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Abstract: Mapping workflow applications onto parallel platforms is a challenging problem, even for simple application patterns such as pipeline graphs. Several antagonist criteria should be optimized, such as throughput and latency (or a combination). In this paper, we study the complexity of the bi-criteria mapping problem for pipeline graphs on communication homogeneous platforms. In particular, we assess the complexity of the well-known chains-to-chains problem for different-speed processors, which turns out to be NP-hard. We provide several efficient polynomial bi-criteria heuristics, and their relative performance is evaluated through extensive simulations.

Key-words: algorithmic skeletons, pipeline, multi-criteria optimization, complexity results, heuristics, heterogeneous platforms.

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Ordonnancement multi-critère des workflows pipelinés

Résumé : L'ordonnancement et l'allocation de workflows sur plates-formes parallèles est un problème crucial, même pour des applications simples comme des graphes en pipeline. Plusieurs critères contradictoires doivent être optimisés, tels que le débit et la latence (ou une combinaison des deux). Dans ce rapport, nous étudions la complexité du problème de l'ordonnancement bi-critère pour les graphes en pipeline sur des plates-formes avec communications homogènes. En particulier nous évaluons la complexité du problème bien connu "chains-on-chains" pour les processeurs hétérogènes, un problème qui s'avère NP-difficile. Nous proposons plusieurs heuristiques bi-critères efficaces en temps polynomial. Leur performance relative est evaluée par des simulations intensives.

Mots-clés : squelettes algorithmiques, pipeline, optimisation multi-critère, plates-formes hétérogènes.

1 Introduction

Mapping applications onto parallel platforms is a difficult challenge. Several scheduling and load-balancing techniques have been developed for homogeneous architectures (see [17] for a survey) but the advent of heterogeneous clusters has rendered the mapping problem even more difficult. Typically, such clusters are composed of different-speed processors interconnected either by plain Ethernet (the low-end version) or by a high-speed switch (the high-end counterpart), and they constitute the experimental platform of choice in most academic or industry research departments.

In this context of heterogeneous platforms, a structured programming approach rules out many of the problems which the low-level parallel application developer is usually confronted to, such as deadlocks or process starvation. Moreover, many real applications draw from a range of well-known solution paradigms, such as pipelined or farmed computations. High-level approaches based on algorithmic skeletons [7, 15] identify such patterns and seek to make it easy for an application developer to tailor such a paradigm to a specific problem. A library of skeletons is provided to the programmer, who can rely on these already coded patterns to express the communication scheme within its own application. Moreover, the use of a particular skeleton carries with it considerable information about implied scheduling dependencies, which we believe can help address the complex problem of mapping a distributed application onto a heterogeneous platform.

In this paper, we therefore consider applications that can be expressed as algorithmic skeletons, and we focus on the pipeline skeleton, which is one of the most widely used. In such workflow applications, a series of data sets (tasks) enter the input stage and progress from stage to stage until the final result is computed. Each stage has its own communication and computation requirements: it reads an input file from the previous stage, processes the data and outputs a result to the next stage. For each data set, initial data is input to the first stage, and final results are output from the last stage. The pipeline workflow operates in synchronous mode: after some latency due to the initialization delay, a new task is completed every period. The period is defined as the longest cycle-time to operate a stage.

Key metrics for a given workflow are the throughput and the latency. The throughput measures the aggregate rate of processing of data, and it is the rate at which data sets can enter the system. Equivalently, the inverse of the throughput, defined as the period, is the time interval required between the beginning of the execution of two consecutive data sets. The latency is the time elapsed between the beginning and the end of the execution of a given data set, hence it measures the response time of the system to process the data set entirely. Note that it may well be the case that different data sets have different latencies (because they are mapped onto different processor sets), hence the latency is defined as the maximum response time over all data sets. Minimizing the latency is antagonistic to minimizing the period, and tradeoffs should be found between these criteria. In this paper, we focus on bi-criteria approaches, i.e. minimizing the latency under period constraints, or the converse.

The problem of mapping pipeline skeletons onto parallel platforms has received some attention, and we survey related work in Section 6. In this paper, we target heterogeneous clusters, and aim at deriving optimal mappings for a bi-criteria objective function, i.e. mappings which minimize the period for a fixed maximum latency, or which minimize the latency for a fixed maximum period. Each pipeline stage can be seen as a sequential procedure which may perform disc accesses or write data in the memory for each task. This data may be reused from one task to another, and thus the rule of the game is always to process the tasks

in a sequential order within a stage. Moreover, due to the possible local memory accesses, a given stage must be mapped onto a single processor: we cannot process half of the tasks on a processor and the remaining tasks on another without exchanging intra-stage information, which might be costly and difficult to implement. In other words, a processor that is assigned a stage will execute the operations required by this stage (input, computation and output) for all the tasks fed into the pipeline.

The optimization problem can be stated informally as follows: which stage to assign to which processor? We require the mapping to be interval-based, i.e. a processor is assigned an interval of consecutive stages. We target *Communication Homogeneous* platforms, with identical links but different speed processors, which introduce a first degree of heterogeneity. Such platforms correspond to networks of workstations interconnected by a LAN, which constitute the typical experimental platforms in most academic or research departments.

The main objective of this paper is to assess the complexity of the bi-criteria mapping problem onto *Communication Homogeneous* platforms. An interesting consequence of one of the new complexity results is the following. Given an array of n elements $a_1, a_2, \ldots, a_n$, the well-known chains-to-chains problem is to partition the array into p intervals whose element sums are well balanced (technically, the aim is to minimize the largest sum of the elements of any interval). This problem has been extensively studied in the literature (see the pioneering papers [6, 10, 13] and the survey [14]). It amounts to load-balance n computations whose ordering must be preserved (hence the restriction to intervals) onto p identical processors. The advent of heterogeneous clusters naturally leads to the following generalization: can we partition the n elements into p intervals whose element sums match p prescribed values (the processor speeds) as closely as possible? The NP-hardness of this important extension of the chains-to-chains problem is established in Section 3. Thus the bi-criteria mapping problem is NP-hard, and we derive efficient polynomial bi-criteria heuristics, which are compared through simulation.

The rest of the paper is organized as follows. Section 2 is devoted the presentation of the target optimization problems. Next in Section 3 we proceed to the complexity results. In Section 4 we introduce several polynomial heuristics to solve the mapping problem. These heuristics are compared through simulations, whose results are analyzed in Section 5. Section 6 is devoted to an overview of related work. Finally, we state some concluding remarks in Section 7.

