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Decision Making Based on Approximate and Smoothed Pareto Curves ⋆

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Abstract. We consider bicriteria optimization problems and investigate the relationship between two standard approaches to solving them: (i) computing the *Pareto curve* and (ii) the so-called *decision maker's approach* in which both criteria are combined into a single (usually non-linear) objective function. Previous work by Papadimitriou and Yannakakis showed how to efficiently approximate the Pareto curve for problems like Shortest Path, Spanning Tree, and Perfect Matching. We wish to determine for which classes of combined objective functions the approximate Pareto curve also yields an approximate solution to the decision maker's problem. We show that an FPTAS for the Pareto curve also gives an FPTAS for the decision maker's problem if the combined objective function is growth bounded like a quasi-polynomial function. If these functions, however, show exponential growth then the decision maker's problem is NP-hard to approximate within any factor. In order to bypass these limitations of approximate decision making, we turn our attention to Pareto curves in the probabilistic framework of smoothed analysis. We show that in a smoothed model, we can efficiently generate the (complete and exact) Pareto curve with a small failure probability if there exists an algorithm for generating the Pareto curve whose worst case running time is pseudopolynomial. This way, we can solve the decision maker's problem w.r.t. any non-decreasing objective function for randomly perturbed instances of, e.g., Shortest Path, Spanning Tree, and Perfect Matching.

1 Introduction

We study *bicriteria optimization* problems, in which there are two criteria, say cost and weight, that we are interested in optimizing. In particular, we consider bicriteria Spanning Tree, Shortest Path and Perfect Matching problems. For such problems with more than one objective, it is not immediately clear how to define an optimal solution. However, there are two common approaches to bicriteria optimization problems.

The first approach is to generate the set of *Pareto optimal* solutions, also known as the *Pareto set*. A solution S^* is Pareto optimal if there exists no other solution S that *dominates* S^*, i.e. has cost and weight less or equal to the cost and weight of S^* and at least one inequality is strict. The set of cost/weight combinations of the Pareto optimal solutions is called the *Pareto curve*. Often it is sufficient to know only one solution for each possible cost/weight combination. Thus we assume that the Pareto set is reduced and does not contain two solutions with equal cost and equal weight. Under this assumption there is a one-to-one mapping between the elements in the reduced Pareto set and the points on the Pareto curve.

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The second approach is to compute a solution that minimizes some *non-decreasing* function $f : \mathbb{R}_+^2 \to \mathbb{R}_+$. This approach is often used in the field of *decision making*, in which a decision maker is not interested in the whole Pareto set but in a single solution with certain properties. For example, given a graph $G = (V, E)$ with cost $c(e)$ and weight $w(e)$ on each edge, one could be interested in finding an s-t-path P that minimizes the value $(\sum_{e\in P} w(e))^2 + (\sum_{e\in P} c(e))^2$. For a given function $f : \mathbb{R}_+^2 \to \mathbb{R}_+$ and a bicriteria optimization problem Π we will denote by f-Π the problem of minimizing f over all solutions of Π.

Note that these two approaches are actually related: for any *non-decreasing* function f, there is a solution that minimizes f that is also Pareto optimal. A function $f : \mathbb{R}_+^2 \to \mathbb{R}_+$ is non-decreasing if for any $x_1, x_2, y_1, y_2 \in \mathbb{R}_+$ where $x_1 \leq x_2$ and $y_1 \leq y_2$: $f(x_1, y_1) \leq f(x_2, y_2)$. Thus, if for a particular bicriteria optimization problem, we can find the Pareto set efficiently and it has polynomial size, then we can efficiently find a solution that minimizes any given non-decreasing function. It is known, however, that there are instances of Spanning Tree, Shortest Path and Perfect Matching problems such that even the reduced Pareto set is exponentially large [6]. Moreover, while efficient (i.e. polynomial in the size of the Pareto set) algorithms are known for a few standard bicriteria optimization problems such as the Shortest Path problem [7, 18], it is not known how to generate the Pareto set efficiently for other well-studied bicriteria optimization problems such as the Spanning Tree and the Perfect Matching problem.

There has been a long history of *approximating* the Pareto set starting with the pioneering work of Hansen [7] on the Shortest Path problem. We say a solution S is ε-approximated by another solution S' if $c(S')/c(S) \leq 1 + \varepsilon$ and $w(S')/w(S) \leq 1 + \varepsilon$ where $c(S)$ and $w(S)$ denote the total cost and weight of a solution S. We say that $\mathcal{P}_\varepsilon$ is an ε-approximation of a Pareto set $\mathcal{P}$ if for any solution $S \in \mathcal{P}$ there is a solution $S' \in \mathcal{P}_\varepsilon$ that ε-approximates it. Papadimitriou and Yannakakis showed that for any Pareto set $\mathcal{P}$, there is an ε-approximation of $\mathcal{P}$ with polynomially many points [13] (w.r.t. the input size and $1/\varepsilon$). Furthermore they gave necessary and sufficient conditions under which there is an FPTAS to generate $\mathcal{P}_\varepsilon$. Vassilvitskii and Yannakakis [17] showed how to compute ε-approximate Pareto curves of almost minimal size.

1.1 Previous Work

There exists a vast body of literature that focuses on f-Π problems. For instance it is well known that, if f is a concave function, an optimal solution of the f-Π problem can be found on the border of the convex hull of the solutions [9]. For some problems there are algorithms generating this set of solutions. In particular, for the Spanning Tree Problem it is known that there are only polynomially many solutions on the border of the convex hull [5], and efficient algorithms for enumerating them exist [1]. Thus, there are polynomial-time algorithms for solving f-Spanning Tree if f is concave. Katoh has described how one can use f-Spanning Tree problems with concave objective functions to solve many other problems in combinatorial optimization [10]. For instance, a well studied application is the Minimum Cost Reliability Spanning Tree Problem, where one is interested in finding a spanning tree minimizing the ratio of cost to reliability. This approach, however, is limited to optimizing the ratio of these two criteria. It is also known how to solve the f-Shortest Path problem for functions f being both pseudoconcave and pseudoconvex in polynomial time [8]. Tsaggouris and Zaroliagis [15] investigated the Non-additive Shortest Path Problem (NASP), which is to find a path P minimizing $f_c(c(P)) + f_w(w(P))$, for some convex functions f_c and f_w. This problem arises as core problem in different applications, e.g., in the context of computing traffic equilibria. They developed exact algorithms with exponential running time using a Lagrangian relaxation and the so called *Extended Hull Algorithm* to solve NASP.

We consider bicriteria optimization problems in the smoothed analysis framework of Spielman and Teng [14]. Spielman and Teng consider a semi-random input model where an adversary specifies an input which is then randomly perturbed. Input instances occurring in practice usually possess a certain structure but usually also have small random influences. Thus, one can hope that semi-random input models are more realistic than worst case and average case input models since the adversary can specify an arbitrary input with a certain structure that is subsequently only slightly perturbed. Since the seminal work of Spielman and Teng explaining the efficiency of the Simplex method in practical applications [14], many other problems have been considered in the framework of smoothed analysis. Of particular relevance to the results in this paper are the results of Beier and Vöcking [3, 4]. First, they showed that the expected number of Pareto optimal solutions of any bicriteria optimization problem with two linear objective functions is polynomial if the coefficients in the objective functions are randomly perturbed [3]. Then they gave a complete characterization which linear binary optimization problems have polynomial smoothed complexity, namely they showed that a linear binary optimization problem has polynomial smoothed complexity if and only if there exists an algorithm whose running time is pseudopolynomially bounded in the perturbed coefficients [4]. The only way to apply their framework to multicriteria optimization is by moving all but one of the criteria from the objective function to the constraints.

