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The disaster emergency unit scheduling problem to control wildfires

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A R T I C L E I N F O

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A B S T R A C T

In this paper, we study optimization and mechanism design relative to the disaster emergency unit (DEU) scheduling problem to control wildfires. We consider a single DEU and a set of forestry companies, in a scenario where the resources are constrained and an emergency induces damage to the nearby towns. Each forestry company has information about the forest density, which in addition to the feedrate of wildfires determines its marginal waiting cost. In practice, it generates a waiting cost for each forestry company according to its position in the sequence and the working time for the DEU. The goal is to determine a schedule and the working times of the DEU, so as to minimize the sum of the total damage and the total waiting cost of the forestry companies subject to constraints on the damage and use of the working time of the DEU. We show that the centralized problem can be solved by Karush-Kuhn-Tucker (KKT) conditions and design an easy-to-implement truthful mechanism for the decentralized problem. This design charges the damage to the forestry companies based on the optimal solution properties obtained from the centralized problem, with overcharging bounded by a constant. A numerical example to illustrate the problem and the usefulness of our contributions is described. Finally, we extend our results to similar problems for sequential use of a resource, in which strictly increasing convex isoelastic damage functions are considered.

1. Introduction

Scheduling problems in disaster operation management (DOM) are an important factor to determine policies of national security (Jackson et al., 2010) and present an opportunity to re-visit and re-define operation research (Simpson and Hancock, 2009). Indeed, there is increasing recognition of the need for applying centralized and decentralized resolution methods in DOM, because it develops a scientific approach to help decision making before, during and after a disaster (Altay and Green, 2006; Galindo and Batta, 2013).

DOM problems arise in four phases: mitigation, preparedness, response and recovery (Haddow et al., 2017). An issue of particular interest in the disaster response phase is the unit scheduling problem, which aims to determine a schedule defined by a sequence of the emergency points to be visited and the working time on these points aiming at minimizing the total damage (Wex et al., 2014).

In this paper, we are focused on the disaster emergency unit scheduling problem to control wildfires from both centralized and decentralized perspectives. We are motivated by the 2017 Chile wildfires, which is described as the worst in Chile's modern history as it destroyed many towns in the central Maule Region, displacing thousands of people.

1.1. Related work

An important problem of fire management is to decide when and where to suppress wildfires and when and where to light prescribed fires or allow wildfires to burn (Martell, 2007). This problem has been studied by several authors from a centralized perspective, considering various assumptions in its formulation and different solution methods, e.g. simulation and stochastic integer programming approach to wildfire initial attack planning (Ntaimo et al., 2013), mixed integer programming model for spatially explicit multi-period landscape level fuel management to mitigate wildfire impacts (Minas et al., 2014), survival analysis methods to model the control time of forest fires (Morin et al., 2015) and chance-constrained programming model to allocate wildfire initial attack resources for a fire season (Wei et al., 2015). However, few have tackled the complex social, economic and ecological issues that complicate modern forest fire management (Rönnqvist et al., 2015). Our work addresses both centralized and decentralized perspectives in a scenario with a limited number of personnel and specialized equipment.

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1.2. Statement of problem

Consider n forestry companies and a single disaster emergency unit (DEU) to control wildfires, under a scenario with a limited number of personnel and specialized equipment. Each forestry company j is located in town j. We assume these companies do not satisfy all safety conditions to fully contain wildfires. An emergency induces a damage to the town j defined by the isoelastic function $D_j(\ell_j) := 4d_j/(\pi\ell_j^{\gamma_j})$, $1 < \gamma_j < 2$, with ℓ_j the working time of DEU to control wildfires in town j, d_j the damage cost associated to the inhabited area in town j affected by wildfires and, $\pi\ell_j^{\gamma_j}/4$ the area controlled by DEU in town j. Notice that an isoelastic damage function makes sense as the percentage change of DEU working time by increasing of area control implies a decreasing percentage change in the town area where the damage is induced. Formally, we consider $\pi\ell_j^{\gamma_j}/4 := \varepsilon_j\pi\ell_j^2/4$ with $\varepsilon_j \in (0,1)$ decreasing in ℓ_j.

Each forestry company j has private information about its forest density, which in addition to the feedrate of wildfires determines its marginal waiting cost p_j due to forest working area to be recovered. The DEU requests the marginal waiting costs $\hat{p}_j$ from each forestry company j and chooses an arbitrary sequence σ that indicates the order to visit the towns by DEU, with $\sigma(j)$ being the position of town j in the sequence σ.

For convenience, we denote $\tau(k)$ as the town in the position k in the sequence σ. Given sequence σ, we have a transfer time $r_{\tau(\sigma(j)-1),j}$ between town $\tau(\sigma(j)-1)$ and town j. We assume an initial point for the DEU, which provides a set of towns that could be visited in the first position of sequence σ.