2 Framework

Applicative framework. We consider a pipeline of n stages $\mathcal{S}_k$, $1 \leq k \leq n$, as illustrated on Figure 1. Tasks are fed into the pipeline and processed from stage to stage, until they exit the pipeline after the last stage. The k-th stage $\mathcal{S}_k$ receives an input from the previous stage, of size δ_{k-1}, performs a number of w_k computations, and outputs data of size δ_k to the next stage. The first stage $\mathcal{S}_1$ receives an input of size δ_0 from the outside world, while the last stage $\mathcal{S}_n$ returns the result, of size δ_n, to the outside world.

Target platform. We target a platform with p processors P_u, $1 \leq u \leq p$, fully interconnected as a (virtual) clique. There is a bidirectional link $\mathsf{link}_{u,v} : P_u \rightarrow P_v$ between any processor pair P_u and P_v, of bandwidth $\mathsf{b}_{u,v}$. Note that we do not need to have a physical link between any processor pair. Instead, we may have a switch, or even a path composed of several physical links, to interconnect P_u and P_v; in the latter case we would retain the bandwidth

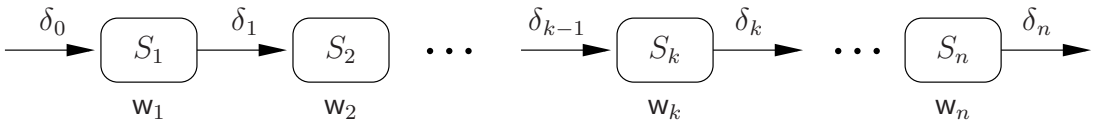


Figure 1: The application pipeline.

of the slowest link in the path for the value of $\mathsf{b}_{u,v}$. In the most general case, we have fully heterogeneous platforms, with different processor speeds and link capacities, but we restrict in this paper to *Communication Homogeneous* platforms with different-speed processors ($\mathsf{s}_u \neq \mathsf{s}_v$) interconnected by links of same capacities ($\mathsf{b}_{u,v} = \mathsf{b}$). They correspond to networks of different-speed processors or workstations interconnected by either plain Ethernet or by a high-speed switch, and they constitute the typical experimental platforms in most academic or industry research departments.

The speed of processor P_u is denoted as s_u, and it takes X/s_u time-units for P_u to execute X floating point operations. We also enforce a linear cost model for communications, hence it takes X/b time-units to send (resp. receive) a message of size X to (resp. from) P_v. Communications contention is taken care of by enforcing the *one-port* model [4, 5]. In this model, a given processor can be involved in a single communication at any time-step, either a send or a receive. However, independent communications between distinct processor pairs can take place simultaneously. The one-port model seems to fit the performance of some current MPI implementations, which serialize asynchronous MPI sends as soon as message sizes exceed a few megabytes [16].

Bi-criteria mapping problem. The general mapping problem consists in assigning application stages to platform processors. For the sake of simplicity, we can assume that each stage $\mathcal{S}_k$ of the application pipeline is mapped onto a distinct processor (which is possible only if $n \leq p$). However, such one-to-one mappings may be unduly restrictive, and a natural extension is to search for interval mappings, i.e. allocation functions where each participating processor is assigned an interval of consecutive stages. Intuitively, assigning several consecutive tasks to the same processors will increase their computational load, but may well dramatically decrease communication requirements. In fact, the best interval mapping may turn out to be a one-to-one mapping, or instead may enroll only a very small number of fast computing processors interconnected by high-speed links.

Interval mappings constitute a natural and useful generalization of one-to-one mappings (not to speak of situations where $p < n$, where interval mappings are mandatory), and such mappings have been studied by Subhlock et al. [19, 20]. The cost model associated to interval mappings is the following. We search for a partition of $[1..n]$ into $m \leq p$ intervals $I_j = [d_j, e_j]$ such that $d_j \leq e_j$ for $1 \leq j \leq m$, $d_1 = 1$, $d_{j+1} = e_j + 1$ for $1 \leq j \leq m-1$ and $e_m = n$. Interval I_j is mapped onto processor $P_{\mathsf{alloc}(j)}$, and the period is expressed as

$$T_{\mathsf{period}} = \max_{1 \leq j \leq m} \left\{ \frac{\delta_{d_j - 1}}{\mathsf{b}} + \frac{\sum_{i=d_j}^{e_j} \mathsf{w}_i}{\mathsf{s}_{\mathsf{alloc}(j)}} + \frac{\delta_{e_j}}{\mathsf{b}} \right\} \quad (1)$$

The latency is obtained by the following expression (data sets traverse all stages, and only interprocessor communications need be paid for):

$$T_{\mathsf{latency}} = \sum_{1 \leq j \leq m} \left\{ \frac{\delta_{d_j - 1}}{\mathsf{b}} + \frac{\sum_{i=d_j}^{e_j} \mathsf{w}_i}{\mathsf{s}_{\mathsf{alloc}(j)}} \right\} + \frac{\delta_n}{\mathsf{b}} \tag{2}$$

The optimization problem is to determine the best mapping, over all possible partitions into intervals, and over all processor assignments. The objective can be to minimize either the period, or the latency, or a combination: given a threshold period, what is the minimum latency that can be achieved? and the counterpart: given a threshold latency, what is the minimum period that can be achieved?

3 Complexity results

To the best of our knowledge, this work is the first to study the complexity of the bi-criteria optimization problem for an interval-based mapping of pipeline applications onto *Communication Homogeneous* platforms.

Minimizing the latency is trivial, while minimizing the period is NP-hard. Quite interestingly, this last result is a consequence of the fact that the natural extension of the chains-to-chains problem [14] to different-speed processors is NP-hard.

Lemma 1. *The optimal pipeline mapping which minimizes the latency can be determined in polynomial time.*

Proof. The minimum latency can be achieved by mapping the whole interval onto the fastest processor j, resulting in the latency $\left(\sum_{i=1}^{n} \mathsf{w}_i\right) / \mathsf{s}_j$. If a slower processor is involved in the mapping, the latency increases, following equation (2), since part of the computations will take longer, and communications may occur. □

Thus, minimizing the latency can be done in polynomial time. However, it is not so easy to minimize the period, and we study the heterogeneous 1D partitioning problem in order to assess the complexity of the period minimization problem.

