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A modified ant colony optimization algorithm to increase the speed of the road network recovery process after disasters

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ABSTRACT

When a disaster strikes many roads are blocked and the affected network may break up into a number of isolated parts. The reconnection of the network is therefore necessary for both relief distribution and planning of construction work. Shortening the time during which the road network is separated into isolated parts helps decrease indirect losses from disasters. The obstacles usually faced during the process of reconstruction include both the large number of blocked links and extensive affected areas (road networks).

A reduction of the network into a much smaller complete graph and metaheuristic based on an ant colony optimization has been introduced to overcome this issue. We demonstrate that, for small networks, the metaheuristic produces the same results as other deterministic algorithms. We further show that the method is still a viable approach for large networks (723 nodes and 974 links, where we artificially blocked 46 links) when the NP-hard nature of this problem began to affect the computational time of the deterministic algorithms.

We demonstrate how the various scenarios can be included into the algorithm. We finally introduce a new ranking of feasible solutions which enables the algorithm to minimize the time of reconstructions for all repair units. Reasonable results were obtained after five minutes of computation. There is nevertheless an up-to-38% improvement of the initial solution. The algorithm can also be used for both relief distribution, when no roads were damaged, and for planning of construction work when damaged roads occur.

1. Introduction

Transportation networks are particularly vulnerable to extreme events with a large spatial extent (usually natural disasters) after which many links might remain closed. These links can be not only blocked by, e.g., falling trees or temporal flooding, but also destroyed as a result of landsliding, fluvial erosion or earthquakes. These simultaneous road closures often result in network disintegration into a number of mutually isolated parts (components). Reestablishing network connectivity is among the most important tasks after such events because of relief distribution and the minimization of economic losses. The duration of this process is to a high degree dependent on the sequence in which the blocked links are (albeit provisionally) reopened. An optimal sequence of repair works will significantly shorten the time needed for network recovery. Shortening the time needed for reconnection of a road network damaged by a disaster ranks among the measures which not only reduce the impact of the disaster but also the disaster risk understood as the probability of the disaster multiplied by its consequences.

The problem of the optimal reconstruction is becoming increasingly important due to limited resources [22,63] and the importance of the disaster recovery was highlighted in Altay and Green [4] or Ergun et al. [22].

The phase of recovery of a network damaged by an event is an important part of the resilience of the network. Two essential definitions of resilience exist. The first one defines resilience as the capability of a system to recover from a large disruption [34], while the other one adds the ability of the system to withstand the disruption with a low impact on its functioning [17,46]. An example of the network resilience, in the form of the time from the event to the recovery, can be seen in Fig. 1.

The figure also demonstrates the effect of the improved resilience. Notwithstanding the definition, one of the main tasks is thus to analyze and improve the resilience of the network (see for instance [64,71], as the most recent examples). The improvement and analysis of the resilience can, however, face many difficulties. One of the problems is how to evaluate the resilience of the network under the numerous uncertainties caused by a disaster. It led to the development of uncertainty based models for road network reliability in [54], which can be

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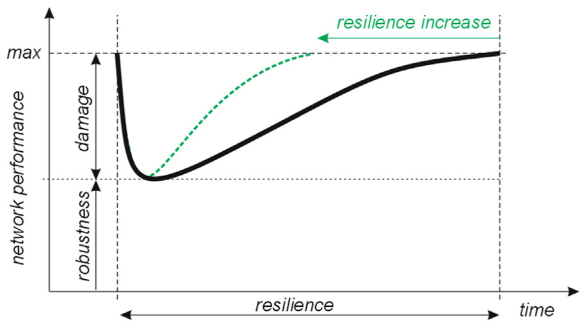

Fig. 1. An example of the network resilience.

understood as an important feature of the resilience. The main evaluating criteria in the paper are the total travel time, flow and consumer surplus. We also refer the reader to [55], where the post-disaster uncertainties are included in physical road capacity, parameters of link travel time function, travel demand and mode choice behavior. The authors studied the influence of several parameters on the final reliability of the network.

In this paper we work on an actual road network which developed its internal structure over time where every change in topology, e.g., construction of new road links, would be an extremely expensive process. The same is valid for a number of existing road networks around the world. The next issue is that many of the disruptions are event-dependent, which means that the ability of the system to restore its functioning can differ significantly under various scenarios (e.g., if only flooding or also landsliding is taking place). We thus pay attention only to the recovery phase. Enormous potential exists in the methods of optimization of the reconstruction process (after disruptive events) which could save resources and shorten the time to the network recovery.

