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Fair task allocation in transportation[☆]

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ABSTRACT

Task allocation problems have traditionally focused on cost optimization. However, more and more attention is being given to cases in which cost should not always be the sole or major consideration. In this paper we study a fair task allocation problem in transportation where an optimal allocation not only has low cost but more importantly, it distributes tasks as even as possible among heterogeneous participants who have different capacities and costs to execute tasks. To tackle this fair minimum cost allocation problem we analyze and solve it in two parts using two novel polynomial-time algorithms. We show that despite the new fairness criterion, the proposed algorithms can solve the fair minimum cost allocation problem optimally in polynomial-time. In addition, we conduct an extensive set of experiments to investigate the trade-off between cost minimization and fairness. Our experimental results demonstrate the benefit of factoring fairness into task allocation. Among the majority of test instances, fairness comes with a very small price in terms of cost.

1. Introduction

Traditionally, optimization of task allocation problems considered only the costs involved in the allocation. However, there has been in recent years more attention to cases where cost should not always be the sole consideration [11]. There are circumstances when other criteria need to be taken into account as well during the decision making process. *Fairness* has been considered as one of the important additional criteria in many application domains [42,28,9]. Although there is no common definition for the term, there are two fairness criteria that are often used in the literature: the Nash bargaining criterion and the Rawlsian maximin criterion. The former is based on Nash's four axioms of pareto optimality, independency of irrelevant alternatives, symmetry, and invariance to affine transformations or equivalent utility representations [41]. The latter is based on Rawls' two principles of justice [46]. Rawls' maximin criterion maximizes the welfare level of the worst-off group member and has therefore been used in allocation problems [30,37].

In this paper, we study task allocation problems in which we take fairness into account in addition to the standard minimum cost criterion. This work was inspired by an actual transportation situation in the port of Rotterdam in the Netherlands. The increase in the number of container terminals in said port will result in a huge increase in inter-terminal transport (ITT). The port authority invited a team of researchers to investigate a sustainable transportation system, called an *asset light solution*, in which trucks that were already present in the port could execute open jobs. The main idea behind this system is that trucks that come from the hinterland to drop off or pick up containers often have spare time in between tasks. Usually, trucks are scheduled to do several jobs to and from various terminals in the port in one day. There may be large gaps between these jobs during which time the truck would be idle due to the nature of the jobs that truck companies agree to do. Terminals could take advantage of these idle trucks by providing them with jobs that they can perform within the port while waiting for their next scheduled job. The trucks will be compensated for these jobs. The compensation from the terminals to the trucking companies would be large enough to cover the costs that the companies would incur. However, the compensation should be less than the costs of purchasing and maintaining, or even renting the vehicles dedicated for such jobs. This way, the trucking companies gain additional income while the terminals save money by using readily available resources. Furthermore, because the utilization rate of existing trucks becomes higher and no new trucks are needed, this is a more durable approach to meeting the transport need within the port.

To realize such a task allocation, terminals need to be informed of the individual schedules of the different trucking companies.

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This poses a hurdle because getting such information is expensive and the trucking companies may be reluctant to share their entire schedules. One way to circumvent this difficulty is to use *auctions* as a means to collect information from different parties. Auctions have become increasingly popular for allocating resources among individual players in many application domains, such as in spectrum auctions [14], health care [49], industrial procurement [23,10] and logistics [48,1]. In the auction for our trucking task allocation case, we assume that all terminals together act as an auctioneer and they announce a set of available jobs. Different trucking companies can bid for those jobs, depending on their idle trucks at specific times. Given the bids of different companies, the terminals then decide on a best allocation of jobs to companies.[1] Because there are ITT movements every day that need to be executed, this task allocation activity would be held daily. Some studies have shown that greedily minimizing cost does not fare well with repeated auctions. Participants could experience starvation in the long run, which will reduce their incentive to continue participating in the allocation activity [28]. Furthermore, repeated auctions may affect the relationships between the auctioneer and bidders, which in turn affects the latter's way of bidding [31]. To prevent these adverse effects, we should not only look at optimizing the costs in the task allocation, but we should also incorporate fairness in the task allocation that results from the auctions. We do this by reassuring that all interested parties will receive some market share, therefore giving trucking companies an incentive to continue participating in the task allocation activity. As we do not know the exact utility functions of the players, the number of jobs allocated to them will be used to measure the fair distribution of the utilities of the players.

