $\pi(j^*+1, \dots, j^*+\ell)\{j^*+\ell+2, \dots, j^*+j\}$.

The `RIGHT_MERGE` procedure is presented in Algorithm 3. Notice that, similarly to the `LEFT_MERGE` procedure, this algorithm takes as input one instance P_σ and provides as an output a set of nodes to branch on, which replaces all its k right-side children nodes of P_σ . It is interesting to notice that the `LEFT_MERGE` procedure is also integrated.

A procedure `MERGE_RIGHT_NODES` (Algorithm 4) is invoked to perform the right merging for each level $\ell = 0, \dots, k-1$ in a recursive way. The initial inputs of this procedure (line 13 in `RIGHT_MERGE`) are the instance P_σ and the list of its k right-side children nodes, denoted by $rnodes$. They are created according to the improved branching (lines 4-12 of Algorithm 3). Besides, the output is a list Q containing the instances to branch on after merging. In the first call to `MERGE_RIGHT_NODES`, the left merge is applied to the first element of $rnodes$ (line 2), all the children nodes of nodes in $rnodes$ not involved in right nor left merging, are added to Q (lines 3-7). This is also the case for the result of the right merging operations at the current level (lines 8-11). In Algorithm 4, the value of r indicates the current size of $rnodes$. It is reduced by one at each recursive call and the value $(k-r)$ identifies the current level with respect to P_σ . As a consequence, each right merging operation consists in finding the instance with the best total tardiness value on its fixed part, among the ones in set $\mathcal{S}_{k-r,j}^\sigma$. This is performed by the `BEST` function (line 10 of `MERGE_RIGHT_NODES`) which extends the one called in Algorithm 2 by taking at most k subinstances as input and returning the dominating one.

The `MERGE_RIGHT_NODES` procedure is then called recursively on the list containing the first child node of the 2nd to r -th node in $rnodes$ (lines 13-17). Note that the procedure `LEFT_MERGE` is applied to every node in $rnodes$ except the last one. In fact, for any specific level, the last node in $rnodes$ belongs to the last branch of P_σ , which is $P_{\sigma, l_b+n-1, \bullet, \beta}$. Since $P_{\sigma, l_b+n-1, \bullet, \beta}$ is put into Q at line 14 of `RIGHT_MERGE`, it means that this node will be re-processed later and `LEFT_MERGE` will be called on it at that moment. Since the recursive call of `MERGE_RIGHT_NODES` (line 18) will merge some nodes to the right-side children nodes of $P_{\alpha, l_b, \bullet, \beta^r}$, the latter one must be added to the list \mathcal{L} of $P_{\alpha, \bullet, \beta^r}$ (line 19). In addition, since we defined \mathcal{L} as a list of size either 0 or $k-1$, lines 20-24 add the other $(k-2)$ nodes to $\mathcal{L}_{\alpha, \bullet, \beta^r}$.

It is also important to notice the fact that a node may have its \mathcal{L} or \mathcal{R} structures non-empty, if and only if it is the first or last child node of its parent node. A direct result is that only one node among those involved in a merging may have its \mathcal{L} or \mathcal{R} non-empty. In this case, these structures need to be associated to the resulting node. The reader can always refer to Figure 4 for a more intuitive representation.

Lemma 4. *The `RIGHT_MERGE` procedure returns a list of $\mathcal{O}(n)$ nodes in polynomial time and space.*

The solution of the associated instances involves the solution of 1 subinstance of size $(n-1)$, of $(k-1)$ subinstances of size $(n-k-1)$, and subinstances of size i and $(n_q - (k-r) - i - 1)$,

Algorithm 3 RIGHT_MERGE Procedure

Input: $P_\sigma = P_{\alpha, \bullet, \beta}$ a instance of size n , with ℓ_b, j^* computed according to Proposition 3