Given an array of n elements $a_1, a_2, \ldots, a_n$, the 1D partitioning problem, also known as the chains-to-chains problem, is to partition the array into p intervals whose element sums are almost identical. More precisely, we search for a partition of $[1..n]$ into p consecutive intervals $\mathcal{I}_1, \mathcal{I}_2, \ldots, \mathcal{I}_p$, where $\mathcal{I}_k = [d_k, e_k]$ and $d_k \leq e_k$ for $1 \leq k \leq p$, $d_1 = 1$, $d_{k+1} = e_k + 1$ for $1 \leq k \leq p-1$ and $e_p = n$. The objective is to minimize

$$\max_{1 \leq k \leq p} \sum_{i \in \mathcal{I}_k} a_i = \max_{1 \leq k \leq p} \sum_{i=d_k}^{e_k} a_i.$$

This problem has been extensively studied in the literature because it has various applications. In particular, it amounts to load-balance n computations whose ordering must be preserved (hence the restriction to intervals) onto p identical processors. Then each a_i corresponds to the execution time of the i-th task, and the sum of the elements in interval $\mathcal{I}_k$ is the load of the processor which $\mathcal{I}_k$ is assigned to. Several algorithms and heuristics have been proposed to solve this load-balancing problem, including [6, 11, 10, 12, 13]. We refer the

reader to the survey paper by Pinar and Aykanat [14] for a detailed overview and comparison of the literature.

The advent of heterogeneous clusters leads to the following generalization of the 1D partitioning problem: the goal is to partition the n elements into p intervals whose element sums match p prescribed values (the processor speeds) as closely as possible. Let $\mathsf{s}_1, \mathsf{s}_2, \ldots, \mathsf{s}_p$ denote these values. We search for a partition of $[1..n]$ into p intervals $\mathcal{I}_k = [d_k, e_k]$ and for a permutation σ of $\{1, 2, \ldots, p\}$, with the objective to minimize:

$$\max_{1 \leq k \leq p} \frac{\sum_{i \in \mathcal{I}_k} a_i}{\mathsf{s}_{\sigma(k)}}.$$

Another way to express the problem is that intervals are now weighted by the s_i values, while we had $\mathsf{s}_i = 1$ for the homogeneous version. Can we extend the efficient algorithms described in [14] to solve the heterogeneous 1D partitioning problem, Hetero-1D-Partition for short? In fact, the problem seems combinatorial, because of the search over all possible permutations to weight the intervals. Indeed, we prove the NP-completeness of (the decision problem associated to) Hetero-1D-Partition.

Definition 1 (Hetero-1D-Partition-Dec). *Given n elements $a_1, a_2, \ldots, a_n$, p values $\mathsf{s}_1, \mathsf{s}_2, \ldots, \mathsf{s}_p$ and a bound K, can we find a partition of $[1..n]$ into p intervals $\mathcal{I}_1, \mathcal{I}_2, \ldots, \mathcal{I}_p$, with $\mathcal{I}_k = [d_k, e_k]$ and $d_k \leq e_k$ for $1 \leq k \leq p$, $d_1 = 1$, $d_{k+1} = e_k + 1$ for $1 \leq k \leq p-1$ and $e_p = n$, and a permutation σ of $\{1, 2, \ldots, p\}$, such that*

$$\max_{1 \leq k \leq p} \frac{\sum_{i \in \mathcal{I}_k} a_i}{\mathsf{s}_{\sigma(k)}} \leq K \quad ?$$

Theorem 1. *The* Hetero-1D-Partition-Dec *problem is NP-complete.*

Proof. The Hetero-1D-Partition-Dec problem clearly belongs to the class NP: given a solution, it is easy to verify in polynomial time that the partition into p intervals is valid and that the maximum sum of the elements in a given interval divided by the corresponding s value does not exceed the bound K. To establish the completeness, we use a reduction from NUMERICAL MATCHING WITH TARGET SUMS (NMWTS), which is NP-complete in the strong sense [9]. We consider an instance $\mathfrak{I}_1$ of NMWTS: given $3m$ numbers $x_1, x_2, \ldots, x_m$, $y_1, y_2, \ldots, y_m$ and $z_1, z_2, \ldots, z_m$, does there exist two permutations σ_1 and σ_2 of $\{1, 2, \ldots, m\}$, such that $x_i + y_{\sigma_1(i)} = z_{\sigma_2(i)}$ for $1 \leq i \leq m$? Because NMWTS is NP-complete in the strong sense, we can encode the $3m$ numbers in unary and assume that the size of $\mathfrak{I}_1$ is $O(m + M)$, where $M = \max_i\{x_i, y_i, z_i\}$. We also assume that $\sum_{i=1}^m x_i + \sum_{i=1}^m y_i = \sum_{i=1}^m z_i$, otherwise $\mathfrak{I}_1$ cannot have a solution.

We build the following instance $\mathfrak{I}_2$ of Hetero-1D-Partition-Dec (we use the formulation in terms of task weights and processor speeds which is more intuitive):

- We define $n = (M+3)m$ tasks, whose weights are outlined below:

$$A_1 \quad \underbrace{111\ldots1}_{M} \quad C \quad D \quad | \quad A_2 \quad \underbrace{111\ldots1}_{M} \quad C \quad D \quad | \quad \ldots \quad | \quad A_m \quad \underbrace{111\ldots1}_{M} \quad C \quad D$$

Here, $B = 2M$, $C = 5M$, $D = 7M$, and $A_i = B + x_i$ for $1 \leq i \leq m$. To define the a_i formally for $1 \leq i \leq n$, let $N = M + 3$. We have for $1 \leq i \leq m$:

$$\begin{cases} a_{(i-1)N+1} = A_i = B + x_i \\ a_{(i-1)N+j} = 1 \text{ for } 2 \leq j \leq M+1 \\ a_{iN-1} = C \\ a_{iN} = D \end{cases}$$

- For the number of processors (and intervals), we choose $p = 3m$. As for the speeds, we let s_i be the speed of processor P_i where, for $1 \leq i \leq m$:

$$\begin{cases} \mathsf{s}_i = B + z_i \\ \mathsf{s}_{m+i} = C + M - y_i \\ \mathsf{s}_{2m+i} = D \end{cases}$$

Finally, we ask whether there exists a solution matching the bound $K = 1$. Clearly, the size of $\mathfrak{I}_2$ is polynomial in the size of $\mathfrak{I}_1$. We now show that instance $\mathfrak{I}_1$ has a solution if and only if instance $\mathfrak{I}_2$ does.