1.2 Our Results

We study the complexity of the bicriteria optimization problems f-Shortest Path, f-Spanning Tree and f-Perfect Matching under different classes of functions f. Our study begins with an analysis showing that these problems are NP-hard even under seemingly harmless objective functions of the form *Minimize* $(\sum_{e\in S} c(e))^a + (\sum_{e\in S} w(e))^b$, where a, b are arbitrary natural numbers with $a \geq 2$ or $b \geq 2$. Thus, we focus on the approximability of these problems. An FPTAS to approximate the Pareto curve of a problem Π can be transformed into an FPTAS for f-Π for any polynomial function f easily. We show that this transformation also works for *quasi-polynomial* functions and, more generally, for non-decreasing functions whose first derivative is bounded from above like the first derivative of a quasi-polynomial function. (A similar result has been shown recently in an independent work by Tsaggouris and Zaroliagis [16].) Additionally, we show that the restriction to quasi-polynomial growth is crucial.

In order to bypass the limitations of approximate decision making seen above, we turn our attention to Pareto curves in the probabilistic framework of smoothed analysis. We show that in a smoothed model, we can efficiently generate the (complete and exact) Pareto curve of Π with a small failure probability if there exists an algorithm for generating the Pareto curve whose worst case running time is pseudopolynomial (w.r.t. costs and weights). Previously, it was known that the number of Pareto optimal solutions is polynomially bounded if the input numbers are randomly perturbed [3]. This result, however, left open the question of how to generate the set of Pareto-optimal solutions efficiently (except for the Shortest Path problem). The key result in the smoothed analysis presented in this paper is that typically the smallest gap (in cost and weight) between neighboring solutions on the Pareto curve is bounded by $n^{-O(1)}$ from below. This result enables us to generate the complete Pareto curve by taking into account only a logarithmic number of bits of each input number. This way, an algorithm with pseudopolynomial worst-case complexity for generating the Pareto curve can be turned into an algorithm with polynomial smoothed complexity.

It can easily be seen that, for any bicriteria problem Π, a pseudopolynomial algorithm for the exact and single objective version of Π (e.g. an algorithm for answering the question "Does there exist a spanning tree with costs exactly C?") can be turned into an algorithm with pseudopolynomial worst-case complexity for generating the Pareto curve. Therefore, in the smoothed model, there exists a polynomial-time algorithm for enumerating the Pareto curve of Π with small failure probability if there exists a pseudopolynomial algorithm for the exact and single objective version of Π. Furthermore, given the exact Pareto curve for a problem Π, one can solve f-Π exactly. Thus, in our smoothed model, we can, for example, find spanning trees that minimize functions that are hard to approximate within any factor in the worst case.

2 Approximating Bicriteria Optimization Problems

In this section, we consider bicriteria optimization problems in which the goal is to minimize a single objective function that takes two criteria as inputs. We consider functions of the form $f(x, y)$ where x represents the total cost of a solution and y represents the total weight of a solution. In Section 2.1, we present NP-hardness and inapproximability results for the f-Spanning Tree, f-Shortest Path, and f-Perfect Matching problems for general classes of functions. In Section 2.2, we show that we can give an FPTAS for any f-Π problem for a large class of quasi-polynomially bounded non-decreasing functions f if there is an FPTAS for generating an ε-approximate Pareto curve for Π. Papadimitriou and Yannakakis showed how to construct such an FPTAS for approximating the Pareto curve of Π given an exact pseudopolynomial algorithm for the problem [13]. For the exact s-t-Path problem, dynamic programming yields a pseudopolynomial algorithm [18]. For the exact Spanning Tree problem, Barahona and Pulleyblank gave a pseudopolynomial algorithm [2]. For the exact Matching problem, there is a fully polynomial RNC scheme [12, 11]. Thus, for any quasi-polynomially bounded non-decreasing objective function, these problems have an FPTAS.

2.1 Some Hardness Results

In this section we present NP-hardness results for the bicriteria f-Spanning Tree, f-Shortest Path and f-Perfect Matching problems in which the goal is to find a feasible solution S that minimizes an objective function in the form $f(x,y) = x^a + y^b$, where $x = c(S)$, $y = w(S)$, and $a, b \in \mathbb{N}$ are constants with $a \geq 2$ or $b \geq 2$. Note that the NP-hardness of such functions when $a = b$ follows quite directly from a simple reduction from PARTITION. When a and b differ, one can modify this reduction slightly by scaling the weights.

Lemma 1 *Let $f(x,y) = x^a + y^b$ with $a, b \in \mathbb{N}$ and $a \geq 2$ or $b \geq 2$. Then the f-SPANNING TREE, f-SHORTEST PATH, and f-PERFECT MATCHING problems are NP-hard.*

We will now have a closer look at exponential functions $f(x,y) = 2^{x^\delta} + 2^{y^\delta}$ for some $\delta > 0$. In the following, we assume that there is an oracle, which given two solutions S_1 and S_2, decides in constant time whether $f(c(S_1), w(S_1))$ is larger than $f(c(S_2), w(S_2))$ or vice versa. We show that even in this model of computation there is no polynomial time approximation algorithm with polynomial approximation ratio, unless $P = NP$. (The proofs of Lemma 1 and Lemma 2 can be found in a full version of this paper.)

Lemma 2 *Let $f(x,y) = 2^{x^\delta} + 2^{y^\delta}$ with $\delta > 0$. There is no approximation algorithm for the f-SPANNING TREE, f-SHORTEST PATH, and f-PERFECT MATCHING problem with polynomial running time and approximation ratio less than 2^{B^d} for any constant $d > 0$ and $B = \sum_{e \in E} c(e) + w(e)$, unless $P = NP$.*

2.2 An FPTAS for a Large Class of Functions

In this section we present a sufficient condition for the objective function f under which there is an FPTAS for the f-SPANNING TREE, the f-SHORTEST PATH and the f-PERFECT MATCHING problem. In fact, our result is not restricted to these problems but applies to every bicriteria optimization problem Π with an FPTAS for approximating the Pareto curve.

We begin by introducing a restricted class of functions f.

Definition 3 *We call a non-decreasing function $f : \mathbb{R}_+^2 \to \mathbb{R}_+$* quasi-polynomially bounded *if there exist constants $c > 0$ and $d > 0$ such that for every $x, y \in \mathbb{R}_+$*

$$\frac{\partial f(x,y)}{\partial x} \cdot \frac{1}{f(x,y)} \leq \frac{c \cdot \ln^d x \cdot \ln^d y}{x}$$

and

$$\frac{\partial f(x,y)}{\partial y} \cdot \frac{1}{f(x,y)} \leq \frac{c \cdot \ln^d x \cdot \ln^d y}{y}.$$

Observe that every non-decreasing polynomial is quasi-polynomially bounded. Furthermore the sum of so-called quasi-polynomial functions of the form $f(x,y) = x^{\text{polylog}(x)} + y^{\text{polylog}(y)}$ is also quasi-polynomially bounded, whereas the sum of exponential functions $f(x,y) = 2^{x^\delta} + 2^{y^\delta}$ is not quasi-polynomially bounded. We are now ready to state our main theorem for this section.

Theorem 4 *There exists an FPTAS for any f-Π problem in which f is monotone and quasi-polynomially bounded if there exists an* FPTAS *for approximating the Pareto curve of Π.*

Proof (Sketch). Our goal is to find a solution for the f-Π problem in question with value no more than $(1+\varepsilon)$ times optimal. The FPTAS for the f-Π problem of relevance is quite simple. It uses the FPTAS for approximating the Pareto curve to generate an ε'-approximate Pareto curve $\mathcal{P}_{\varepsilon'}$ and tests which solution in $\mathcal{P}_{\varepsilon'}$ has the lowest f-value. Recall that the number of points in $\mathcal{P}_{\varepsilon'}$ is polynomial in the size of the input and $1/\varepsilon'$ [13]. The only question to be settled is how small ε' has to be chosen to obtain an ε-approximation for f-Π by this approach. Moreover, we have to show that $1/\varepsilon'$ is polynomially bounded in $1/\varepsilon$ and the input size since then, an ε'-approximate Pareto curve contains only polynomially many solutions and, thus, our approach runs in polynomial time.