The optimization problem is now discussed more thoroughly. One can assume that we have a system represented by a road network which was affected by an extreme event. The result is usually a large number of concurrently blocked links [12,7,8]. Common traffic patterns are changed significantly during such events [29,32,33,37]. The resilience of the affected network is therefore closely related to the process of reconstruction of the blocked links. This raises several important questions. Are all blocked links equally important during the reconstruction process? If not, what criteria determine their importance? Is it possible or desirable to reconstruct the most important links among the first ones? What sequence of repair works shall an administrator set, if only a limited number of repair units are available? How shall the administrator place the resources (as heavy machinery) in order to ensure optimal reconstruction? And what does the optimal reconstruction actually mean? The answers to these questions are not trivial and all of them lead to optimization problems. The main task is thus to find such sequences of blocked links whose reconstruction is in some sense preferable over other existing sequences.

There are two basic approaches to this problem. The first one focuses on ranking the elements of the network which should be repaired, but does not consider the routing of the repair units [10,35,9]. The other one draws attention to the scheduling and routing of the repair units under various assumptions and constraints. It can take into account the maximum time needed to reconnect the network and minimize it [1,36]. The optimization problem can be, however, made more complicated. In [13], an asymmetric traffic assignment model was incorporated into their algorithm. [25], analyzed an early stage of the repair activities with the aim of maximizing the performance of the emergency road repair activities, maximizing the number of people that benefit from it and minimizing the risk for repair units. The problem can also be formulated as an integer network flow problem [66,68]. Both approaches can be further combined with distribution relief [45,51,65,67], limited resources [39,43,44], time constraints and other related operating constraints [69]. These extensions of the model lead to various types of loss functions which can also involve the total weighted earliness of all the cleared paths [3], accessibility [47], travel cost [42] and the total prize gained by reconnecting the network [2,36]. A number of models attempt to cope with incomplete information concerning the debris along the roads and try to find an optimal sequence of links for each period of reconstruction [11] and with stochastic factors during the operational stage [70]. Additional relevant papers dealing with the reconstruction process include [26,27,5,52,62].

The primary problem of all the approaches is that the optimal solution has to be found in a large state space. Let us assume, for instance, 40 concurrently blocked links. There are $8{\times}10^{47}$ possible sequences of blocked links which should be evaluated. It is apparent that it is impossible to evaluate all the sequences in a reasonable time. The number above can be significantly reduced if we know the position (the base) of the repair units. Despite this simplification, the problem unfortunately still remains highly nontrivial and ranks among the so-called NP hard problems. This means that the time, we need to find its solution, depends strongly on the size and structure of the network and cannot be found in a reasonable time when a large network is investigated. Despite this fact, the deterministic and stochastic algorithms are developed to cope with larger networks. The problems of network reconstruction were modeled using mixed integer programming and solved with a fuzzy genetic algorithm [13], GRASP and VNS metaheuristics [43], dynamic programming and an iterated greedy-randomized constructive procedure [45], a rule-based constructive heuristic [47], a Markov decision process reconstruction [11], a greedy algorithm using critical links [42], a heuristic algorithm based on problem decomposition and variable fixing techniques [69,70], an ant colony optimization algorithm [65,68], simulated annealing [27], tabu search [27] and genetic algorithms [5,62]. The results produced by the above algorithms are often incomparable due to the use of different loss functions. However, in [65], one finds a comparison among an ant-colony based heuristic algorithm with an original algorithm Cplex 12.5 of a deterministic nature on a small network. The heuristic algorithm produced results which seem to be close enough to the best solution in a much shorter time. A similar approach for one repair crew can be found in [45], where two algorithms were developed and analyzed. The first one is based on dynamic programing and is able to find exact solutions on small networks (up to 41 nodes). The other iterated greedy-randomized constructive procedure is then tested on the small networks as well and further on medium and large networks (up to 401 nodes). In [27], the authors compare two stochastic algorithms (simulated annealing and hill-climbing procedure) and a tabu search algorithm. In [43], two metaheuristics (GRASP and VNS) are analyzed using small networks with known optimal solutions and then applied to large networks (216 nodes) without known optimal solutions. In [47], the authors presented four rule based heuristics and an analysis of the averages of their results and their variability. Optimality of the solutions was not, however, discussed. The study of the resilience can be more complex if we include other phases in the whole process including pre-event and post-event resilience. The three phase process stochastic model, based on evaluating possible scenarios combined with the user equilibria-traffic assignment problem, was introduced in [24].

The size of this problem can be reduced by a ranking of the blocked links under various criteria (see [53,6,61]). This can be seen, for instance, in [53,61] where the Network robustness index and Network trip robustness were used to evaluate the importance of links after their interruption or decreased capacity. The disadvantage of the method is that the ranking can change under various events when more links are blocked. A link may, for example, exist which is not very important for the functioning of the network. If several other links are blocked, however, and the link is the last one preventing the network from disintegration, the importance of the link dramatically increases. The next problem is that the repair of the links, according to their ranking,