Suppose first that $\mathfrak{I}_1$ has a solution, with permutations σ_1 and σ_2 such that $x_i + y_{\sigma_1(i)} = z_{\sigma_2(i)}$. For $1 \leq i \leq m$:

- We map each task A_i and the following $y_{\sigma_1(i)}$ tasks of weight 1 onto processor $P_{\sigma_2(i)}$.
- We map the following $M - y_{\sigma_1(i)}$ tasks of weight 1 and the next task, of weight C, onto processor $P_{m+\sigma_1(i)}$.
- We map the next task, of weight D, onto the processor P_{2m+i}.

We do have a valid partition of all the tasks into $p = 3m$ intervals. For $1 \leq i \leq m$, the load and speed of the processors are indeed equal:

- The load of $P_{\sigma_2(i)}$ is $A_i + y_{\sigma_1(i)} = B + x_i + y_{\sigma_1(i)}$ and its speed is $B + z_{\sigma_2(i)}$.
- The load of $P_{m+\sigma_1(i)}$ is $M - y_{\sigma_1(i)} + C$, which is equal to its speed.
- The load and speed of P_{2m+i} are both D.

The mapping does achieve the bound $K = 1$, hence a solution to $\mathfrak{I}_1$.

Suppose now that $\mathfrak{I}_2$ has a solution, i.e. a mapping matching the bound $K = 1$. We first observe that $\mathsf{s}_i < \mathsf{s}_{m+j} < \mathsf{s}_{2m+k} = D$ for $1 \leq i, j, k \leq m$. Indeed $\mathsf{s}_i = B + z_i \leq B + M = 3M$, $5M \leq \mathsf{s}_{m+j} = C + M - y_j \leq 6M$ and $D = 7M$. Hence each of the m tasks of weight D must be assigned to a processor of speed D, and it is the only task assigned to this processor. These m singleton assignments divide the set of tasks into m intervals, namely the set of tasks before the first task of weight D, and the $m - 1$ sets of tasks lying between two consecutive tasks of weight D. The total weight of each of these m intervals is $A_i + M + C > B + M + C = 10M$, while the largest speed of the $2m$ remaining processors is $6M$. Therefore each of them must be assigned to at least 2 processors each. However, there remains only $2m$ available processors, hence each interval is assigned exactly 2 processors.

Consider such an interval A_i 111...1 C with M tasks of weight 1, and let P_{i_1} and P_{i_2} be the two processors assigned to this interval. Tasks A_i and C are not assigned to the same processor (otherwise the whole interval would). So P_{i_1} receives task A_i and h_i tasks of weight 1 while P_{i_2} receives $M - h_i$ tasks of weight 1 and task C. The weight of P_{i_2} is $M - h + C \geq C = 5M$ while $\mathsf{s}_i \leq 3M$ for $1 \leq i \leq m$. Hence P_{i_1} must be some P_i, $1 \leq i \leq m$ while P_{i_2} must be some P_{m+j}, $1 \leq j \leq m$. Because this holds true on each interval, this defines two permutations $\sigma_2(i)$ and $\sigma_1(i)$ such that $P_{i_1} = P_{\sigma_2(i)}$ and $P_{i_2} = P_{\sigma_1(i)}$. Because the bound $K = 1$ is achieved, we have:

- $A_i + h_i = B + x_i + h_i \leq B + z_{\sigma_2(i)}$
- $M - h_i + C \leq C + M - y_{\sigma_1(i)}$

  Therefore $y_{\sigma_1(i)} \leq h_i$ and $x_i + h_i \leq z_{\sigma_2(i)}$, and

$$\sum_{i=1}^{m} x_i + \sum_{i=1}^{m} y_i \leq \sum_{i=1}^{m} x_i + \sum_{i=1}^{m} h_i \leq \sum_{i=1}^{m} z_i$$

By hypothesis, $\sum_{i=1}^{m} x_i + \sum_{i=1}^{m} y_i = \sum_{i=1}^{m} z_i$, hence all the previous inequalities are tight, and in particular $\sum_{i=1}^{m} x_i + \sum_{i=1}^{m} h_i = \sum_{i=1}^{m} z_i$.

We can deduce that $\sum_{i=1}^{m} y_i = \sum_{i=1}^{m} h_i = \sum_{i=1}^{m} z_i - \sum_{i=1}^{m} x_i$, and since $y_{\sigma_1(i)} \leq h_i$ for all i, we have $y_{\sigma_1(i)} = h_i$ for all i.

Similarly, we deduce that $x_i + h_i = z_{\sigma_2(i)}$ for all i, and therefore $x_i + y_{\sigma_1(i)} = z_{\sigma_2(i)}$.

Altogether, we have found a solution for $\mathfrak{I}_1$, which concludes the proof.

□

This important result leads to the NP-completeness of the period minimization problem.

Theorem 2. *The period minimization problem for pipeline graphs is NP-complete.*

Proof. Obviously, the optimization problem belongs to the class NP. Any instance of the HETERO-1D-PARTITION problem with n tasks a_i, p processor speeds s_i and bound K can be converted into an instance of the mapping problem with n stages of weight $\mathsf{w}_i = a_i$, letting all communication costs $\delta_i = 0$, targeting a *Communication Homogeneous* platform with the same p processors and homogeneous links of bandwidth $\mathsf{b} = 1$, and trying to achieve a period not greater than K. This concludes the proof. □

Since the period minimization problem is NP-hard, all bi-criteria problems are NP-hard.

4 Heuristics

The bi-criteria optimization problem is NP-hard, this is why we propose in this section several polynomial heuristics to tackle the problem. In the following, we denote by n the number of stages, and by p the number of processors.

4.1 Minimizing latency for a fixed period

In the first set of heuristics, the period is fixed a priori, and we aim at minimizing the latency while respecting the prescribed period. All the following heuristics sort processors by non-increasing speed, and start by assigning all the stages to the first (fastest) processor in the list. This processor becomes *used*.

H1-Sp mono P: Splitting mono-criterion – At each step, we select the used processor j with the largest period and we try to split its stage interval, giving some stages to the next fastest processor j' in the list (not yet used). This can be done by splitting the interval at any place, and either placing the first part of the interval on j and the remainder on j', or the other way round. The solution which minimizes $max(period(j), period(j'))$ is chosen if it is better than the original solution. Splitting is performed as long as we have not reached the fixed period or until we cannot improve the period anymore.

