

The crew scheduling and routing problem in road restoration

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ABSTRACT

The crew scheduling and routing problem (CSRP) consists of determining the best routes and schedules of multiple crews to repair damaged nodes in a network affected by extreme events. The problem also involves the design of paths to connect a depot to demand nodes that become accessible only after the damaged nodes in these paths are repaired. The objective is to minimize the total time that demand nodes remain inaccessible from the depot. This paper summarizes the main contributions related to mathematical models and solution methods developed to solve the CSRP in the thesis “The crew scheduling and routing problem in road restoration”. The proposed methods were the first exact methods able to provide valid lower bounds and optimality gaps for all the benchmark instances of the problem. In addition, the thesis presents new extensions considering more realistic characteristics of the problem and data uncertainty.

KEYWORDS. Decomposition methods. Road restoration. Robust optimization.

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1. Introduction

Every year, millions of people are affected by large-scale disasters, such as hurricanes, floods, and earthquakes. These disasters can cause partial or total disruption of the basic transportation infrastructure composed of roads, bridges, tunnels, etc. Consequently, affected areas may become inaccessible, which often causes delays in the distribution of vital first-aid commodities as well as in the evacuation operations, thus resulting in victim's suffering and loss of life. Road restoration, one of the main activities in this context, is a complex activity due to its inherent decisions that must be taken quickly and under uncertainty, such as the assignment of resources (crews) and the scheduling/routing of the crews to perform the repair operations. The objective is to restore the damaged nodes in the network as soon as possible, as they are necessary to connect a source node (depot) with demand nodes where there exists some demand for humanitarian assistance. Additionally, we need to define relief paths to connect the central depot with the demand nodes.

The crew scheduling and routing problem (CSRP) and related variants have received increased attention in the last few years. Most studies use heuristic/metaheuristic algorithms, such as ant colony-based systems [Shin et al., 2019], GRASP [Maya Duque et al., 2016], and specialized heuristic depending on the particular characteristics of the problem [Akbari e Salman, 2017a,b]. Exact methods based on dynamic programming and partially observable Markov decision process model have been proposed in the literature [Çelik et al., 2015; Maya Duque et al., 2016]. However, these methods are not efficient to solve even small instances of the problem. In the thesis "The crew scheduling and routing problem in road restoration" [Moreno, 2020] we help to fill this gap by proposing state-of-the-art exact approaches based on Benders decomposition. Initially, we developed solution methods for the basic variant of the CSRP, which considers a single crew available to perform the repair operations. For this variant, we developed two branch-and-Benders-cut (BBC) algorithms. The first BBC has a master problem with scheduling decisions while the crew routing and the design of relief paths are considered in the subproblems. The second BBC considers the crew scheduling and relief path decisions in the master problem and a subproblem with the routing decisions. Also, we proposed metaheuristics based on genetic algorithm (GA) and simulated annealing (SA) to solve the CSRP. These metaheuristics operate on a subproblem representing the scheduling decisions and call for specialized algorithms to optimize the crew route and the relief path decisions. Finally, we proposed a hybrid BBC method (HBBC) that combines the metaheuristics and the BBC to solve the CSRP.

In practical contexts, multiple crews associated with various agencies, such as civil defenses, armed forces, and firefighters, may be available to perform the repair operations. The crews may differ in the time required to repair the damaged nodes, in the travel time between nodes, and in the set of damaged nodes that they can repair. However, for variants of the problem addressing multiple crews, we notice that there is a lack of studies considering heterogeneous crews in road restoration problems. Furthermore, the works related to homogeneous crews do not take into account synchronization constraints [Akbari e Salman, 2017b,a] that are inherent to the problem and/or decisions related to the definition of the relief paths connecting the source node with the demand nodes. To reduce this gap, we proposed three mathematical formulations and valid inequalities for the CSRP with synchronized multiple heterogeneous crews.

Finally, although repair times are uncertain in road restoration problems, few works have focused on it [Çelik et al., 2015], and without integrating the decisions attributed to the CSRP. Furthermore, none of these studies consider multiple heterogeneous crews. In the thesis, we consider uncertain repair times via robust optimization. The BBC algorithms, the metaheuristics, and the valid inequalities proposed for the deterministic CSRP were adapted to solve the robust CSRP.

The remainder of this paper is organized as follows. Section 2 describes the CSRP. Section 3 outlines the developed solution methods for the CSRP with a single crew. Section 4 outlines the proposed models for the CSRP with multiple heterogeneous crews. Finally, Section 5 presents the concluding remarks.