Output: Q : a list of instances to branch on after merging

```
1: function RIGHT_MERGE( $P_\sigma$ )
2:    $Q \leftarrow \emptyset$ 
3:    $\text{nodes} \leftarrow \emptyset$ 
4:   if  $\mathcal{R}_\sigma = \emptyset$  then
5:     for  $q = n - k + 1$  to  $n$  do
6:       Create  $P_{\alpha, \ell_b + q - 1, \bullet, \beta}$  by branching
7:        $\delta \leftarrow$  the sequence of positions of jobs  $\{j^* + q, \dots, j^* + n - 1\}$  fixed by TTBR2
8:        $\text{nodes} \leftarrow \text{nodes} + P_{\alpha, \ell_b + q - 1, \bullet, \delta, \beta}$ 
9:     end for
10:  else
11:     $\text{nodes} \leftarrow \mathcal{R}_\sigma$ 
12:  end if
13:   $Q \leftarrow Q \cup \text{MERGE\_RIGHT\_NODES}(\text{nodes}, P_\sigma)$ 
14:   $Q \leftarrow Q \cup \text{nodes}[k]$  ▷ The last node will be re-processed
15:  return  $Q$ 
16: end function
```

for all $r = 2, \dots, k; q = 1, \dots, (r - 1); i = k, \dots, (n - 2k + r - 2)$.

Proof. The first part of the result follows directly from Algorithm 3. The only lines where nodes are added to Q in RIGHT_MERGE are lines 13-14. In line 14, only one instance is added to Q , thus it needs to be proved that the call on MERGE_RIGHT_NODES (line 13) returns $\mathcal{O}(n)$ nodes. This can be computed by analysing the lines 2-7 of Algorithm 4. Considering all recursive calls, the total number of nodes returned by MERGE_RIGHT_NODES is $(\sum_{i=1}^{k-1} (k - i)(n - 2k - i)) + k - 1$ which yields $\mathcal{O}(n)$. The number of all the nodes considered in right merging is bounded by a linear function on n . Furthermore, all the operations associated to the nodes (merging, creation, etc) have a polynomial cost. As a consequence, Algorithm 3 runs in polynomial time and space.

Regarding the sizes of the subinstances returned by RIGHT_MERGE, the node added in line 14 of Algorithm 3 contains one subinstance of size $(n - 1)$, corresponding to branching the longest job on the last available position. Then, the instances added by the call to MERGE_RIGHT_NODES are added to Q . In line 2 of Algorithm 4, the size of the instance returned by LEFT_MERGE is reduced by one unit when compared to the input instance which is of size $(n - k - (k - r))$. Note that $(k - r)$ is the current level with respect to the node tackled by Algorithm 4. As a consequence, the size of the resulting subinstance is $(n - k - (k - r) - 1)$. Note that this line is executed $(k - 1)$ times, for all $r = k, \dots, 2$, corresponding to the number of calls to MERGE_RIGHT_NODES. In line 5 of Algorithm 4, the list of nodes which are not involved in any merging operation are added to Q . This corresponds

Algorithm 4 MERGE_RIGHT_NODES Procedure

Input: $\text{rnodes} = [P_{\alpha, n_1, \bullet, \beta^1}, \dots, P_{\alpha, n_r, \bullet, \beta^r}]$, ordered list of r last children nodes with ℓ_b defined on any node in rnodes . $|\alpha| + 1$ is the job to branch on and $n_r = n_1 + r - 1$.