H2a-3-Explo mono: 3-Exploration mono-criterion – At each step we select the used processor j with the largest period and we split its interval into three parts. For this purpose we try to map two parts of the interval on the next pair of fastest processors in the list, j' and j'', and to keep the third part on processor j. Testing all possible permutations and all possible positions where to cut, we choose the solution that minimizes $max(period(j), period(j'), period(j''))$.

H2b-3-Explo bi: 3-Exploration bi-criteria – In this heuristic the choice of where to split is more elaborated: it depends not only of the period improvement, but also of the latency increase. Using the same splitting mechanism as in **3-Explo mono**, we select the solution that minimizes $max_{i\in\{j,j',j''\}}(\frac{\Delta latency}{\Delta period(i)})$. Here $\Delta latency$ denotes the difference between the global latency of the solution before the split and after the split. In the same manner $\Delta period(i)$ defines the difference between the period before the split (achieved by processor j) and the new period of processor i.

H3-Sp bi P: Splitting bi-criteria – This heuristic uses a binary search over the latency. For this purpose at each iteration we fix an authorized increase of the optimal latency (which is obtained by mapping all stages on the fastest processor), and we test if we get a feasible solution via splitting. The splitting mechanism itself is quite similar to **H1 Sp mono P** except that we choose the solution that minimizes $max_{i\in\{j,j'\}}(\frac{\Delta latency}{\Delta period(j)})$ within the authorized latency increase to decide where to split. While we get a feasible solution, we reduce the authorized latency increase for the next iteration of the binary search, thereby aiming at minimizing the mapping global latency.

4.2 Minimizing period for a fixed latency

In this second set of heuristics, latency is fixed, and we try to achieve a minimum period while respecting the latency constraint. As in the heuristics described above, first of all we sort processors according to their speed and map all stages on the fastest processor. The approach used here is the converse of the heuristics where we fix the period, as we start with an optimal solution concerning latency. Indeed, at each step we downgrade the solution with respect to its latency but improve it regarding its period.

H4-Sp mono L: Splitting mono-criterion – This heuristic uses the same method as **H1-Sp mono P** with a different break condition. Here splitting is performed as long as we do not exceed the fixed latency, still choosing the solution that minimizes $max(period(j), period(j'))$.

H5-Sp bi L: Splitting bi-criteria – This variant of the splitting heuristic works similarly to **H4 Sp mono L**, but at each step it chooses the solution which minimizes $max_{i\in\{j,j'\}}(\frac{\Delta latency}{\Delta period(i)})$ while the fixed latency is not exceeded.

The code for all these heuristics can be found on the Web at:
`http://graal.ens-lyon.fr/~vrehn/code/multicriteria/`

5 Experiments

Several experiments have been conducted in order to assess the performance of the heuristics described in Section 4. First we describe the experimental setting, then we report the results, and finally we provide a summary.

5.1 Experimental setting

We have generated a set of random applications with $n \in \{5, 10, 20, 40\}$ stages and a set of random *Communication Homogeneous* platforms with $p = 10$ or $p = 100$ processors.

In all the experiments, we fix $\mathsf{b} = 10$ for the link bandwidths. Moreover, the speed of each processor is randomly chosen as an integer between 1 and 20. We keep the latter range of variation throughout the experiments, while we vary the range of the application parameters from one set of experiments to the other. Indeed, although there are four categories of parameters to play with, i.e. the values of δ, w, s and b, we can see from equations (1) and (2) that only the relative ratios $\frac{\delta}{\mathsf{b}}$ and $\frac{\mathsf{w}}{\mathsf{s}}$ have an impact on the performance.

Each experimental value reported in the following has been calculated as an average over 50 randomly chosen application/platforms pairs. For each of these pairs, we report the performance of the six heuristics described in Section 4.

We report four main sets of experiments conducted both for $p = 10$ and $p = 100$ processors. For each experiment, we vary some key application/platform parameter to assess the impact of this parameter on the performance of the heuristics.

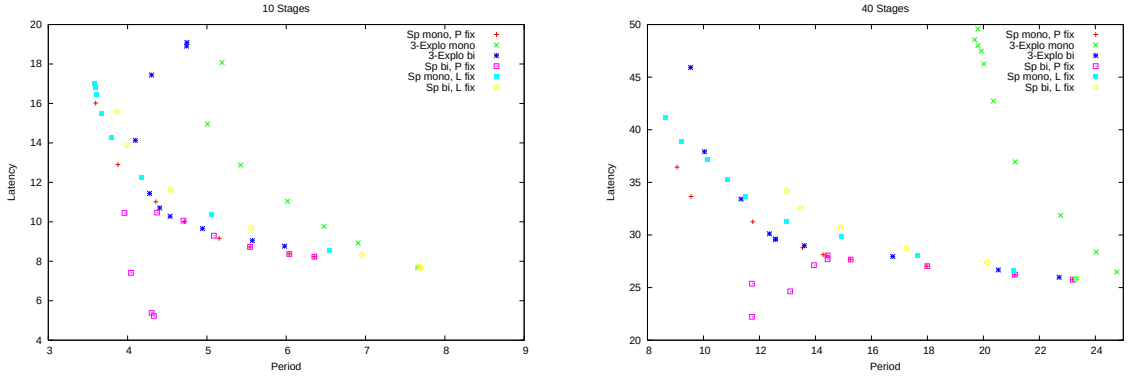
The first two experiments deal with applications where communications and computations have the same order of magnitude, and we study the impact of the degree of heterogeneity of the communications, i.e. of the variation range of the δ parameter:

- **(E1): balanced communication/computation, and homogeneous communications.** In the first set of experiments, the application communications are homogeneous, we fix $\delta_i = 10$ for $i = 0..n$. The computation time required by each stage is randomly chosen between 1 and 20. Thus, communications and computations are balanced within the application.

- **(E2): balanced communications/computations, and heterogeneous communications.** In the second set of experiments, the application communications are heterogeneous, chosen randomly between 1 and 100. Similarly to Experiment 1, the computation time required by each stage is randomly chosen between 1 and 20. Thus, communications and computations are still relatively balanced within the application.

The last two experiments deal with imbalanced applications: the third experiment assumes large computations (large value of the w to δ ratio), and the fourth one reports results for small computations (small value of the w to δ ratio):

- **(E3): large computations.** In this experiment, the applications are much more demanding on computations than on communications, making communications negligible with respect to computation requirements. We choose the communication time between 1 and 20, while the computation time of each application is chosen between 10 and 1000.