Let S^* denote an optimal solution to the f-Π problem. Since f is non-decreasing we can w.l.o.g. assume S^* to be Pareto optimal. We denote by C^* the cost and by W^* the weight of S^*. We know that an ε'-approximate Pareto curve contains a solution S' with cost C' and weight W' such that $C' \leq (1+\varepsilon')C^*$ and $W' \leq (1+\varepsilon')W^*$. We have to choose $\varepsilon' > 0$ such that $f(C', W') \leq (1+\varepsilon)f(C^*, W^*)$ holds, in fact, we will choose ε' such that

$$f((1+\varepsilon') \cdot C^*, (1+\varepsilon') \cdot W^*) \leq (1+\varepsilon) \cdot f(C^*, W^*). \tag{1}$$

A technical calculation shows that choosing

$$\varepsilon' = \frac{\varepsilon^2}{c2^{d+4} \cdot \ln^{d+1} C \cdot \ln^{d+1} W},$$

where C denotes sum of all costs $c(e)$ and W denotes the sum of all weights $w(e)$, satisfies (1). Observe that $1/\varepsilon'$ is polynomially bounded in $1/\varepsilon$ and $\ln C^*$ and $\ln W^*$, i.e. the input size. □

Observe that Theorem 4 is almost tight since for every $\delta > 0$ we can construct a function f for which the quotients of the partial derivatives and $f(x, y)$ are lower bounded by $\delta/x^{1-\delta}$ respectively by $\delta/y^{1-\delta}$ and for which the f-Π problem does not posses an FPTAS, namely $f(x, y) = 2^{x^\delta} + 2^{y^\delta}$.

3 Smoothed Analysis of Bicriteria Problems

In the previous section we have shown that f-Π problems are NP-hard even for simple polynomial objective functions, and we have also shown that it is even hard to approximate them for rapidly increasing objective functions, if Π is either the bicriteria Spanning Tree, Shortest Path or Perfect Matching problem. In this section we will analyze f-Π problems in a probabilistic input model rather than from a worst-case viewpoint. In this model, we show that, for every $p > 0$ for which $1/p$ is polynomial in the input size, the f-Π problem can be solved in polynomial time for *every* non-decreasing objective function with probability $1-p$, if there exists a pseudopolynomial time algorithm for generating the Pareto set of Π. It is known that for the bicriteria graph problems we deal with the expected size of the Pareto set in the considered probabilistic input model is polynomially bounded [3]. Thus, if we had an algorithm for generating the set of Pareto optimal solutions whose running time is bounded polynomially in the input size and the number of Pareto optimal solutions then we could, for any non-decreasing objective function f, devise an algorithm for the f-Π problem that is efficient on semi-random inputs.

For a few problems, e.g. the SHORTEST PATH [18, 7] problem, efficient (w.r.t. the input size and the size of the Pareto set) algorithms for generating the Pareto set are known. But it is still unknown whether such an algorithm exists for the SPANNING TREE or the PERFECT MATCHING problem, whereas it is known that there exist for, e.g., the SPANNING TREE and the PERFECT MATCHING problem pseudopolynomial time algorithms (w.r.t. cost and weight) for generating the reduced Pareto set. This follows since the exact versions of the single objective versions of these problems, i.e. the question, "Is there a spanning tree/perfect matching with cost exactly c?", can be solved in pseudopolynomial time (w.r.t to the costs) [2, 12, 11]. We will show how such pseudopolynomial time algorithms can be turned into algorithms for efficiently generating the Pareto set of semi-random inputs.

3.1 Probabilistic Input Model

Usually, the input model considered in smoothed analysis consists of two stages: First an adversary chooses an input instance then this input is randomly perturbed in the second stage. For the bicriteria graph problems considered in this paper, the input given by the adversary is a graph $G = (V, E, w, c)$ with weights $w : E \to \mathbb{R}_+$ and costs $c : E \to \mathbb{R}_+$ and in the second stage these weights and costs are perturbed by adding independent random variables to them.

We can replace this two-step model by a one-step model where the adversary is only allowed to specify a graph $G = (V, E)$ and, for each edge $e \in E$, two probability distributions, namely one for $c(e)$ and one for $w(e)$. The costs and weights are then independently drawn according to the given probability distributions. Of course, the adversary is not allowed to specify arbitrary distributions since this would include deterministic inputs as a special case. We place two restrictions upon the distributions concerning the expected value and the maximal density. To be more precise, for each weight and each cost, the adversary is only allowed to specify a distribution which can be described by a piecewise continuous density function $f : \mathbb{R}_+ \to \mathbb{R}_+$ with expected value at most 1 and maximal density at most ϕ, i.e. $\sup_{x\in\mathbb{R}_+} f(x) = \phi$, for a given $\phi \geq 1$.

Observe that restricting the expected value to be at most 1 is without loss of generality, since we are only interested in the Pareto set which is not affected by scaling weights and costs. The parameter ϕ can be seen as a parameter specifying how close the analysis is to a worst case analysis. The larger ϕ the more concentrated the probability distribution can be. Thus, the larger ϕ, the more influence the adversary has. We will call inputs created by this probabilistic input model *ϕ-perturbed inputs.*

Note that the costs and weights are irrational with probability 1 since they are chosen according to continuous probability distributions. We ignore their contribution to the input length and assume that the bits of these coefficients can be accessed by asking an oracle in time $O(1)$ per bit. Thus, in our case only the representation of the graph $G = (V, E)$ determines the input length. In the following let m denote the number of edges, i.e. $m = |E|$.

We assume that there do not exist two different solutions S and S' with either $w(S) = w(S')$ or $c(S) = c(S')$. We can assume this without loss of generality since in our probabilistic input model two such solutions exist only with probability 0.

3.2 Generating the Pareto set

In this section we will show how a pseudopolynomial time algorithm $\mathcal{A}$ for generating the Pareto set can be turned into a polynomial time algorithm which succeeds with probability at least $1-p$ on semi-random inputs for any given $p > 0$ where $1/p$ is polynomial in the input size. In order to apply $\mathcal{A}$ efficiently it is necessary to round the costs and weights, such that they are only polynomially large after the rounding, i.e., such that the length of their representation if only logarithmic. Let $\lfloor c \rfloor_b$ and $\lfloor w \rfloor_b$ denote the costs and weights rounded down to the b-th bit after the decimal point. We denote by $\mathcal{P}$ the Pareto set of the ϕ-perturbed input $G = (V, E, w, c)$ and by $\mathcal{P}_b$ the Pareto set of the rounded ϕ-perturbed input $G = (V, E, \lfloor w \rfloor_b, \lfloor c \rfloor_b)$.

Theorem 5 *For $b = \Theta\left(\log\left(\frac{m\phi}{p}\right)\right)$ it holds that $\mathcal{P} \subseteq \mathcal{P}_b$ with probability at least $1-p$.*

This means, we can round the coefficients after only a logarithmic number of bits and use the pseudopolynomial time algorithm, which runs on the rounded input in polynomial time, to obtain $\mathcal{P}_b$. With probability at least $1-p$ the set $\mathcal{P}_b$ contains all Pareto optimal solutions from $\mathcal{P}$ but it can contain solutions which are not Pareto optimal w.r.t. to w and c. By removing these superfluous solutions we obtain with probability at least $1-p$ the set $\mathcal{P}$.

Corollary 6 *There exists an algorithm for generating the Pareto set of Π on ϕ-perturbed inputs with failure probability at most p and running time $\mathrm{poly}(m, \phi, 1/p)$ if there exists a pseudopolynomial time algorithm for generating the reduced Pareto set of Π.*

In this extended abstract we will only try to give intuition why Theorem 5 is valid. Details of the proof can be found in a full version of this paper. From the definition of a Pareto optimal solution, it follows that the optimal solution S of a constrained problem, i.e. the weight-minimal solution among all solutions fulfilling a cost constraint $c(S) \leq t$, is always a Pareto optimal solution. This is because if there were a solution S' that dominates S, then S' would also be a better solution to the constrained problem. We will show that, for every $S \in \mathcal{P}$, with sufficiently large probability we can find a threshold t such that S is the optimal solution to the constrained problem $\min \lfloor w \rfloor_b(S)$ w.r.t. $\lfloor c \rfloor_b(S) \leq t$, i.e. with sufficiently large probability every $S \in \mathcal{P}$ is Pareto optimal w.r.t. the rounded coefficients.

