Multi-objective list scheduling of workflow applications in distributed computing infrastructures

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**HIGHLIGHTS**
- We propose a multi-objective scheduling framework for scientific workflows.
- We instantiate the framework for makespan, cost, energy, and reliability.
- We design a novel multi-objective list scheduling heuristic for workflows.
- We approximate the optimal solutions based on Pareto domination of user preferences.
- The solutions have better coverage compared to two related approaches.

**ABSTRACT**
Executing large-scale applications in distributed computing infrastructures (DCI), for example modern Cloud environments, involves optimization of several conflicting objectives such as makespan, reliability, energy, or economic cost. Despite this trend, scheduling in heterogeneous DCIs has been traditionally approached as a single or bi-criteria optimization problem. In this paper, we propose a generic multi-objective optimization framework supported by a list scheduling heuristic for scientific workflows in heterogeneous DCIs. The algorithm approximates the optimal solution by considering user-specified constraints on objectives in a dual strategy: maximizing the distance to the user's constraints for dominant solutions and minimizing it otherwise. We instantiate the framework and algorithm for a four-objective case study comprising makespan, economic cost, energy consumption, and reliability as optimization goals. We implemented our method as part of the ASKALON environment (Fahringer et al., 2007) for Grid and Cloud computing and demonstrate through extensive real and synthetic simulation experiments that our algorithm outperforms related bi-criteria heuristics while meeting the user constraints most of the time.

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1. Introduction
Scientific workflows emerged in the last decade as an attractive paradigm for programming large-scale applications in heterogeneous distributed computing infrastructures (DCI) such as Grids and Clouds. In this context, scheduling heterogeneous tasks including workflows is one of the traditional challenges in parallel and distributed computing. If we focus on the execution time also referred as makespan, the problem has been shown to be NP-complete, hence no polynomial algorithm for solving it exists (assuming $P \neq NP$). While this has been for decades the only optimization parameter of interest, modern DCIs are bringing along nowadays other parameters of equal importance such as reliability and economic cost (in Clouds), while recently energy consumption raises ever greater concerns too. Real-world scenarios are therefore confronted with a multi-objective optimization problem where many of these objectives are conflicting. For example, fast processors are typically rented by Cloud providers at higher prices, consume more energy, and may become unreliable due to the large user contention. In these scenarios, there is no single solution that optimizes all objectives, but a set of tradeoff solutions known as the Pareto frontier.

Until today, traditional scheduling researches [19] targeted makespan as the only optimization goal, while several isolated efforts addressed the problem by considering at most two objectives [17,21]. Although scheduling problems involve today multi-objective optimizations [14], a generic scheduling algorithm and framework for optimizing multiple conflicting objectives is still missing. Due to the NP-hard complexity of the makespan scheduling problem, practical approaches need to resort on heuristics to approximate the optimal solutions also in the multi-objective case. In this paper, we present a polynomial multi-objective algorithm for scientific workflow applications in heterogeneous DCIs that brings a two-fold novelty. First, we propose a general framework based on the multi-objective optimization theory for static
The work in [21] proposes a bi-criteria genetic optimization algorithm that defines the fitness function as a combination of the partial fitness functions of the objectives. The algorithm is budget-constrained and considers no execution deadline. The algorithm in [2] targets DAG execution time minimization while keeping the number of failures equal to a constant $x$ by replicating $x + 1$ copies of each activity to different processors. The authors also suggest an extended algorithm which tries to improve the system reliability using redundancy.

2.3. Pareto-based approaches

The algorithm in [23] considers multi-objectives evolutionary algorithms for general workflow scheduling. The output is an approximation of the Pareto set and selecting the proper solution from this set remains a problem. The work in [11] is a similar approach for Grid workflow scheduling based on a multi-objective differential evolutionary algorithm that approximates the Pareto set by considering time and cost as objectives. In general, the major weakness of the evolutionary algorithms for scheduling problems is their slow convergence to good solutions, as we demonstrate in our experiments (Section 8). In contrast to Pareto-based approaches, our proposed algorithm can be categorized as an a-priori multi-objective scheduling method [14] looking for a single solution that satisfies the user’s preferences and constraints. Our case study considers four objectives and uses Pareto relationships to find a solution that dominates or approaches the user constraints.

3. Multi-objective optimization background

We introduce several important concepts of the multi-objective optimization theory used in our method involving two steps: finding a set of optimal solutions and selecting the fittest solutions according to user preferences. We must distinguish two spaces as part of multi-objective optimization problems:

1. solution (or design) space $X$ comprising all feasible solutions, for example the complete set of possible schedules of an application;
2. objective (or criterion) space $O$ comprising an image of every element of $X$ mapped to objective values.

In other words, each $x \in X$ maps to an image $o \in O$ which represents the objective values of $x$, as depicted in Fig. 1. A point $o \in O$ dominates $o' \in O$, denoted as $o \succ o'$, if $o$ is not worse than $o'$ with respect to all objectives and $o$ is better for at least one of them. A point $o' \in O$ is said to be non-dominated if there is no $o \in O$ that dominates $o'$. A solution $x \in X$ is Pareto optimal (efficient) if its image in the objective space is non-dominated. The set of all Pareto-optimal solutions is called a Pareto-optimal set. The image set of all members of a Pareto-optimal set in the objective space is called a Pareto frontier. A vector comprising the best possible values for all objectives is called a Utopia point representing the ideal solution. Such a vector typically dominates the whole Pareto frontier and is therefore impossible to realistically achieve. A vector comprising the worst possible values for all existing objectives is called a Nadir point. The entire Pareto frontier dominates this point.

Let us assume that Fig. 1(b) depicts the objective space of the solution space of Fig. 1(a). The three solutions $x$, $x'$ and $x''$ map to points $o$, $o'$ and $o''$ in the objective space. If the optimization in this sample is minimizing both objectives $O_1$ and $O_2$, then the point $o$ in the objective space is dominated by the point $o'$, while $o''$ has better values for both objectives $O_1$ and $O_2$. Two points $o'$ and $o''$ are non-dominated points and consequently, the set $\{o', o''\}$ is the Pareto frontier. Therefore, the corresponding solutions $x'$ and $x''$ are Pareto optimal and the set $\{x', x''\}$ is the Pareto set. The Utopia point is determined by selecting the best values of the objectives, as shown in Fig. 1(b). In contrast, the Nadir point is determined by selecting the worst values of the objectives. Typically, we need a single final solution selected by analysis of the preferences.
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