(a) 10 stages.

(b) 40 stages.

Figure 2: (E1) Balanced communications/computations, and homogeneous communications.

- **(E4): small computations.** The last experiment is the opposite to Experiment 3 since computations are now negligible compared to communications. The communication time is still chosen between 1 and 20, but the computation time is now chosen between 0.01 and 10.

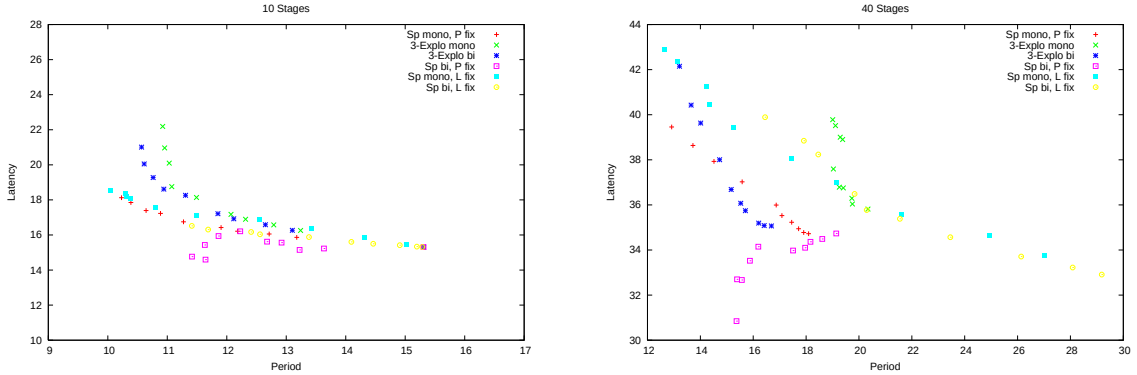
5.2 Results

Results for the entire set of experiments can be found on the Web at http://graal.ens-lyon.fr/~vrehn/code/multicriteria/. In the following we only present the most significant plots.

5.2.1 With $p = 10$ processors

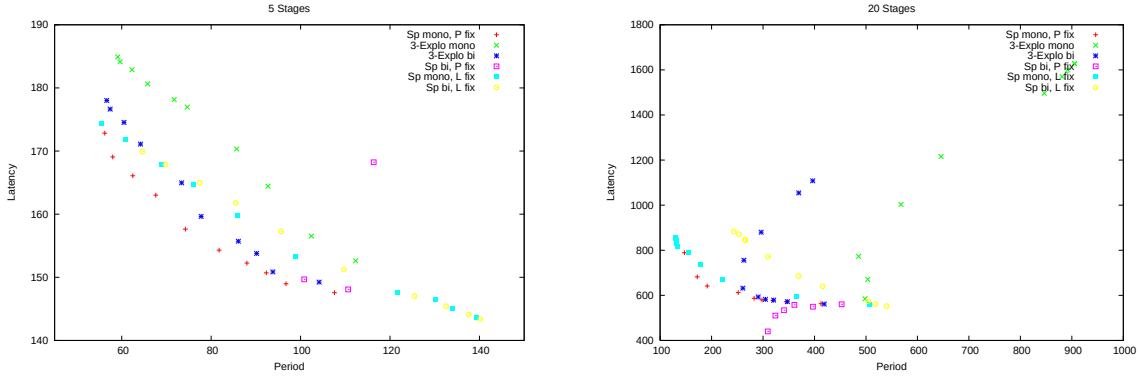
For (E1) we see that all heuristics follow the same curve shape, with the exception of heuristic **Sp bi P** (cf. Figure 2), which has a different behavior. We observe this general behavior of the different heuristics in all the experiments. The heuristic **Sp bi P** initially finds a solution with relatively small period and latency, and then tends to increase both. The other five heuristics achieve small period times at the price of long latencies and then seem to converge to a somewhat shorter latency. We notice that the simplest splitting heuristics perform very well: **Sp mono P** and **Sp mono L** achieve the best period, and **Sp mono P** has the lower latency. **Sp bi P** minimizes the latency with competitive period sizes. Its counterpart **Sp bi L** performs poorly in comparison. **3-Explo mono** and **Sp bi L** cannot keep up with the other heuristics (but the latter achieves better results than the former). In the middle range of period values, **3-Explo bi** achieves comparable latency values with those of **Sp mono P** and **Sp bi P**.

For (E2), if we leave aside **Sp bi P**, we see that **Sp mono P** outperforms the other heuristics almost everywhere with the following exception: with 40 stages and a large fixed period, **3-Explo bi** obtains the better results. **Sp bi P** achieves by far the best latency times, but the period times are not as good as those of **Sp bi P** and **3-Explo bi**. We observe that the competitiveness of **3-Explo bi** increases with the increase of the number of stages. **Sp mono L** achieves period values just as small as **Sp mono P** but the corresponding latency is



(a) 10 stages. (b) 40 stages.

Figure 3: (E2) Balanced communications/computations, and heterogeneous communications.



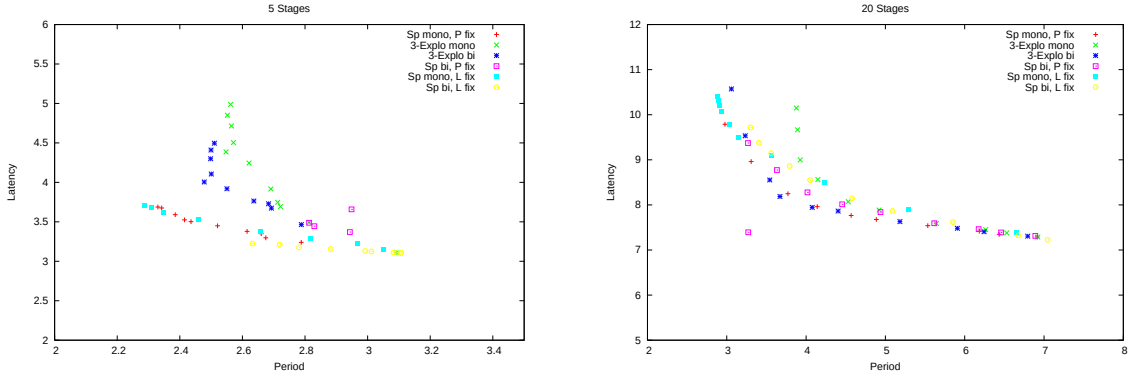
(a) 5 stages. (b) 20 stages.