In the proof we will, for an appropriate z, consider z many constrained problems each with weights $\lfloor w \rfloor_b$ and costs $\lfloor c \rfloor_b$. The thresholds we consider are $t_i = i \cdot \varepsilon$, for $i \in [z] := \{1, 2, \ldots, z\}$, for an appropriately chosen ε. By $\Delta_{\min}$ we will denote the minimal cost difference between two different Pareto optimal solutions, i.e.

$$\Delta_{\min} = \min_{\substack{S_1, S_2 \in \mathcal{P} \\ S_1 \neq S_2}} |c(S_1) - c(S_2)|.$$

If $\Delta_{\min}$ is larger than ε, then $\mathcal{P}$ consists only of solutions to constrained problems of the form $\min w(T)$, w.r.t. $c(t) \leq t_i$, since, if $\varepsilon < \Delta_{\min}$ we do not miss a Pareto optimal solution by our choice of thresholds. Based on results by Beier and Vöcking [4] we will prove that, for each $i \in [z]$, the solution $S^{(i)}$ to the constrained problem $\min w(S)$ w.r.t. $c(S) \leq t_i$ is the same as the solution $S_b^{(i)}$ to the constrained problem $\min \lfloor w \rfloor_b(S)$ w.r.t. $\lfloor c \rfloor_b(S) \leq i \cdot \varepsilon$ with sufficiently large probability. Thus, if $\varepsilon < \Delta_{\min}$ and $S^{(i)} = S_b^{(i)}$ for all $i \in [z]$, then $\mathcal{P} \subseteq \mathcal{P}_b$.

We do not know how to determine $\Delta_{\min}$ in polynomial time but we can show a lower bound ε for $\Delta_{\min}$ that holds with a certain probability. Based on this lower bound, we can appropriately choose ε. We must choose z sufficiently large so that $c(S) \leq z \cdot \varepsilon$ holds with sufficiently high probability for every solution S. Thus, our analysis fails only if one of the following three failure events occurs:

$\mathcal{F}_1$: $\Delta_{\min}$ is smaller than the chosen ε.
$\mathcal{F}_2$: For one $i \in [z]$ the solution $S^{(i)}$ to $\min w(S)$ w.r.t. $c(S) \leq t_i$ does not equal the solution $S_b^{(i)}$ to $\min \lfloor w \rfloor_b(S)$ w.r.t. $\lfloor c \rfloor_b(S) \leq i \cdot \varepsilon$.
$\mathcal{F}_3$: There exists a solution S with $c(S) > z \cdot \varepsilon$.

For appropriate values of z, ε and b we can show that these events are unlikely, yielding Theorem 5.

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A Reductions from PARTITION to the bicriteria SPANNING TREE, SHORTEST PATH and PERFECT MATCHING problem

By simple reductions from PARTITION ([6]) one can prove that it is NP-hard to decide whether a graph with edge costs and weights has a spanning tree (or s-t-path or perfect matching) with cost at most C and weight at most W, where $C, W \in \mathbb{R}$. For the sake of completeness we reproduce these reductions here.

We use these reductions in Appendix B to show that f-SPANNING TREE, f-SHORTEST PATH and f-PERFECT MATCHING are NP-hard for $f(x,y) = x^a + y^b$, where $a, b \in \mathbb{N}$ and a, b are constants with $a \geq 2$ or $b \geq 2$. A PARTITION instance consists of n natural numbers $\{a_1, \ldots, a_n\}$ and the goal is to decide whether there is a partition $\mathcal{A}_1 \dot{\cup} \mathcal{A}_2 = \{a_1, \ldots, a_n\}$ of the a_i's such that $\sum_{a_i \in \mathcal{A}_1} a_i = \sum_{a_j \in \mathcal{A}_2} a_j = A/2$. The graphs used in these reductions posses the property that for every solution S it holds $c(S) + w(S) \geq A$ and that there is a solution S with $c(S) = w(S) = A/2$ if and only if the corresponding PARTITION instance has a solution. Observe that if a solution S with $c(S) = w(S) = A/2$ exists it is an optimal solution to the function $f(x) = x^a + y^a$ for $a \geq 2$. Thus, minimizing f is as difficult as solving PARTITION. Note that similar arguments can also be applied to other families of functions f such as $f(x,y) = (xy)^{-1}$.

Given an instance $\{a_1, \ldots, a_n\}$ of PARTITION we describe reductions from PARTITION to the bicriteria SPANNING TREE, SHORTEST PATH and PERFECT MATCHING problems already given in [6]. We show how to construct instances $G = (V, E, c, w)$ of these problems. We start with a reduction to the SHORTEST PATH problem and refer to Figure 1 to show the topology of G. The cost and the weight of an edge are given in brackets. Let $s = v_1$ and $t = v_{n+1}$ and let

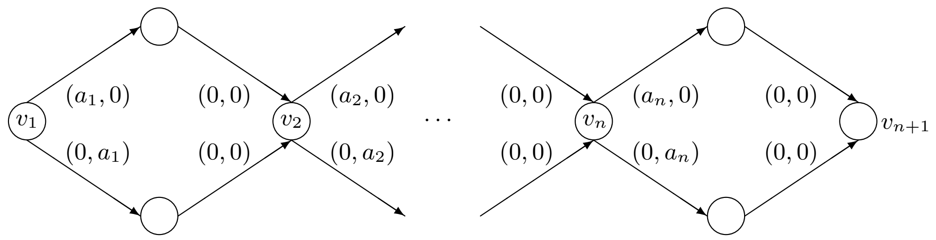

Fig. 1. A reduction from PARTITION to the s-t-PATH problem.

P be any s-t-path in G. Observe that $c(P) + w(P) = \sum_{i=1}^{n} a_i$. We denote by $V_{upper}(P)$ the set of nodes v_i, such that P takes the upper path from v_i to v_{i+1} and by $V_{lower}(P)$ the set of nodes, such that P takes the lower path from v_i to v_{i+1}. Using these sets we can easily construct a partition $\mathcal{A}_1, \mathcal{A}_2$ of the a_i's:

$$\mathcal{A}_1 = \{a_i \mid v_i \in V_{upper}(P)\}$$
$$\mathcal{A}_2 = \{a_i \mid v_i \in V_{lower}(P)\}$$

Observe now if there is a path P with $c(P) \leq C$ and $w(P) \leq W$, then there is also a partition $\mathcal{A}_1, \mathcal{A}_2$ of the a_i's such that $\sum_{a_i \in \mathcal{A}_1} a_i \leq C$ and $\sum_{a_i \in \mathcal{A}_2} a_i \leq W$.