2. Problem description

The CSRP can be defined on an undirected graph $G = (\mathcal{V}, \mathcal{E})$, in which $\mathcal{V}$ is the set of nodes and $\mathcal{E}$ is the set of undirected arcs. The graph G represents a damaged network affected by extreme events. The subset $\mathcal{V}^d \subset \mathcal{V}$ characterizes the demand nodes while the subset $\mathcal{V}^r \subset \mathcal{V}$ contains the collection of damaged nodes. Furthermore, there may be transshipment nodes, which represent the intersection of two or more arcs. There is one depot (node 0) that is a supply node to be connected with the demand nodes and from which the crews initially depart to repair the damaged nodes. Figure 1(a) shows an example of a graph G representing a damaged network.

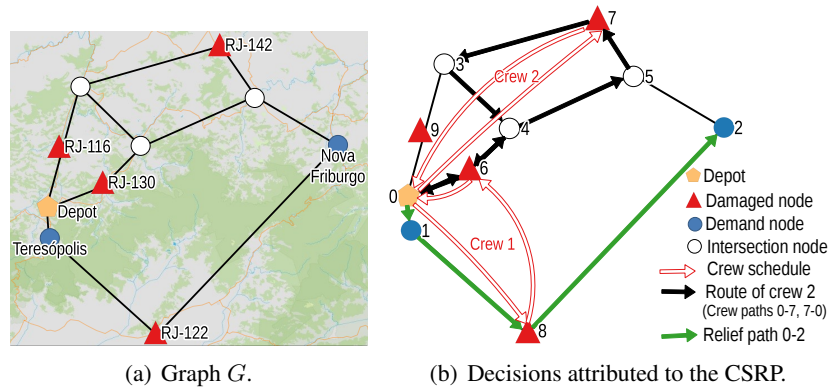


Figure 1: Example of a graph G and decisions attributed to the CSRP [Moreno et al., 2020a].

A set $\mathcal{K}$ of multiple heterogeneous crews is available to perform the restoration activities. The crews are initially located in the central depot and differ in the time required to repair the damaged nodes (δ_{ki}), in the travel time on the arcs (τ_{ke}), and in the set of damaged nodes that each crew can repair. In the basic variant of the problem, the set $\mathcal{K}$ is composed by only one crew. The CSRP consists of determining (i) the paths to connect the depot to the demand nodes (relief path decisions), (ii) the assignment of crews to the damaged nodes (assignment decisions), (iii) the schedule of one or more crews to repair the damaged nodes (scheduling decisions), and (iv) the routes of crews to repair the damaged nodes and return to the depot (routing decisions). Figure 1(b) illustrates the main decisions, highlighting the schedule of two crews (red arrows), the route of a crew (black arrows), and one relief path (green arrows).

The relief path decisions correspond to determine the sequence of nodes and arcs used to connect the depot with the demand nodes. The assignment decisions determine the damaged nodes that need to be repaired as well as the crews that must repair them. The scheduling decisions define the sequence in which each crew will repair the damaged nodes. In the case with multiple crews, it is assumed that more than one crew cannot simultaneously repair a damaged node. Thus, if a crew arrives at a damaged node while another crew is performing the restoration, then it has to wait until the damaged node be repaired. The routing decisions determine the routes to be used by each crew to repair the damaged nodes and return to the depot. Nodes and edges can be traversed multiples times. A damaged node is repaired the first time it is visited by the crew allocated for its restoration.

3. Single crew scheduling and routing problem

We start outlining the solution methods for the single crew scheduling and routing problem (SCSRP), the basic variant of the CSRP in which only one crew is available to perform the repair operations. For this variant, we developed two BBC algorithms that exploit the fact that when the scheduling decisions are fixed, the crew routing and relief path decisions can be easily solved. In the first BBC only the scheduling decisions are kept in the master problem, while the crew routing and the design of relief paths are considered in two subproblems. The second BBC considers the crew scheduling and relief path decisions in the master problem and a subproblem with the routing decisions.

The resulting master problem obtained from the Benders decomposition is solved by a single search tree, exploring the generation of cuts inside the tree. Due to the discrete domain of the subproblems, standard duality theory cannot be applied to derive cuts. Therefore, different types of feasibility and optimality Benders' cuts based on particular characteristics of the problem were proposed. A detailed explanation of the proposed BBC algorithms can be found in Moreno et al. [2019, 2020b].