Output: Q , a list of instances to branch on after merging

```
1: function MERGE_RIGHT_NODES( $\text{rnodes}, P_\sigma$ )
2:    $Q \leftarrow \text{LEFT\_MERGE}(P_{\alpha, n_1, \bullet, \beta^1})$ 
3:   for  $q = 1$  to  $r - 1$  do
4:     for  $j = \ell_b + k$  to  $\ell_b + n_1 - 1$  do
5:        $Q \leftarrow Q \cup P_{\alpha, j, \bullet, \beta^q}$ 
6:     end for
7:   end for
8:   for  $j = \ell_b + n_1$  to  $\ell_b + n_r$  do
9:     Solve all the subinstances of size less than  $k$  in  $\mathcal{S}_{k-r, j}^\sigma$ 
10:     $\mathcal{R}_{\alpha, n_r, \bullet, \beta^r} \leftarrow \mathcal{R}_{\alpha, n_r, \bullet, \beta^r} + \text{BEST}(\mathcal{S}_{k-r, j}^\sigma)$ 
11:   end for
12:   if  $r > 2$  then
13:      $\text{newnodes} \leftarrow \emptyset$ 
14:     for  $q = 2$  to  $r - 1$  do
15:        $\text{newnodes} \leftarrow \text{newnodes} + \text{LEFT\_MERGE}(P_{\alpha, n_q, \bullet, \beta^q})$ 
16:     end for
17:      $\text{newnodes} \leftarrow \text{newnodes} + P_{\alpha, \ell_b, \bullet, \beta^r}$ 
18:      $Q \leftarrow Q \cup \text{MERGE\_RIGHT\_NODES}(\text{newnodes}, P_\sigma)$ 
19:      $\mathcal{L}_{\alpha, n_r, \bullet, \beta^r} \leftarrow P_{\alpha, \ell_b, n_{r-1}, \beta^r}$ 
20:     for  $q = 2$  to  $k - 1$  do
21:       Create  $P_{\alpha, \ell_b + q - 1, \bullet, \beta^r}$  by branching
22:        $\delta \leftarrow$  the sequence of positions of jobs  $\{|\alpha| + 2, \dots, |\alpha| + q\}$  fixed by TTBR2
23:        $\mathcal{L}_{\alpha, n_r, \bullet, \beta^r} \leftarrow \mathcal{L}_{\alpha, n_r, \bullet, \beta^r} + P_{\alpha, \ell_b + q - 1, \delta, n_{r-1}, \beta^r}$ 
24:     end for
25:   end if
26:   return  $Q$ 
27: end function
```

to pairs of instances of size i and $(n_q - (k - r) - i - 1)$, for all $i = k, \dots, (n - k - 1)$ and this proves the last part of the lemma. \square

Lemma 5. *Consider a version of algorithm TTBR which uses the right merging mechanism to prune nodes. Instances such that $LPT = EDD$ correspond to worst-case instances for this algorithm.*

Proof. The proof follows a similar reasoning to the proof of Lemma 3. We analyze the time reduction obtained from the last k subtrees of the current node. Notice that the time reduction is measured as the decrease in the worst-case time complexity implied by not exploring pruned nodes. The following cases are considered:

1. $1 = [j]$, $j \leq (n - k + 1)$ and $2 = [j']$, $j' \leq (n - k)$;
2. $1 = [j]$, $j \leq (n - k + 1)$ and $2 = [j']$, $j' > (n - k)$;
3. $1 = [j]$, $j > (n - k + 1)$.

We refer the reader to Figure 5 for a better understanding of the proof. Since the structure of right merging is the same at different levels (except level 0) of the tree, it is sufficient to consider the time reduction from level 0 and level 1. We denote the resulting time reduction by $TR1$, $TR2$ and $TR3$ for each of the three cases, respectively. We also note $TR_{LPT=EDD}$ the time reduction corresponding to the case $LPT = EDD$.

In case 1, all black nodes at level 1 of Figure 5 are created and merged to one. Therefore, the corresponding time reduction $TR1 \geq TR_{LPT=EDD} = \sum_{i=1}^{k-1} iT(n - i - 2)$.

In case 2, some black nodes at level 1 of Figure 5 are not created due to Property 2, while the black nodes that remain can still be merged to the last subtree. Therefore, $TR2 \geq TR1$.

In case 3, the subtrees rooted by $\{P_1, \dots, P_{j-1}\}$ are not created due to Property 2. This is obviously a stronger reduction than only merging some nodes from inside these subtrees. In addition, for subtrees that remain except the last one, i.e., those rooted by $\{P_j, \dots, P_n\}$, time reduction is still guaranteed by, either right merging or the non-creation of some nodes due to Property 2, depending on the position of job 2 in EDD ordering.