We continue with the reduction to the SPANNING TREE problem and refer to Figure 2 to show the topology of G. Let T be any spanning tree of G. Observe

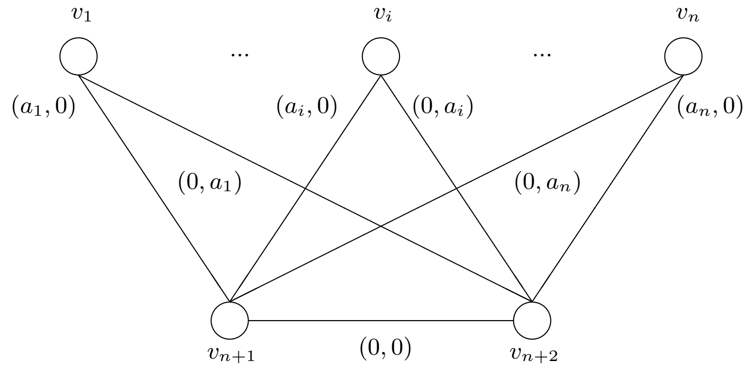

Fig. 2. A reduction from PARTITION to the SPANNING TREE problem.

that $c(T)+w(T) \geq \sum_{i=1}^{n} a_i$ since there might by a vertex v_i, $1 \leq i \leq n$ such that the edges (v_i, v_{n+1}) and (v_i, v_{n+2}) belong to T. In this case the edge (v_{n+1}, v_{n+2}) does not belong to T. If we assume that $a_i \geq 0$ for all $1 \leq i \leq n$ than we can remove either edge (v_i, v_{n+1}) or (v_i, v_{n+2}) and use the edge (v_{n+1}, v_{n+2}) instead without increasing the cost or the weight of T. Thus we can always assume that there is no vertex v_i such that both edges (v_i, v_{n+1}) and (v_i, v_{n+2}) belong to T. We denote by $V_{left}(P)$ the set of nodes v_i, $1 \leq i \leq n$ such that the edge (v_i, v_{n+1}) and not (v_i, v_{n+2}) belongs to T. Furthermore we denote by $V_{right}(P)$ the set of nodes v_i, $1 \leq i \leq n$ such that the edge (v_i, v_{n+2}) and not (v_i, v_{n+1}) belongs to T. Using these sets we can easily construct a partition $\mathcal{A}_1, \mathcal{A}_2$ of the a_i's:

$$\mathcal{A}_1 = \{a_i \mid v_i \in V_{right}(P)\}$$
$$\mathcal{A}_2 = \{a_i \mid v_i \in V_{left}(P)\}$$

Observe now if there is a spanning tree T with $c(T) \leq C$ and $w(T) \leq W$, then there is also a partition $\mathcal{A}_1, \mathcal{A}_2$ of the a_i's such that $\sum_{a_i \in \mathcal{A}_1} a_i \leq C$ and $\sum_{a_i \in \mathcal{A}_2} a_i \leq W$.

Finally we give a reduction from PARTITION to the PERFECT MATCHING problem. The graph G consists of n gadgets g_i as presented in Figure 3. Let M by any perfect matching of G. Observe that $c(M)+w(M) = \sum_{i=1}^{n} a_i$. We denote by $G_{1,2}(M)$ the set of gadgets g_i of G, such that the edge $(v_{1,i}, v_{2,i})$ belongs to M and by $G_{1,3}(M)$ the set of gadgets g_i of G, such that the edge $(v_{1,i}, v_{3,i})$ belongs to M. Again using these sets we can easily construct a partition $\mathcal{A}_1, \mathcal{A}_2$ of the a_i's.

$$\mathcal{A}_1 = \{a_i \mid g_i \in G_{1,2}(M)\}$$
$$\mathcal{A}_2 = \{a_i \mid g_i \in G_{1,3}(M)\}$$

Observe now if there is a perfect matching M with $c(M) \leq C$ and $w(M) \leq W$, then there is also a partition $\mathcal{A}_1, \mathcal{A}_2$ of the a_i's such that $\sum_{a_i \in \mathcal{A}_1} a_i \leq C$ and $\sum_{a_i \in \mathcal{A}_2} a_i \leq W$.

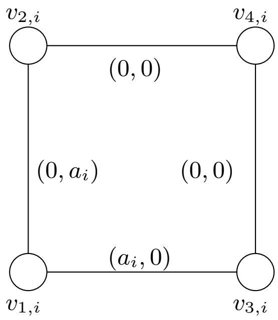

Fig. 3. A reduction from PARTITION to the PERFECT MATCHING problem.

B Proofs of Hardness Results

Proof (Proof of Lemma 1). We use the reductions from PARTITION to the bicriteria SPANNING TREE, SHORTEST PATH and PERFECT MATCHING problems as presented above, except that we scale the cost of each edge (but not its weight) by a factor of α. Thus for any solution S, we have that $c(S)/\alpha + w(S) = A$. Let $x = w(S)$, then $c(S) = \alpha(A-x)$. Define $g(x) := f(\alpha(A-x), x) = \alpha(A-x)^a + x^b$. Our goal is to choose α such that the function $g(x)$ is minimized when $x = A/2$. Thus, we want to show that $g'(A/2) = 0$ and $g''(A/2) > 0$. We take the derivative of $g(x)$ and obtain, $g'(x) = -a \cdot \alpha^a (A-x)^{a-1} + bx^{b-1}$. Now we have:

$$g'\left(\frac{A}{2}\right) = 0 \iff -a \cdot \alpha^a \left(\frac{A}{2}\right)^{a-1} + b\left(\frac{A}{2}\right)^{b-1} = 0$$
$$\iff \alpha^a = \frac{b}{a}\left(\frac{A}{2}\right)^{b-a}$$
$$\iff \alpha = \left(\frac{b}{a}\left(\frac{A}{2}\right)^{b-a}\right)^{\frac{1}{a}}$$

Now we evaluate the second derivative of $g(x)$ at point $A/2$ and show that it is positive. We have, $g''(x) = a(a-1)\alpha^a(A-x)^{a-2} + b(b-1)x^{b-2}$. Thus, $g''(A/2) > 0$ when $a > 1$ or $b > 1$. Observe that, in general, α is irrational but rounding α after a polynomial number of bits preserves the desired property. □

Proof (Proof of Lemma 2). We use the reductions of PARTITION to the problems we consider as presented in Appendix A. Assume that we are given an instance $\{a_1, \ldots, a_n\}$ of PARTITION. Assume that we scale the natural numbers a_i by a factor of $b > 0$ before constructing the graphs. If there is a desired partition in the original instance, then there is also a solution in the scaled instance with $f(S) = 2^{(b \cdot a)^\delta + 1}$. If there is no desired partition, then $f(S) \geq 2^{(b \cdot a + b)^\delta}$ for any solution S. Obviously this is a $(2^{(b \cdot a)^\delta + 1}, 2^{(b \cdot a + b)^\delta})$ gap problem for which no polynomial time approximation algorithm with approximation ratio less than $2^{(b \cdot a+b)^\delta}/2^{(b \cdot a)^\delta+1} = 2^{(b \cdot a+b)^\delta - (b \cdot a)^\delta - 1}$ exists, unless $P = NP$. Now choosing

$$b > \left(\frac{B^d + 1}{(a+1)^\delta - a^\delta}\right)^{1/\delta}$$

yields

$$\frac{2^{(b\cdot a+b)^\delta}}{2^{(b\cdot a)^\delta+1}} > 2^{B^d}.$$

Note that the length of the representation of $B = \sum_{e\in E} c(e) + w(e)$ is polynomially bounded in the input size. The same holds for b as well. Thus, if there were a polynomial time approximation algorithm for f-Π with approximation ratio less than 2^{B^d}, P would be equal to NP. □

C Additions to the Proof of Theorem 4

We start by rewriting $f((1+\varepsilon')C^*, (1+\varepsilon')W^*)$ as follows

$$f((1+\varepsilon')\cdot C^*, (1+\varepsilon')\cdot W^*) = \begin{cases} f(C^*, W^*) + f((1+\varepsilon')\cdot C^*, W^*) \\ -f(C^*, W^*) + f((1+\varepsilon')\cdot C^*, (1+\varepsilon')\cdot W^*) \\ -f((1+\varepsilon')\cdot C^*, W^*). \end{cases}$$

Now, it is enough to find ε' such that

$$f((1+\varepsilon')\cdot C^*, W^*) - f(C^*, W^*) \le \frac{\varepsilon}{2}\cdot f(C^*, W^*) \tag{2}$$

and

$$f((1+\varepsilon')\cdot C^*, (1+\varepsilon')W^*) - f((1+\varepsilon')\cdot C^*, W^*) \le \frac{\varepsilon}{2}\cdot f(C^*, W^*). \tag{3}$$

We have to prove that setting

$$\varepsilon' = \frac{\varepsilon^2}{c2^{d+4}\cdot \ln^{d+1} C^* \cdot \ln^{d+1} W^*}$$

fulfilles the conditions (2) and (3). Before we estimate the terms in (2) and (3) we remind the reader of a version of Bernoulli's inequality which we will use later.