Figure 4: (E3) Large computations.

higher and once again it performs better than its bi-criteria counterpart **Sp bi L**. The poorest results are obtained by **3-Explo mono**.

The results of (E3) are much more scattered than in the other experiments (E1, E2 and E4) and this difference even increases with rising n. When $n = 5$, the results of the different heuristics are almost parallel so that we can state the following hierarchy: **Sp mono P**, **3-Explo bi**, **Sp mono L**, **Sp bi L** and finally **3-Explo mono**. For this experiment **Sp bi P** achieves rather poor results. With the increase of the number of stages n, the performance of **Sp bi P** gets better and this heuristic achieves the best latency, but its period values cannot compete with **Sp mono P** and **3-Explo bi**. These latter heuristics achieve very good results concerning period durations. On the contrary, **3-Explo mono** bursts its period and latency times. **3-Explo bi** loses its second position for small period times compared to **Sp mono L**, but when period times are higher it recovers its position in the hierarchy.

In (E4), **3-Explo mono** performs the poorest. Nevertheless the gap is smaller than in (E3) and for high period times and $n \geq 20$, its latency is comparable to those of the other



(a) 5 stages.

(b) 20 stages.

Figure 5: (E4) Small computations.

Exp.	Heur.	Number of stages				Exp.	Heur.	Number of stages			
		5	10	20	40			5	10	20	40
E1	H1	3.0	3.3	5.0	5.0	E2	H1	9.7	10.0	11.0	11.0
	H2	3.0	4.7	9.0	18.0		H2	10.3	10.0	12.0	19.0
	H3	3.0	4.0	5.0	5.0		H3	10.0	10.0	11.0	11.0
	H4	3.3	3.3	6.0	10.0		H4	11.3	11.0	13.0	15.0
	H5	4.5	6.0	13.0	25.0		H5	11.7	15.0	22.0	32.0
	H6	4.5	6.0	13.0	25.0		H6	11.7	15.0	22.0	32.0
E3	H1	50.0	70.0	100.0	250.0	E4	H1	2.2	2.3	2.3	2.3
	H2	50.0	140.0	450.0	950.0		H2	2.4	2.7	3.7	7.0
	H3	50.0	90.0	250.0	400.0		H3	2.4	2.7	3.0	4.0
	H4	100.0	140.0	300.0	650.0		H4	2.8	2.7	3.0	4.0
	H5	140.0	270.0	500.0	1000.0		H5	3.0	4.0	7.0	11.0
	H6	140.0	270.0	500.0	1000.0		H6	3.0	4.0	7.0	11.0

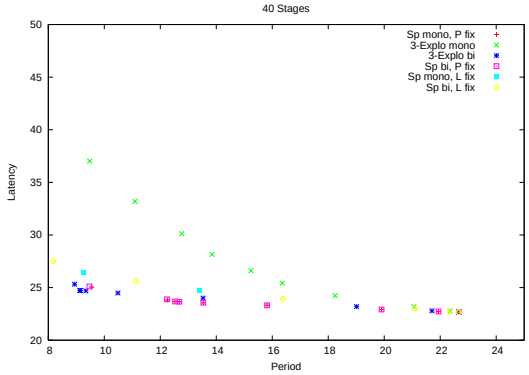
Table 1: Failure thresholds of the different heuristics in the different experiments.

heuristics. For $n \geq 20$, **3-Explo bi** achieves for the first time the best results and the latency of **Sp bi P** is only one time lower. When $n = 5$, **Sp bi L** achieves the best latency, but the period values are not competitive with **Sp mono P** and **Sp mono L**, which obtain the smallest periods (for slightly higher latency times).

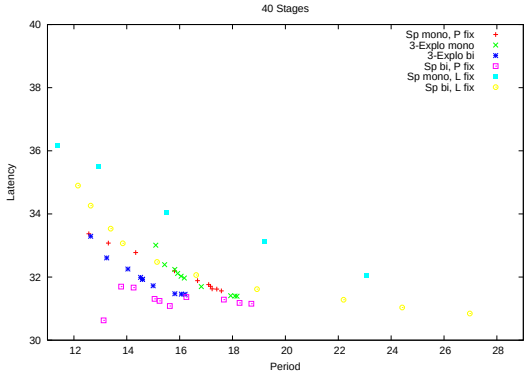
In Table 1 the **failure thresholds** of the different heuristics are shown. We denote by failure threshold the largest value of the fixed period or latency for which the heuristic was not able to find a solution. We state that **Sp mono P** has the smallest failure thresholds whereas **3-Explo mono** has the highest values. Surprisingly the failure thresholds (for fixed latencies) of the heuristics **Sp mono L** and **Sp bi L** are the same, but their performance differs enormously as stated in the different experiments.

5.2.2 With $p = 100$ processors

Many results are similar with $p = 10$ and $p = 100$ processors, thus we only report the main differences. First we observe that both periods and latencies are lower with the increasing number of processors. This is easy to explain, as all heuristics always choose fastest processors

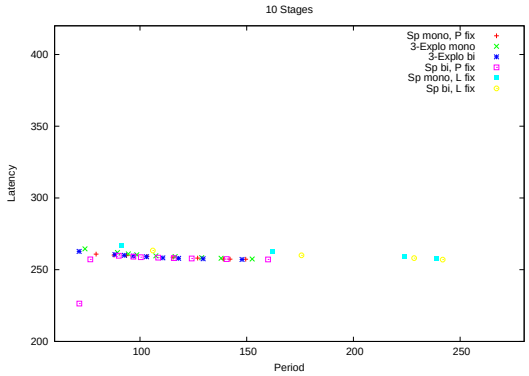


(a) (E1) 40 stages, hom. comms.

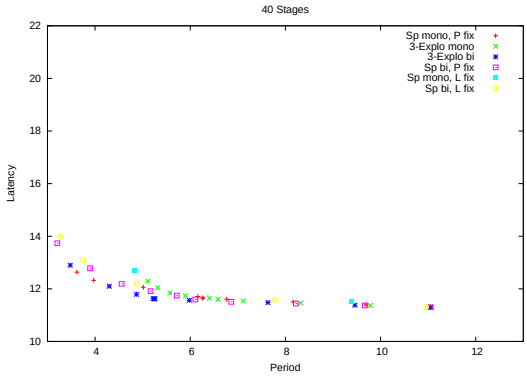


(b) (E2) 40 stages, het. comms.