In other words, if $LPT \neq EDD$ then the number of nodes in $\mathcal{S}_{\ell,j}^\sigma$ (defined in Proposition 7) can be less, since some nodes may not be created due to Property 2. However, all the nodes inside $\mathcal{S}_{\ell,j}^\sigma$ can still be merged to one except when $\mathcal{S}_{\ell,j}^\sigma$ is empty. In either case, we can achieve at least the same reduction as the case of $LPT = EDD$. This reasoning obviously holds when extending the consideration to all levels of the tree and to all recursions. Therefore, $LPT = EDD$ is the worst-case scenario. \square

3.3. Complete algorithm and analysis

We are now ready to define the main procedure TTBM (Total Tardiness Branch-and-Merge), stated in Algorithm 5 which is called on the initial input instance $P : \{1, \dots, n\}$. The algorithm has a similar recursive structure as TTBR1. However, each time a node is opened, the sub-branches required for the merging operations are generated, the subinstances of size less than k are solved and the procedures LEFT_MERGE and RIGHT_MERGE are called. Then, the algorithm proceeds recursively by extracting the next node from Q with a depth-first

Algorithm 5 Total Tardiness Branch and Merge (TTBM)

Input: $P : \{1, \dots, n\}$: input instance of size n
 $\frac{n}{2} > k \geq 2$: an integer constant

Output: seqOpt: an optimal sequence of jobs

```
1: function TTBM( $P, k$ )
2:    $Q \leftarrow P$ 
3:   seqOpt  $\leftarrow$  the EDD sequence of jobs
4:   while  $Q \neq \emptyset$  do
5:      $P^* \leftarrow$  extract next instance from  $Q$  (depth-first order)
6:     if the size of  $P^* < 2k$  then
7:       Solve  $P^*$  by calling TTBR2
8:     end if
9:     if all jobs  $\{1, \dots, n\}$  are fixed in  $P^*$  then
10:      seqCurrent  $\leftarrow$  the solution defined by  $P^*$ 
11:      seqOpt  $\leftarrow$  best solution between seqOpt and seqCurrent
12:    else
13:       $Q \leftarrow Q \cup \text{LEFT\_MERGE}(P^*)$  ▷ Left-side nodes
14:      for  $i = k + 1, \dots, n - k$  do
15:        Create the  $i$ -th child node  $P_i$  by branching scheme of TTBR1
16:         $Q \leftarrow Q \cup P_i$ 
17:      end for
18:       $Q \leftarrow \text{RIGHT\_MERGE}(P^*)$  ▷ Right-side nodes
19:    end if
20:  end while
21:  return seqOpt
22: end function
```

strategy and terminates when Q is empty. Note that the algorithm is still described for the worst-case scenario.

Proposition 8 determines the time complexity of the proposed algorithm. In this regard, the complexity of the algorithm depends on the value given to k . The higher it is, the more subinstances can be merged and the better is the worst-case time complexity of the approach.

Proposition 8. *Algorithm TTBM requires polynomial space and has a worst-case time complexity which tends to $\mathcal{O}^*(2^n)$ when k increases.*

Proof. The proof is based on the analysis of the number and the size of the subinstances put in Q when a single instance P^* is expanded. As a consequence of Lemma 3 and Lemma 5, TTBM induces the following recursion:

$$\begin{aligned} T(n) = & 2T(n-1) + 2T(n-k-1) + \dots + 2T(k) \\ & + \sum_{r=2}^k \sum_{q=1}^{r-1} \sum_{i=k}^{n_1-(k-r)-2} (T(i) + T(n_q - (k-r) - i - 1)) \\ & + (k-1)T(n_1-1) + \mathcal{O}(p(n)), \end{aligned}$$

where $T(n)$ represents the time needed by TTBM to solve an instance of n jobs. First, a simple lower bound on the complexity of the algorithm can be derived by the fact that the procedures `RIGHT_MERGE` and `LEFT_MERGE` provide (among the others) two instances of size $(n-1)$, based on which the following inequality holds:

$$T(n) > 2T(n-1). \quad (7)$$

By solving the recurrence, we obtain that $T(n) = \omega(2^n)$. As a consequence, the following inequality holds:

$$T(n) > T(n-1) + \dots + T(1). \quad (8)$$

In fact, if it does not hold, we have a contradiction on the fact $T(n) = \omega(2^n)$. Now, we consider the summation $\sum_{i=k}^{n_1-(k-r)-2} (T(n_q - (k-r) - i - 1))$. Since $n_q = n_1 + q - 1$, we can simply expand the summation as follows:

$$\sum_{i=k}^{n_1-(k-r)-2} (T(n_q - (k-r) - i - 1)) = T(q) + \dots + T(n_1 - (k-r) + q - k - 2).$$