We also proposed metaheuristics based on genetic algorithm (GA) and simulated annealing (SA) to solve the SCSRP. These metaheuristics operate on an auxiliary problem representing the scheduling decisions and call for specialized algorithms to optimize the crew routing and the relief path decisions as well as to determine the feasibility and cost of the proposed schedule in the original SCSRP. The proposed metaheuristics do not explicitly consider all possible crew routes and relief paths but only the best ones of a given scheduling solution, which significantly reduces the space of solutions explored by them. They use a construction heuristic that is able to find feasible solutions for all instances of the problem and five local search operators to diversify the search in the solution space. A detailed explanation of the metaheuristics and the construction heuristic is presented in Moreno et al. [2020b].

Finally, we proposed a hybrid BBC method (HBBC) that combines the metaheuristics with the BBC to solve the SCSRP. We use the metaheuristics in a innovative way, not only to improve the master problem solutions but also to derive Benders cuts from their neighborhood. Hybridizing Benders decomposition methods with heuristics or metaheuristics can simultaneously improve both the lower and upper bounds.

In total, more than 15 variants of the methods were tested using different types of feasibility and optimality cuts, valid inequalities, warm-start strategies, and combination of the BBC with metaheuristics. Among the tested strategies, the best approach was a hybrid method combining the second BBC with the SA metaheuristic.

4. Multi crew scheduling and routing problem

We defined for the first time the multicrew scheduling and routing problem (MCSRP) for road restoration. In this context, we developed three mixed-integer optimization (MIP) models that differ in the way of modeling the scheduling decisions and the synchronization of the crews. The first formulation (MCSRP1) is based on the three-index vehicle flow formulation of the vehicle routing problem (VRP) to define the schedule of the crews, while the synchronization of the crews is controlled with a four-index variable. The second formulation (MCSRP2) is based on the two-index vehicle flow formulation of the VRP to define the crew scheduling, while the synchronization of the crews is controlled with a new three-index variable. Finally, the third formulation (MCSRP3) is a modified version of MCSRP2 with the elimination of some variables related to the routing decisions. Furthermore, some additional constraints are introduced to prohibit the restoration of the

damaged nodes that do not affect the accessibility of the demand nodes. For the three proposed models, we derived valid inequalities based on theoretical properties of the problem. The valid inequalities are based on the dominance of the paths between nodes in the damaged network. A detailed explanation of the MIP models and inequalities is available in Moreno et al. [2020a].

The three models with and without the valid inequalities were solved by a general-purpose MIP solver (namely, IBM CPLEX Optimization Studio v. 12.10) using instances from the literature (set L) and instances derived from a real disaster situation (set CS). In the computational experiments, the performance of the solver with MCSRP1 was superior than with MCSRP2 and MCSRP3 regarding the number of optimal solutions, but it had difficulty in finding feasible solutions in more cases. Eliminating some symmetric solutions in the third formulation (model MCSRP3+VIs) was effective in finding feasible solutions for all the considered instances within the time limit, but the number of solutions that were proved optimal was smaller than in MCSRP1+VIs. The effectiveness of MCSRP3+VIs appeared to be related to the number of nodes that can be processed in the BBC tree, which is significantly higher when compared to the other two formulations. Evidently, there is a trade-off that can be explored in practical situations according to preferences or necessities of the decision-maker.

Finally, we consider uncertain repair times into the MCSRP via robust optimization. In this context, we proposed a robust counterpart model (RCSR) based on the well-known budgeted uncertainty set. This model resulted from incorporating, into the deterministic model MCSRP3, recursive equations that verify for each damaged node in the schedule of the crews, if its repair time must be considered as one attaining its worst-case value. A similar approach was developed in the context of the robust VRP [Munari et al., 2019]. The BBC algorithms, the metaheuristics, and the proposed valid inequalities were adapted to solve the RCSR. Detailed explanation of the RCSR and its computational results are available in Moreno [2020].

5. Conclusions

This work summarized the main mathematical formulations, valid inequalities and solution methods to solve the CSRP, as proposed in Moreno [2020]. Two novel branch-and-Benders-cut (BBC) algorithms, two metaheuristics (GA and SA), and a hybrid approach (HBBC) were developed for the CSRP. The proposed methods were the first exact methods able to provide valid lower bounds, and optimality gaps, for all the tested instances of the problem. In addition, three new mathematical formulations were proposed to incorporate practical characteristic of the problem that were neglected so far in the literature. For the three proposed models, we studied particular properties of the problem and derived valid inequalities based on these properties. The three mathematical formulations showed improvement with the addition of the VIs. Computational experiments based on a real-world case disaster were performed, enabling us to derive prescriptive recommendations to the political bodies in charge of post-disaster operations. In this context, the thesis “The crew scheduling and routing problem in road restoration” made important contributions to the areas of Optimization and Humanitarian Logistics, promoting the integration of these areas and the use of Operations Research to help decision makers in the response of disasters situations.

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