We study a “max-min fair minimum cost allocation problem” (MFMCA). The majority of existing work involving fairness uses mathematical programming models in which fairness is incorporated in either the constraints [40,45] or in the objective function [8,9,2]. However, we aim for a polynomial-time solution. The difficulty of our problem lies in the additional fairness criterion, which requires the developed algorithm to satisfy three criteria: allocation maximization, fairness, and cost minimization. To the best of our knowledge, no existing polynomial-time algorithm can be directly applied to solve our problem. In this paper, we propose polynomial-time algorithms to solve MFMCA as a two-level optimization problem. First, we aim at a fairest allocation among companies while ensuring that a maximal set of tasks can be allocated for execution. We call this the “max-min fair allocation problem” (MMFA). Second, because there might be an exponential number of allocations that are considered max-min fair, we would like to determine which of these fair allocations has the lowest cost. The resulting allocation is max-min fair with minimum cost. To this end, we develop a polynomial-time optimal method that consists of two novel algorithms: (1) to solve MMFA, we construct an algorithm, called IMaxFlow, using a progressive filling idea in a flow network [5], and then (2) by using the solution obtained from MMFA, we propose another algorithm, called FairMinCost, that smartly alters the structure of the problem to solve MFMCA optimally.

The contribution of this paper is two-fold.

1. Despite the new fairness criterion, we are able to develop an optimization method to solve the task allocation problem to optimality in polynomial-time.
2. Using computational results, we provide insights into situations in which fairness can be incorporated without giving up too much efficiency.

The rest of the paper is organized as follows. We start with a literature review in Section 2, followed by a problem definition in Section 3. In Section 4, we introduce two polynomial-time algorithms to solve MMFA and MFMCA, respectively. We prove that the output of these algorithms is the optimal allocation in terms of fairness and cost minimization. In Section 5, using different sets of scenarios, we test the algorithm in terms of its effect on the cost and job distribution. We conclude and point out interesting directions of future work in Section 6.

2. Literature review

The idea of factoring fairness into decision making has been studied in various fields. One of the earlier and still important areas of application where fairness has been considered is that of bandwidth allocation in telecommunication networks [30,53]. In this area, continuous flows with predefined origin-destination pairs are used, leading to algorithms that increase flow over all paths simultaneously until links are saturated, or that split up bandwidth equally among competitors. Bertsekas et al. [5] give a simple algorithm for computing max-min fair rate vectors for flow control in networks, the so-called progressive filling algorithm, which is treated as one of the standard fairness concepts within the telecommunications or network applications [42]. In their problem setting, they assume that each session has an associated fixed path in the network. The algorithm starts with no flow, and then flow gets gradually increased over all paths simultaneously until a link in a path is saturated. The algorithm then continues from step to step, equally incrementing the flow in all paths that are not using saturated links, until all paths contain at least one saturated link. Tomaszewski [51] provides a general mathematical programming formulation for solving max-min fair problems using the progressive filling algorithm. Although we cannot use these proposed solution methods directly, we are able to borrow the idea of the progressive filling algorithm when developing our method for solving MMFA.

Fairness, or equity, has also been incorporated in staff scheduling. They attempt to distribute the workload fairly and evenly among personnel, where it is a typical strategy to construct cyclic rosters [20]. The more popular measures for equity in this field are the variance and variants of the Gini index. Equity is then incorporated in mathematical models in either the objective function, e.g. minimizing the variation in workload, or through the use of constraints, which provide lower and upper bounds on the workload [18]. Resource allocation is yet another field in which fairness plays an important role. An example of a very weak fairness constraint in this field is that any task will be able to use its requested resource eventually. A much stricter fairness requirement can be found in proportionate fairness [3]. With proportionate fairness, the difference in the number of resource allocations to tasks will never be more than one, ensuring that all tasks have similar access to resources. Dominant Resource Fairness is another type of fairness requirement, which is a generalization of max-min fairness for multiple resources, where it maximizes the minimum dominant share across all users [24]. Fairness influences the order in which resources are scheduled to tasks, as certain tasks may take precedence.

Another domain in which fairness is incorporated is the field of air traffic management. In this field, fairness is important for air traffic flow management [39,2], flight scheduling [36], and allocation of take-off and landing slots at airports [8,9]. These studies consider a fair distribution of the utilities of all players usually expressed in monetary units or delay time. The air traffic flow

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[1] Auctions are used in this research as a way to collect local information from the participants. We do not consider the bidding behavior of the bidders in this paper.

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