We know that $k \geq q$, then $q - k \leq 0$ and the following inequality holds:

$$T(q) + \dots + T(n_1 - (k-r) + q - k - 2) \leq \sum_{i=q}^{n_1-(k-r)-2} T(i).$$

As a consequence, we can bound above $T(n)$ as follows:

$$\begin{aligned}
T(n) &= 2T(n-1) + 2T(n-k-1) + \dots + 2T(k) \\
&+ \sum_{r=2}^k \sum_{q=1}^{r-1} \sum_{i=k}^{n_1-(k-r)-2} (T(i) + T(n_q - (k-r) - i - 1)) \\
&\leq 2T(n-1) + 2T(n-k-1) + \dots + 2T(k) \\
&\quad + \sum_{r=2}^k \sum_{q=1}^{r-1} \sum_{i=q}^{n_1-(k-r)-2} 2T(i) + (k-1)T(n_1-1) + \mathcal{O}(p(n)) \\
&\leq 2T(n-1) + 2T(n-k-1) + \dots + 2T(k) \\
&\quad + \sum_{r=2}^k \sum_{q=1}^{r-1} \sum_{i=1}^{n_1-(k-r)-2} 2T(i) + (k-1)T(n_1-1) + \mathcal{O}(p(n)).
\end{aligned}$$

By using Equation 8, we obtain the following:

$$\begin{aligned}
T(n) &\leq 2T(n-1) + 2T(n-k-1) + \dots + 2T(k) \\
&\quad + \sum_{r=2}^k \sum_{q=1}^{r-1} \sum_{i=1}^{n_1-(k-r)-2} 2T(i) + (k-1)T(n_1-1) + \mathcal{O}(p(n)) \\
&\leq 2T(n-1) + 2T(n-k-1) + \dots + 2T(k) \\
&\quad + \sum_{r=2}^k \sum_{q=1}^{r-1} 2T(n_1 - (k-r) - 1) + (k-1)T(n_1-1) + \mathcal{O}(p(n)).
\end{aligned}$$

Finally, we apply some algebraic steps and we use the equality $n_1 = n - k$ to derive the following upper limitation of $T(n)$:

$$\begin{aligned}
T(n) &\leq 2T(n-1) + 2T(n-k-1) + \dots + 2T(k) \\
&\quad + \sum_{r=2}^k (r-1)2T(n_1 - (k-r) - 1) + (k-1)T(n_1-1) + \mathcal{O}(p(n)) \\
&\leq 2T(n-1) + 2T(n-k-1) + \dots + 2T(k) + 2(k-1)T(n_1-1) \\
&\quad + \sum_{r=2}^{k-1} (r-1)2T(n_1 - (k-r) - 1) + (k-1)T(n_1-1) + \mathcal{O}(p(n)) \\
&\leq 2T(n-1) + 2T(n-k-1) + \dots + 2T(k) \\
&\quad + (k-1)4T(n_1-1) + (k-1)T(n_1-1) + \mathcal{O}(p(n)) \\
&\leq 2T(n-1) + 4T(n-k-1) + 5(k-1)T(n-k-1) + \mathcal{O}(p(n)) \\
&= 2T(n-1) + (5k-1)T(n-k-1) + \mathcal{O}(p(n)).
\end{aligned}$$

k	$T(n)$
3	$\mathcal{O}^*(2.5814^n)$
4	$\mathcal{O}^*(2.4302^n)$
5	$\mathcal{O}^*(2.3065^n)$
6	$\mathcal{O}^*(2.2129^n)$
7	$\mathcal{O}^*(2.1441^n)$
8	$\mathcal{O}^*(2.0945^n)$
9	$\mathcal{O}^*(2.0600^n)$
10	$\mathcal{O}^*(2.0367^n)$
11	$\mathcal{O}^*(2.0217^n)$
12	$\mathcal{O}^*(2.0125^n)$
13	$\mathcal{O}^*(2.0070^n)$
14	$\mathcal{O}^*(2.0039^n)$
15	$\mathcal{O}^*(2.0022^n)$
16	$\mathcal{O}^*(2.0012^n)$
17	$\mathcal{O}^*(2.0007^n)$
18	$\mathcal{O}^*(2.0004^n)$
19	$\mathcal{O}^*(2.0002^n)$
20	$\mathcal{O}^*(2.0001^n)$