Figure 6: Extension to 100 processors, balanced communications/computations.



(a) (E3) 10 stages, large computations.



(b) (E4) 40 stages, small computations.

Figure 7: Extension to 100 processors, imbalanced communications/computations.

first, an there is much more choice with $p = 100$. All heuristics keep their general behavior, i.e. their curve characteristics. But the relative performance of some heuristics changes dramatically. The results of **3-Explo mono** are much better, and we do get adequate latency times (compare Figures 2(b) and 6(a)). Furthermore the multi-criteria heuristics turn out to be much more performant. An interesting example can be seen in Figure 6(b): all multi-criteria heuristics outperform their mono-criterion counterparts, even **Sp bi L**, which never had a better performance than **Sp mono L** when $p = 10$.

In the case of imbalanced communications/computations, we observe that all heuristics achieve almost the same results. The only exception is the binary-search heuristic **Sp bi P**, which shows a slightly superior performance as can be seen in Figure 7(a). The performance of **3-Explo bi** depends on the number of stages. In general it is superseded by **Sp mono P**, when $n \leq 10$, but for $n \geq 20$ **3-Explo bi** it owns the second position after **Sp bi L** and even performs best in the configuration small computations/$n = 40$ (see Figure 7(b)).

5.2.3 Summary

Overall we conclude that the performance of bi-criterion heuristics versus mono-criterion heuristics highly depends on the number of available processors.

For a small number of processors, the simple splitting technique which is used in **Sp mono P** and **Sp mono L** is very competitive as it almost always minimizes the period with acceptable latency values. The bi-criteria splitting **Sp bi P** mainly minimizes latency values at the price of longer periods. Nevertheless depending upon the application, this heuristics seems to be very interesting, whenever small latencies are demanded. On the contrary, its counterpart **Sp bi L** does not provide convincing results. Finally, both 3-Exploration heuristics do not achieve the expected performance.

However when increasing he number of available processors, we observe a significant improvement of the behavior of bi-criteria heuristics. **Sp bi L** turns out to outperform the mono-criterion version and **Sp bi P** upgrades its period times such that it outplays its competitors. Finally both 3-Exploration heuristics perform much better and **3-Explo bi** finds its slot.

6 Related work

As already mentioned, this work is an extension of the work of Subhlok and Vondran [19, 20] for pipeline applications on homogeneous platforms. We extend the complexity results to heterogeneous platforms. We have also discussed the relationship with the chains-to-chains problem [6, 11, 10, 12, 13, 14] in Section 1.

Several papers consider the problem of mapping communicating tasks onto heterogeneous platforms, but for a different applicative framework. In [21], Taura and Chien consider applications composed of several copies of the same task graph, expressed as a DAG (directed acyclic graph). These copies are to be executed in pipeline fashion. Taura and Chien also restrict to mapping all instances of a given task type (which corresponds to a stage in our framework) onto the same processor. Their problem is shown NP-complete, and they provide an iterative heuristic to determine a good mapping. At each step, the heuristic refines the current clustering of the DAG. Beaumont et al. [1] consider the same problem as Taura and Chien, i.e. with a general DAG, but they allow a given task type to be mapped onto several processors, each executing a fraction of the total number of tasks. The problem remains NP-complete, but becomes polynomial for special classes of DAGs, such as series-parallel graphs. For such graphs, it is possible to determine the optimal mapping owing to an approach based upon a linear programming formulation. The drawback with the approach of [1] is that the optimal throughput can only be achieved through very long periods, so that the simplicity and regularity of the schedule are lost, while the latency is severely increased.

Another important series of papers comes from the DataCutter project [8]. One goal of this project is to schedule multiple data analysis operations onto clusters and grids, decide where to place and/or replicate various components [3, 2, 18]. A typical application is a chain of consecutive filtering operations, to be executed on a very large data set. The task graphs targeted by DataCutter are more general than linear pipelines or forks, but still more regular than arbitrary DAGs, which makes it possible to design efficient heuristics to solve the previous placement and replication optimization problems. However, we point out that a recent paper [22] targets workflows structured as arbitrary DAGs and considers bi-criteria optimization problems on homogeneous platforms. The paper provides many interesting ideas

and several heuristics to solve the general mapping problem. It would be very interesting to experiment these heuristics on the simple pipeline mapping problem, and to compare it to our own heuristics designed specifically for pipeline workflows.

7 Conclusion

In this paper, we have studied a difficult bi-criteria mapping problem onto *Communication Homogeneous* platforms. We restricted ourselves to the class of applications which have a pipeline structure, and studied the complexity of the problem. To the best of our knowledge, it is the first time that a multi-criteria pipeline mapping is studied from a theoretical perspective, while it is quite a standard and widely used pattern in many real-life applications.

While minimizing the latency is trivial, the problem of minimizing the pipeline period is NP-hard, and thus the bi-criteria problem is NP-hard. We provided several efficient polynomial heuristics, either to minimize the period for a fixed latency, or to minimize the latency for a fixed period.

These heuristics have been extensively compared through simulation. Results highly depend on platform parameters such as number of stages and number of available processors. Simple mono-criterion splitting heuristics perform very well when there is a limited number of processors, whereas bi-criterion heuristics perform much better when increasing the number of processors. Overall, the introduction of bi-criteria heuristics was not fully successful for small clusters but turned out to be mandatory to achieve good performance on larger platforms.

There remains much work to extend the results of this paper. We designed heuristics for *Communication Homogeneous* platforms, and finding efficient bi-criteria heuristics was already a challenge. It would be interesting to deal with fully heterogeneous platforms, but it seems to be a difficult problem, even for a mono-criterion optimization problem. In the longer term, we plan to perform real experiments on heterogeneous platforms, using an already-implemented skeleton library, in order to compare the effective performance of the application for a given mapping (obtained with our heuristics) against the theoretical performance of this mapping.

A natural extension of this work would be to consider other widely used skeletons. For example, when there is a bottleneck in the pipeline operation due to a stage which is both computationally-demanding and not constrained by internal dependencies, we can nest another skeleton in place of the stage. For instance a farm or deal skeleton would allow to split the workload of the initial stage among several processors. Using such deal skeletons may be either the programmer's decision (explicit nesting in the application code) or the result of the mapping procedure. Extending our mapping strategies to automatically identify opportunities for deal skeletons, and implement these, is a difficult but very interesting perspective.

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