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Incentive compatible mechanisms for scheduling two-parameter job agents on parallel identical machines to minimize the weighted number of late jobs

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ABSTRACT

We consider the problem of designing polynomial time truthful mechanisms for machine scheduling problems with parallel identical machines where some of the jobs' characteristics are private information of their respective owners and a central decision maker is in charge of computing the schedule. We study a two-parameter setting, where weights and due dates are private information while processing times are publicly known. The global objective is to minimize the sum of the weights of those jobs that are completed after their due dates. We derive a set of properties that is equivalent to the well known condition of cycle monotonicity, which is a general condition for truthful mechanisms in non-convex valuation function domains. Our results utilize knowledge about the underlying scheduling problem, so that the resulting properties are easier to implement and verify than the general condition of cycle monotonicity. We illustrate the use of our results by analyzing an example algorithm that has recently been proposed in the literature for the case of one machine.

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1. Introduction and contribution

When analyzing exact and heuristic methods for solving scheduling problems, we often assume that a *central decision maker* is equipped with all relevant data related to the problem. However, there exist many real world applications where this is not the case because part of the relevant data is private information of selfish players who aim to influence the solution determined by the scheduling algorithm by submitting false information to the decision maker. In some cases, however, the decision maker can extract the true information by designing an appropriate algorithm that sets the right incentives for these players. This in turn enables the decision maker to generate "fair" solutions with respect to some *social criterion* that considers the interests of all players. The design of such algorithms is subject of a field of research that is usually referred to as *algorithmic mechanism design* [32,33].

1.1. Basic problem setting and applications

In this paper we will consider scheduling problems with parallel (identical) machines and publicly known processing times. These problems will be considered in the context of algorithmic mechanism design, with the job-owners being

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strategic players or *agents*. The agents are assumed to be risk-neutral. Each job-owner reports a *valuation function* to the mechanism. This valuation function may deviate from the true valuation function, which is private information of the job-owner. The mechanism itself is composed of a *social choice function* and *payment functions*. In the context of scheduling problems, the social choice function (or *allocation function*) determines a feasible schedule based on the valuation functions reported to the mechanism. A typical objective of the social choice function is maximizing social welfare, which corresponds to maximizing the sum of all valuation functions. However, each job-owner selfishly aims to maximize her utility function, which corresponds to the sum of her valuation of the schedule and a corresponding (potentially negative) payment from the mechanism to the job-owner. Thus, it is likely that the job-owner lies about the valuation function in order to achieve a greater utility function value than in the case of reporting the true valuation function. Obviously, if the job-owners do not report their true valuation functions to the mechanism, it is impossible to design a mechanism that maximizes social welfare. To overcome this problem, it is necessary to design the mechanism to be (dominant strategy) *incentive compatible* or *truthful*. That is, the mechanism must guarantee that reporting the true valuation function always maximizes the utility function of a rationally acting agent.

As described by Kovalyov and Pesch [23], applications of this problem setting can, for instance, be found in the field of intermodal transport, where some kind of service provider operates cranes in a container terminal (e.g. at a sea port or a rail-road terminal) to load and unload trains. The service provider has service contracts with his customers. Each contract is related to a specific customer of the service provider and vice versa. Each customer requests a train to be loaded or unloaded in a given planning period. These requests correspond to jobs to be processed by the service provider. A similar setting may arise when considering the problem of determining an execution sequence for computer tasks that have been accepted by a computing service provider who operates computing devices. In both examples, the customers compete for quick execution of their jobs in the schedule determined by the service provider for the planning period. The processing time for each job is publicly known. Jobs may incur additional costs to their owners if their completion time is too large, for example because of strict deadlines and corresponding contractual penalties. The related parameters are private information of the customers. The service provider's revenue for executing a job is fixed. Hence, the service provider seeks to determine a "fair" schedule that takes into account the interests of all customers. To generate this schedule, the service provider must know the private information of the players. Hence, the service provider must design an incentive compatible algorithm for scheduling the execution of the jobs.

1.2. Related literature

A general introduction to the field of algorithmic mechanism design can be found in Nisan et al. [34]. Additionally, there is a fairly large number of publications dealing with mechanism design in the context of machine scheduling. An excellent overview is given by Heydenreich et al. [18]. A literature overview and a classification scheme is presented by Kress et al. [24].

One of the most important general results in the field of mechanism design is the *Vickrey–Clarke–Groves mechanism* (VCG mechanism), that was suggested by Vickrey [39] and generalized by Clarke [10] and Groves [15]. A mechanism is called a VCG mechanism, if the social choice function maximizes social welfare, i.e. the sum of all valuation functions, and if the payment functions are of some special structure. A VCG mechanism is incentive compatible, but a major drawback is the need for finding optimal solutions to the underlying problem of maximizing social welfare, which may be NP-hard (see, for instance, Nisan [31]). Hence, in the context of scheduling problems, VCG mechanisms are oftentimes not appropriate even if the objective function of the specific scheduling problem corresponds to maximizing social welfare. One must therefore make use of other theoretical results related to incentive compatibility that are suitable for approximate and heuristic algorithms. These results oftentimes turn out to "boil down to a certain algorithmic condition of *monotonicity*" [27].

One can identify two streams of literature dealing with mechanism design in the context of scheduling problems. The first group of publications presumes that the machines are selfish agents (*machine agents*); see Christodoulou and Koutsoupias [8] and Kress et al. [24] for an overview. These papers follow the seminal work of Nisan and Ronen [32] and include Lavi and Swamy [27], Archer and Tardos [4], Christodoulou et al. [9], Koutsoupias and Vidali [22]. The second stream of literature assumes that the jobs are selfish agents (*job agents*), which is the perspective taken in this paper.

Angel et al. [1–3], Auletta et al. [5], and Christodoulou et al. [7], for example, consider the design of incentive compatible mechanisms in different settings with parallel identical machines, parallel related machines, and parallel unrelated machines. The job agents may manipulate the schedule by providing false information regarding the processing times. Angel et al. [2] also consider online settings, where the existence of jobs is unknown until their release dates. The global objective in all settings is to minimize the makespan.

Other authors analyze the global objective of minimizing the total weighted completion time. Duives et al. [11] and Hoeksma and Uetz [20], for instance, assume that there is only one machine and restrict themselves to considering discrete valuation function domains. They consider a one-parameter setting, where the processing time of each job is public knowledge and the job's weights are private information (see also Hain and Mitra [16] for a related model with processing times being private information), and a two-parameter setting, where both processing times and weights are private information. They derive *optimal mechanisms* that are not only truthful, but at the same time minimize the total (expected) payments that are made to the job-owners. In some applications, however, one may want to achieve different properties of the payments. For example, Suijs [38] presents ("*budget balanced*") VCG payment functions for the one-parameter case in continuous valuation function domains such that the clients, on average, neither win nor lose money (see also [17,29,30] for related and more general results).

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