Lemma 7 *Let $x > -1$, $x \in \mathbb{R}$ and $n \in \mathbb{N}$. Then*

$$1 + \frac{x}{n(1+x)} \le \sqrt[n]{1+x} \le 1 + \frac{x}{n}.$$

Estimating $\mathbf{f((1+\varepsilon')C^*, W^*) - f(C^*, W^*)}$ We start by estimating the term $f((1+\varepsilon')C^*, W^*) - f(C^*, W^*)$. Therefore we define a function $g : \mathbb{R}_+ \to \mathbb{R}_+$ by $g(x) = f(x, W^*)$. Then we can express the difference we are interested in as $g((1+\varepsilon')C^*) - g(C^*)$. Furthermore, for all $x \in \mathbb{R}_+$, we know

$$\frac{g'(x)}{g(x)} \le \frac{c\cdot \ln^d x \cdot \ln^d W^*}{x} \tag{4}$$

and $g(C^*) = z^*$. The difference $g((1+\varepsilon')C^*) - g(C^*)$ becomes maximal when the derivative of g is as large as possible. Thus, we assume w.l.o.g that inequality (4) is satisfied with equality, i.e.

$$\frac{g'(x)}{g(x)} = \frac{c\cdot \ln^d x \cdot \ln^d W^*}{x}.$$

This differential equation with the additional condition $g(C^*) = z^*$ has a unique solution, namely

$$g(x) = \frac{z^*}{e^{\frac{c}{d+1} \cdot \ln^{d+1} C^* \cdot \ln^d W^*}} e^{\frac{c}{d+1} \cdot \ln^{d+1} x \cdot \ln^d W^*}.$$

We want to show $g((1+\varepsilon')C^*) - g(C^*) \leq \varepsilon/2 \cdot g(C^*)$ which is equivalent to $g((1+\varepsilon')C^*)/g(C^*) \leq 1 + \varepsilon/2$. For the sake of simplicity, we assume w.l.o.g. $\varepsilon' < 1$, $C^* \geq e$ and $W^* \geq e$ which implies $\ln(1+\varepsilon') < 1$, $\ln C^* > 1$ and $\ln W^* > 1$. Then we have the following

$$\begin{aligned}
\frac{g((1+\varepsilon')C^*)}{g(C^*)} &= \exp\left(\frac{c}{d+1} \cdot \ln^d W^* (\ln^{d+1}((1+\varepsilon')C^*) - \ln^{d+1} C^*)\right) \\
&\leq \exp\left(\frac{c}{d+1} \cdot \ln^d W^* \cdot \sum_{i=1}^{d+1} \binom{d+1}{i} \ln^i(1+\varepsilon') \ln^{d+1-i} C^*\right) \\
&\leq \exp\left(\frac{c}{d+1} \cdot \ln^d W^* \cdot d2^{d+1} \ln(1+\varepsilon') \ln^{d+1} C^*\right) \\
&\leq (1+\varepsilon')^{\lceil c2^{d+1} \cdot \ln^{d+1} C^* \cdot \ln^d W^* \rceil}
\end{aligned}$$

It holds

$$\begin{aligned}
\varepsilon' &\leq \left(1 + \frac{\varepsilon}{2}\right)^{\frac{1}{\lceil c2^{d+1} \cdot \ln^{d+1} C^* \cdot \ln^d W^* \rceil}} - 1 \\
\Rightarrow (1+\varepsilon')^{\lceil c2^{d+1} \cdot \ln^{d+1} C^* \cdot \ln^d W^* \rceil} &\leq 1 + \frac{\varepsilon}{2}.
\end{aligned}$$

We can apply Lemma 7 to obtain

$$\begin{aligned}
\varepsilon' &\leq \frac{\varepsilon/2}{\lceil c2^{d+1} \cdot \ln^{d+1} C^* \cdot \ln^d W^* \rceil (1+\varepsilon/2)} \\
\Rightarrow \varepsilon' &\leq \left(1 + \frac{\varepsilon}{2}\right)^{\frac{1}{\lceil c2^{d+1} \cdot \ln^d W^* \cdot \ln^{d+1} C^* \rceil}} - 1.
\end{aligned}$$

Thus, choosing

$$\varepsilon' = \frac{\varepsilon}{c2^{d+4} \cdot \ln^{d+1} C^* \cdot \ln^d W^*} \tag{5}$$

yields $g((1+\varepsilon')C^*) - g(C^*) \leq \varepsilon/2 \cdot g(C^*)$.

Estimating $\mathbf{f}((\mathbf{1}+\varepsilon')\mathbf{C}^*, (\mathbf{1}+\varepsilon')\mathbf{W}^*) - \mathbf{f}((\mathbf{1}+\varepsilon')\mathbf{C}^*, \mathbf{W}^*)$ Now define $h : \mathbb{R}_+ \to \mathbb{R}_+$ by $h(y) = f((1+\varepsilon')C^*, y)$. Observe that we can use the arguments in the previous paragraph to show $h((1+\varepsilon')W^*) - h(W^*) \leq \varepsilon/2 \cdot h(W^*)$ for an analogously chosen ε' but this is not enough since $h(W^*) = f((1+\varepsilon')C^*, W^*) \geq f(C^*, W^*)$.

Following the arguments of the last paragraph we can show that setting

$$\varepsilon' = \frac{\varepsilon^2}{c2^{d+4} \cdot \ln^d C^* \cdot \ln^{d+1} W^*} \tag{6}$$

yields

$$f((1+\varepsilon')C^*, (1+\varepsilon')W^*) - f((1+\varepsilon')C^*, W^*) \leq \frac{\varepsilon^2}{2} f((1+\varepsilon')C^*, W^*).$$

We assume w.l.o.g. $\varepsilon < 0.7$. Then, a second application of the result of the last paragraph shows

$$\begin{aligned} f((1+\varepsilon')C^*, W^*) - f(C^*, W^*) &\le \frac{\varepsilon}{2} f(C^*, W^*) \\ \Rightarrow \qquad f((1+\varepsilon')C^*, W^*) &\le \frac{2+\varepsilon}{2} f(C^*, W^*) \\ \Rightarrow \qquad \tfrac{2}{2+\varepsilon} f((1+\varepsilon')C^*, W^*) &\le f(C^*, W^*) \\ \Rightarrow \qquad \varepsilon f((1+\varepsilon')C^*, W^*) &\le f(C^*, W^*), \end{aligned}$$

where the last inequality follows from the assumption $\varepsilon < 0.7$. Putting it together yields

$$\begin{aligned} f((1+\varepsilon')C^*, (1+\varepsilon')W^*) - f((1+\varepsilon')C^*, W^*) &\le \frac{\varepsilon^2}{2} f((1+\varepsilon')C^*, W^*) \\ &\le \frac{\varepsilon}{2} f(C^*, W^*). \end{aligned}$$

Observe that the choice of ε' in (5) and (6) is dependent on the cost C^* and the weight W^* of an optimal solution. These values are unknown but can be upper bounded by C and W the sum of all costs $c(e)$ respectively all weights $w(e)$. Thus, in (5) and (6) we can replace C^* by C and W^* by W and choose

$$\varepsilon' = \frac{\varepsilon^2}{c 2^{d+4} \cdot \ln^{d+1} C \cdot \ln^{d+1} W}.$$

D Proof of Theorem 5

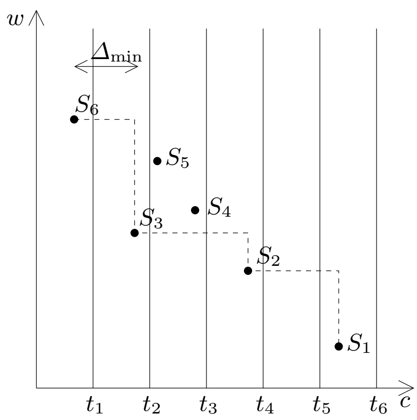

Fig. 4. Illustration of the definition of $\Delta_{\min}$. S_1, S_2, S_3, S_6 are Pareto optimal. Each of them is an optimal solution to at least one of the constrained problems.