Table 1: The time complexity of TTBM for values of k from 3 to 20

Note that $\mathcal{O}(p(n))$ includes the cost for creating all nodes for each level and the cost of all the merging operations, performed in constant time.

The recursion $T(n) = 2T(n-1) + (5k-1)T(n-k-1) + \mathcal{O}(p(n))$ is an upper limitation of the running time of TTBM. Recall that its solution is $T(n) = \mathcal{O}^*(c^n)$ where c is the largest root of the function:

$$f_k(x) = 1 - \frac{2}{x} - \frac{5k-1}{x^{k+1}}. \quad (9)$$

As k increases, the function $f_k(x)$ converges to $1 - \frac{2}{x}$, which induces a complexity of $\mathcal{O}^*(2^n)$. Table 1 shows the time complexity of TTBM obtained by solving Equation 9 for all the values of k from 3 to 20. The base of the exponential is computed by solving Equation 9 by means of a mathematical solver and rounding up the fourth digit of the solution. The table shows that the time complexity is $\mathcal{O}^*(2.0001^n)$ for $k \geq 20$. \square

Lemma 6. *The problem $1||\sum T_i$ can be solved in $\mathcal{O}^*((2+\varepsilon)^n)$ time and polynomial space, where $\varepsilon > 0$ converges towards 0 when k increases.*

Proof. Lemma 3 and lemma 5 proved that $LPT = EDD$ is the worst-case scenario for left merging and right merging. Since $k \leq \frac{n}{2}$, the time reduction obtained from left merging and right merging, when both are incorporated into TTBM, can be combined. Thus, lemma 3 and lemma 5 together prove that instances with $LPT = EDD$ are the worst-case instances for TTBM. Therefore, the current lemma is proved according to Proposition 8. \square

4. Conclusions

This paper focused on the design of exact branching algorithms for the single machine total tardiness problem. By exploiting some inherent properties of the problem, we first proposed two branch-and-reduce algorithms, indicated with TTBR1 and TTBR2. The former runs in time $\mathcal{O}^*(3^n)$, while the latter achieves a better time complexity in $\mathcal{O}^*(2.4143^n)$. The space requirement is polynomial in both cases. Furthermore, a technique called branch-and-merge, is presented and applied onto TTBR1 in order to improve its performance. The final achievement is a new algorithm (TTBM) with time complexity converging to $\mathcal{O}^*(2^n)$ and polynomial space. The same technique can be tediously adapted to improve the performance of TTBR2, but the resulting algorithm achieves the same asymptotic time complexity as TTBM, and thus it was omitted. To the best of authors' knowledge, TTBM is the polynomial space algorithm that has the best worst-case time complexity for solving this problem.

Beyond the new established complexity results, the main contribution of the paper is the branch-and-merge technique. The basic idea is very simple, and it consists of speeding up branching algorithms by avoiding solving identical instances which corresponding nodes in the search tree are merged in polynomial time and space. When applied systematically in the search tree, this technique enables to achieve a good worst-case time bound. The same goal is traditionally pursued by means of *Memorization* [6], where the solution of already solved subinstances are stored and then queried when an identical subinstance appears. This is at the cost of exponential space. On a computational side, it is interesting to notice that doing memorization with a fixed size memory can already lead to substantially good practical results according to T'kindt et al. [22], at least on some scheduling problems, even though the worst-case time complexity of the algorithm is no more guaranteed.

As a future development of this work, our aim is twofold. First, we aim at applying the branch-and-merge algorithm to other combinatorial optimization problems in order to establish its potential generalization to other problems. Second, we want to explore the practical efficiency of this algorithm on the single machine total tardiness problem and compare it with memorization with a fixed memory space used to store already branched nodes.

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