The total cost damage and damage cost of each town j are constrained by $\overline{D}$ and $\overline{D_j}$, respectively. Similarly, the total and the particular DEU working time in each town j are constraint by $\overline{L}$ and $\overline{\ell_j}$. These constraints aim to state (i) lower bounds on total damage and the particular damage of town communities; and (ii) upper bounds on the total and particular waiting times for DEU of towns, whose values could be estimated according to the operative constraints of the DEU (e.g. equipment capacity, working shift, geographic, whether and environmental conditions, among others) and/or a potential maximum collateral damage of town communities in this emergency setting. Note that for a working time $\ell_j \leq t$, t constant, $D_j(\ell_j) \geq D_j(t)$.

We want to compute the optimal *social cost* given a sequence σ for working time of DEU, which is given by

$$\sum_j D_j(\ell_j) + \sum_j \hat{p}_j\left(\sum_{\sigma(i)\leq\sigma(j)} \ell_{\sigma(i)} + r_{\tau(\sigma(j)-1),j}\right), \tag{1}$$

subject to

$$\sum_j \ell_j \leq \overline{L} \tag{2}$$

$$\ell_j + r_{\tau(\sigma(j)-1),j} \leq \overline{\ell_j} \quad \forall j \tag{3}$$

$$\sum_j D_j(\ell_j) \leq \overline{D} \tag{4}$$

$$D_j(\ell_j) \leq \overline{D}_j \quad \forall j \tag{5}$$

In this social cost, we consider the conversion of damage and waiting cost into monetary values and assume that the conversion factors are hidden in the damage function.

The assumption about the waiting cost values $\hat{\boldsymbol{p}}$ announced from the forestry companies defines to the perspectives of the problem. While in the centralized perspective the DEU knows the real waiting cost from the forestry companies, i.e., $\hat{\boldsymbol{p}} = \boldsymbol{p}$, in the decentralized perspective the DEU knows only the announced values $\hat{\boldsymbol{p}}$, which are not necessary the real values $\boldsymbol{p}$, and then a truthful mechanism would of interest.

1.3. Our contribution

We show that the centralized problem can be solved by developing and using Karush-Kuhn-Tucker (KKT) conditions, and further design an easy-to-implement truthful mechanism for the decentralized problem. This truthful mechanism charges the damage to the forestry companies based on the optimal solution properties obtained from centralized problem, with an overcharging bounded by a constant. A numerical example to illustrative the problem and the usefulness of our contributions is described. Finally, we extend our results to similar problems for sequential use of a resource, in which isoelastic damage functions are considered.

2. The centralized perspective

We consider the centralized problem consisting of minimizing the sum of the damage functions and the waiting costs, under the assumption that the DEU knows the real waiting cost from the forestry companies. Consequently, the DEU changes directly the damage generates by each forestry company j. Theorem 1 defines the unique optimal working time of DEU for the town j in the sequence σ.

Theorem 1. *Fix a sequence σ and consider the minimization of the social cost (1) subject to constraints on the working time of DEU (2)- (3), and the damage (4)- (5). The unique optimal working time of DEU for the town j in the sequence σ satisfies*

$$\ell_j^* = \left(\frac{\gamma_j d_j 4(1+\lambda_2+\lambda_{2j})}{\pi\left(\sum_{\sigma(i)\geq\sigma(j)} \hat{p}_i + \lambda_1 + \lambda_{1j}\right)}\right)^{\frac{1}{1+\gamma_j}},$$

where $\lambda_1, \lambda_{1j}, \lambda_2$ and λ_{2j} are the KKT multiplier associated to the (2), (3), (4) and (5), respectively.

Proof. First, we show that the minimization of the social cost subject to the damage and working time of DEU constraints for a given sequence σ is a convex programming problem.

We fix a sequence σ. We claim that the minimization of social cost subject to the constraints on the damage and working time of DEU has convex and affine constraints and a convex objective function (1). The former statement is trivial and follows the working time of DEU and damage function definition, i.e., $D_j''(\ell_j) = \frac{4(1+\gamma_j)\gamma_j d_j}{\pi(\ell_j)^{\gamma_j}} > 0$, for $1 < \gamma_j < 2$ and the latter statement follows from the first derivative of the objective function (1) in ℓ_j

$$D_j'(\ell_j) + \sum_{\sigma(i)\geq\sigma(j)} \hat{p}_i,$$

which is independent of ℓ_i *for any* $i \neq j$, and so its Hessian has zero non-diagonal terms, whereas the second derivative of the objective function (1) in ℓ_j is $D_j''(\ell_j) > 0$. Thus, we have that the diagonal terms of the Hessian are positive, the Hessian is positive definite and the objective function (1) is convex.

Since (1) is convex, the Karush-Kuhn-Tucker (KKT) conditions give necessary and sufficient conditions on an optimal solution (Boyd and Vandenberghe, 2004). We write the Lagrangian associated to the problem, apply the KKT conditions and have:

$$D_j'(\ell_j) = -\frac{\sum_{\sigma(i)\geq\sigma(j)} \hat{p}_i + \lambda_1 + \lambda_{1j}}{1+\lambda_2+\lambda_{2j}} \tag{6}$$

$$= -\frac{4\gamma_j d_j}{\pi(\ell_j)^{1+\gamma_j}}, \tag{7}$$