Bounding $\mathbf{Pr}[\mathcal{F}_1]$ First, we write Π as binary program. We introduce a variable $x_e \in \{0,1\}$ for every edge $e \in E$ and we denote by $\mathcal{S} \subseteq \{0,1\}^m$ the set of all solutions of Π for input G, e.g. the set of all spanning trees of G. For bounding $\Delta_{\min}$ it is not necessary that the weights are chosen at random since the bound

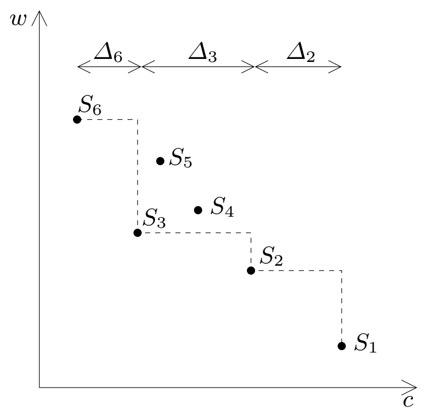

Fig. 5. $\Delta_4 = \Delta_5 = 0$.

we will prove holds for every deterministic choice of the weights. Thus, we assume the weights to be fixed arbitrarily.

Now let $S_1, \ldots, S_l$ denote a sequence containing all elements from $\mathcal{S}$ ordered such that $w(S_1) \leq \ldots \leq w(S_l)$ holds. For $j \in \{2, \ldots, l\}$, we define $\Delta_j = \min_{i \in [j-1]} c(S_i) - \min_{i \in [j]} c(S_i)$. Observe that a solution S_j, for $j \in \{2, \ldots, l\}$, is Pareto optimal if and only if $\Delta_j > 0$ and that Δ_j describes how much less S_j costs compared to the cheapest solution S_i with $i < j$ (see Figure 5). Thus, we can write $\Delta_{\min}$ as follows

$$\Delta_{\min} = \min_{j \in [l] \setminus \{1\}} \{\Delta_j | \Delta_j > 0\}.$$

We want to bound the probability that $\Delta_{\min}$ lies below a given value ε. Therefore, we rewrite $\Delta_{\min}$ as follows:

$$\begin{aligned} \mathbf{Pr}[\Delta_{\min} < \varepsilon] &= \mathbf{Pr}[\exists j \in [l] \setminus \{1\} : 0 < \Delta_j < \varepsilon] \\ &\leq \sum_{j \in [l] \setminus \{1\}} \mathbf{Pr}[\Delta_j > 0] \cdot \mathbf{Pr}[\Delta_j < \varepsilon | \Delta_j > 0] . \end{aligned} \tag{7}$$

Assume, we could bound $\mathbf{Pr}[\Delta_j < \varepsilon | \Delta_j > 0]$ from above for every j by some term a. Then we would have

$$\mathbf{Pr}[\Delta_{\min} < \varepsilon] \leq a \cdot \sum_{j \in [l] \setminus \{1\}} \mathbf{Pr}[\Delta_j > 0] \leq a \cdot \mathbf{E}[q],$$

where q denotes the number of Pareto optimal solutions.

In this scenario we can apply the analysis of Beier and Vöcking [3] to obtain a polynomial upper bound on the expected number of Pareto optimal solutions. The crucial point in their analysis is a lower bound on $\mathbf{E}[\Delta_j | \Delta_j > 0]$ for every $j \in [l] \setminus \{1\}$. Unfortunately, we cannot apply their results directly to bound the conditional probability $\mathbf{Pr}[\Delta_j < \varepsilon | \Delta_j > 0]$ since, in general, a bound on the conditional expectation does not imply a bound on the conditional probability. In Appendix E we prove the following result.

Theorem 8 *Assume the costs to be independent random variables whose expectations are bounded by* 1 *and whose densities are bounded by* ϕ*, i.e. for all* $x \in \mathbb{R}_+$ *and for all* $e \in E$ *it holds* $f_e(x) \le \phi$*. Then, for* $\varepsilon \le (4m^8\phi^2)^{-1}$*,*

$$\mathbf{Pr}\left[\Delta_{\min} < \varepsilon\right] \le 2(4\varepsilon m^5\phi^2)^{1/3}.$$

Bounding $\mathbf{Pr}\left[\mathcal{F}_2\right]$ For $i \in [z]$, let $\mathcal{F}_2^{(i)}$ denote the event that the solution $S^{(i)}$ does not equal the solution $S_b^{(i)}$. In [4] the following result is proven.

Theorem 9 ([4]) *For every* $i \in [z]$, $\mathbf{Pr}\left[\mathcal{F}_2^{(i)}\right] \le 2^{-b+2}m^3\phi$.

Applying a union bound yields.

Corollary 10 $\mathbf{Pr}\left[\mathcal{F}_2\right] \le z \cdot 2^{-b+2}m^3\phi$.

Now we will use these results to prove Theorem 5.

Proof (Proof of Theorem 5). We want to choose ε, z and b in such a way that each of the failure probabilities $\mathbf{Pr}\left[\mathcal{F}_i\right]$ is bounded by $p/3$. By Theorem 8 choosing $\varepsilon = p^3(864m^8\phi^2)^{-1}$ yields $\mathbf{Pr}\left[\mathcal{F}_1\right] \le p/3$. By a simple application of Markov's bound we obtain that choosing

$$z = \frac{2592m^9\phi^2}{p^4}$$

implies $\mathbf{Pr}\left[\mathcal{F}_2\right] \le p/3$. With Corollary 10 we obtain that setting $b = \log(\alpha m^12\phi^3/p^5)$, for an appropriate constant α, yields $\mathbf{Pr}\left[\mathcal{F}_3\right] \le p/3$.

This proves the theorem since for $b = \log(\alpha m^12\phi^3/p^5) = \Theta(\log(m\phi/p))$ the failure probability is at most p. □

E Proof of Theorem 8

Analogously to the analysis in [3] we will also look at long-tailed distributions first and, after that, use the results for long-tailed distributions to analyze the general case.

Long-tailed Distributions One can classify continuous probability distributions by comparing their tails with the tail of the exponential distribution. In principle, if the tail function of a distribution can be lower bounded by the tail function of an exponential function, then we say the distribution has a "long tail".

Of special interest to us is the behavior of the tail function under a logarithmic scale. Given any continuous probability distribution with density $g : \mathbb{R}_+ \to \mathbb{R}_+$, the tail function $T : \mathbb{R}_+ \to [0,1]$ is defined by $T(t) = \int_t^\infty g(x)dx$. We define the *slope* of T at $x \in \mathbb{R}_+$ to be the first derivative of the function $-\ln(T(\cdot))$ at x, i.e. $\text{slope}_T(x) = -[\ln(T(x))]'$. For example, the tail function of the exponential distribution with parameter λ is $T(x) = \exp(-\lambda x)$ so that the slope of this function is $\text{slope}_T(x) = \lambda$, for every $x \ge 0$. The tail of a continuous probability distribution is defined to be *long* if there exists a constant $\alpha > 0$ such that $\text{slope}_T(x) \le \alpha$, for every $x \ge 0$.

We denote by T_e the tail function of $c(e)$ and by f_e the corresponding density.

Lemma 11 ([3]) *Assume $c(e)$ to be a long-tailed random variable with expected value at most μ, for each $e \in E$, and let α be a positive real number satisfying $\text{slope}_{T_e}(x) \leq \alpha$, for every $x \geq 0$ and every $e \in E$. Finally, let q denote the number of Pareto optimal solutions. Then*

$$\mathbf{E}[q] \leq \alpha\mu m^2 + 1 \leq 2\alpha\mu m^2$$

In order to bound the conditional probability $\mathbf{Pr}[\Delta_j < \varepsilon | \Delta_j > 0]$ we have to take a closer look at the proof of Lemma 11. The following lemma is implicitly contained in this proof.

Lemma 12 ([3]) *Let α and μ as in Lemma 11 then, for every $j \in [l]$, it holds*

$$\mathbf{Pr}[\Delta_j < \varepsilon | \Delta_j > 0] \leq 1 - \exp(-m\alpha\varepsilon).$$

Let $\varepsilon < 1/(m\alpha)$ be fixed arbitrarily. Combining Lemma 11 and 12 with equation (7) yields

$$\begin{aligned}\mathbf{Pr}[\Delta_{\min} < \varepsilon] &\leq \sum_{j \in [l] \setminus \{1\}} \mathbf{Pr}[\Delta_j > 0] \cdot \mathbf{Pr}[\Delta_j < \varepsilon | \Delta_j > 0] \\ &\leq (1 - \exp(-m\alpha\varepsilon)) \cdot \mathbf{E}[q] \\ &\leq \varepsilon \cdot m\alpha \cdot \mathbf{E}[q] \\ &\leq \varepsilon \cdot 2m^3\alpha^2\mu.\end{aligned}$$

Thus, we obtain the following lemma.

Lemma 13 *Assume $c(e)$ to be a long-tailed random variable with expected value at most μ, for each $e \in E$, and let α be a positive real number satisfying $\text{slope}_{T_e}(x) \leq \alpha$, for every $x \geq 0$ and every $e \in E$. Then, for every $\varepsilon \in [0, 1/(m\alpha))$, it holds*

$$\mathbf{Pr}[\Delta_{\min} < \varepsilon] \leq \varepsilon \cdot 2m^3\alpha^2\mu.$$

General distributions with bounded mean and bounded density For general distributions, a statement like Lemma 12 is not true any more. Nonetheless, Beier and Vöcking were able to bound the expected number of Pareto optimal solutions for any continuous distribution with bounded mean and bounded density.

Lemma 14 ([3]) *Assume the costs to be independent random variables whose expectations are bounded by μ and whose densities are bounded by ϕ, i.e. for all $x \in \mathbb{R}_+$ and for all $e \in E$ it holds $f_e(x) \leq \phi$. Then*

$$\mathbf{E}[q] = O(\phi\mu m^4).$$

We will use Lemma 14 to prove the following bound for $\Delta_{\min}$ which contains Theorem 8 as a special case.

Theorem 15 *Let μ and ϕ as in Lemma 14. Then, for $\varepsilon \leq (4m^8\phi^2\mu)^{-1}$,*

$$\mathbf{Pr}[\Delta_{\min} < \varepsilon] \leq 2(4\varepsilon m^5\phi^2\mu)^{1/3}.$$

Proof. For every $e \in E$ we define a random variable $x_e = T_e(c(e))$. For any $a > 0$, let $\mathcal{F}_a$ denote the event that, for at least one $e \in E$, it holds $x_e \leq a$. We will show that we can apply the analysis for long-tailed distributions if $\mathcal{F}_a$ does not occur. We obtain

$$\mathbf{Pr}\left[\Delta_{\min} < \varepsilon\right] \leq \mathbf{Pr}\left[\mathcal{F}_a\right] + \mathbf{Pr}\left[\Delta_{\min} < \varepsilon \wedge \neg\mathcal{F}_a\right]. \tag{8}$$

Observe that the x_e's are uniformly distributed over $[0,1]$, thus, we obtain

$$\mathbf{Pr}\left[\mathcal{F}_a\right] = \mathbf{Pr}\left[\exists e \in E : x_e \leq a\right] \leq ma. \tag{9}$$

We would like to estimate $\mathbf{Pr}\left[\Delta_{\min} < \varepsilon \wedge \neg\mathcal{F}_a\right]$ in such a way that we get rid of the event $\neg\mathcal{F}_a$ since, under the condition $\neg\mathcal{F}_a$, the random variables $c(e)$ are short-tailed instead of long-tailed. If the event $\mathcal{F}_a$ does not occur the distribution of $c(e)$ for values larger than $T_e^{-1}(a)$ is not important, thus, we can replace the tail function T_e by the tail function T_e^* with

$$T_e^*(x) = \begin{cases} T_e(x) & \text{if} \quad x \leq T_e^{-1}(a) \\ a \cdot \exp(-\phi m(x - T_e^{-1}(a)) & \text{otherwise} \end{cases}.$$

We denote by $\Delta_{\min}^*$ the random variable equivalent to $\Delta_{\min}$ but w.r.t. costs drawn according to the tail functions T_e^* instead of T_e and obtain

$$\mathbf{Pr}\left[\Delta_{\min} < \varepsilon \wedge \neg\mathcal{F}_a\right] = \mathbf{Pr}\left[\Delta_{\min}^* < \varepsilon \wedge \neg\mathcal{F}_a\right] \leq \mathbf{Pr}\left[\Delta_{\min}^* < \varepsilon\right]. \tag{10}$$

We can apply Lemma 13 to the random variable $\Delta_{\min}^*$ since it is long-tailed because an easy calculation shows

$$\text{slope}_{T_e^*}(x) \leq \begin{cases} \phi/a \text{ if} & x \leq T_e^{-1}(a) \\ \phi m \text{ otherwise} \end{cases}.$$

For $a \leq 1/m$ we obtain

$$\text{slope}_{T_e^*}(x) \leq \phi/a.$$

Before we can apply Lemma 13 we have to calculate the expectation of random variables drawn according to the tail function T_e^*, for every $e \in E$. Let f_e^* denote a density corresponding to the tail function T_e^*. It holds

$$\begin{aligned} \int_{-\infty}^{\infty} f_e^*(x)dx &= \int_{-\infty}^{T_e^{-1}(a)} f_e(x)dx + \int_{T_e^{-1}(a)}^{\infty} f_e^*(x)dx \\ &\leq \mu + a\phi m \int_{T_e^{-1}(a)}^{\infty} \exp(-\phi m(x - T_e^{-1}(a)))dx \\ &\leq \mu + \left[-a\exp(-\phi nx)\right]_0^{\infty} \\ &= \mu + a \leq \mu + 1. \end{aligned}$$

Applying Lemma 13 with $\alpha' = \phi/a$ and $\mu' = \mu + 1 \leq 2\mu$ yields, for $\varepsilon \in [0, a/(m\phi))$

$$\mathbf{Pr}\left[\Delta_{\min}^* < \varepsilon\right] \leq \frac{4\varepsilon m^3\phi^2\mu}{a^2}. \tag{11}$$

For $\varepsilon \in [0, a/(m\phi))$, equations (8) to (11) result in the following bound

$$\mathbf{Pr}\left[\Delta_{\min} < \varepsilon\right] \leq ma + \frac{4\varepsilon m^3\phi^2\mu}{a^2}.$$

We choose $a = (4\varepsilon m^2 \phi^2 \mu)^{1/3}$ and obtain

$$\mathbf{Pr}\left[\Delta_{\min} < \varepsilon\right] \leq 2(4\varepsilon m^5 \phi^2 \mu)^{1/3}.$$

We assumed a to be less or equal to $1/m$, thus, we have to choose ε such that $(4\varepsilon m^5 \phi^2 \mu)^{1/3} \leq 1/m$ holds. This is equivalent to $\varepsilon \leq (4m^8 \phi^2 \mu)^{-1}$. Furthermore, because of Lemma 13 we have to choose ε such that $\varepsilon \leq 1/(m\alpha')$. This is already implied by $\varepsilon \leq (4m^8 \phi^2 \mu)^{-1}$. □

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