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GeoSafe – Evacuation planning problems

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1 Introduction

This paper aims at identifying new challenging variants of the evacuation planning problems, especially in case of bush fires, based on exchanges with practitioners in the context of the GeoSafe project [5]. A large amount of work has been carried out at NICTA [9, 2, 10, 8, 3, 4, 6, 11] mainly in the context of floodings, which can be easily transposed to evacuation in case of fires. The recent survey by Bayram [1] presents the state-of-the-art on large scale network evacuation planning and management.

2 Basic evacuation data

We adopt the notation and terminology given in [4]. There is a directed graph $\mathcal{G}(\mathcal{N} = \mathcal{E} \cup \mathcal{T} \cup \mathcal{S}, \mathcal{A})$ representing e.g. a road network in a region that must be evacuated. The graph is made of:

- the set of *evacuation* nodes \mathcal{E} . An evacuation node represents a zone where people to be evacuated are regrouped),

- the set of *safe* nodes \mathcal{S} . A safe node represent a safe geographical zone that people located in the evacuation nodes must reach during the planning horizon
- the set of *transit* nodes \mathcal{T} . A transit node represent an intersection in the road network that can be traversed by the vehicles carrying evacuated people from the evacuation zones to the safe zones.

Suppose the time is discretized in minutes. Each evacuation node $k \in \mathcal{E}$ is associated with a number of evacuees d_k . Each arc $q \in \mathcal{A}$ has a capacity u_e in evacuees/minute, a travel time t_e giving the number of minutes that a vehicle takes to traverse the arc and a end time b_e , which gives the time at which the arc becomes unavailable due to the fire propagation.

Other characteristics may appear in the variants considered in the cited papers.

3 Previously considered evacuation problems

We first reviews the NICTA papers. The first considered problem and solution methods were presented by Pillac *et al.* in 2013 in a research report that was later published in [9]. One of the practical motivation of the work was that in an urgency situation, the possibility of choices in a road network, such as a fork, generate stress among the population. This is why it is preferable to define a single evacuation path for each evacuation zone. Hence the problem considered in [9] can be described as a two-level optimization problem, which can be solved in an integrated way or by a two-phase approach. At the first level, exactly one evacuation path is determined from each evacuation node to a single safe node. At the second level the flow of evacuees is scheduled trough the path. A MILP (called the restricted flow model RF) is proposed to solve the problem in an integrated way. It is based on time-expanded graph, in which each node is duplicated for each time period. Arc capacities u_e in the time expanded network ensure that the traffic does not exceed the road capacity, especially when several paths use the same arc. The model includes continuous flow variable per evacuation node per arc and in the expanded network and also a binary variable per edge in the (non-expanded) graph \mathcal{G} to ensure the uniqueness of the path for each evacuation node. As the MILP is intractable on a set of instances (HN) derived from a real case

scenario involving 70000 evacuees in the Hawkesbury-Nepean floodplain, located North-West of Sydney, an iterative column-generation-like two-phase heuristic is proposed. Given a set of potential paths, a master problem solves the path selection and flow scheduling problem with another MILP (called the conflict-based heuristic path generation master problem, CPG-MP) involving a reduced number of binary constraints (one per path). And a sub-problem finds new path based for a subset of critical nodes by solving a multiple-origin, multiple-destination shortest path problem. A lexicographic objective is considered. The main objective is to maximize the number of evacuated people during the time horizon, while a secondary objective aims at maximizing the evacuation start time, based on the practical relevance. Note that the second objective is only indirectly tackled by weighting each arc in the time-expanded graph by a cost inversely proportional to the arc time, hence solving a min-cost flow problem.

Subsequent papers describe variants of the models and new methods. A more sophisticated variant of the heuristic was proposed in Pillac *et al.* (2014) [10] for the same problem with, however, a different secondary objective for the min-cost flow, aiming at minimizing the evacuation time (called the clearance time), which is indirectly obtained by weighting the arc in the time-expanded graph by a cost proportional to the arc time.

In Even *et al.* (2014) [2], an additional degree of freedom is introduced, giving the possibility of selecting contraflow roads, which consists in reversing the direction of some major roads. In practical cases, this possibility can highly increase the network capacity for evacuation. This is done by introducing a subset \mathcal{A}_c of arcs that can be used in contraflows and by modifying the CPG-MP, interestingly without the need of introducing additional binary variables. A software called the NICTA Evacuation Planner is also presented, with new instances with up to 1 000 000 evacuees, which are solved requiring up to 30 min. of CPU time.

In Even *et al.* (2015)[3], the case where the selected paths must form a convergent subgraph, i.e. for which each node has at most one outgoing arc in the set of paths, is considered. This is motivated by the fact that convergent evacuation paths can be better controlled. Indeed, even if in the previous model, a single path was assigned to each evacuation node, in the case where two paths are merged and then are separated again, a driver can be confronted to a choice and take a decision that would not correspond to what was planned. Hence the set of paths now form a tree rooted at the safe node. The solution method is still a two-phase method but does not follow

anymore the column generation principle. A tree is first built by a MIP working on an aggregated graph (without time discretization). The second phase is the flow scheduling problem given the computed tree, which is a maximum flow problem. The first phase is now able to produce good upper bounds on the maximum number of evacuees and on the minimum clearance time. A simulation study shows that the convergent model outperforms the general model when the presence of a fork in the network generated an hesitation for the driver that is capture by a 0.75 second delay.

This model is further developed by Kumar *et al.* (2016) [6] to incorporate network design aspects in the problem to model possible infrastructure enhancement decisions, as for the west Sydney case concerns about the capacity of the road network were expressed. Two additional decisions are introduced : adding lanes to a road (arc) and elevating a road (arc). The first decision results in an increase of the capacity of the arc while the second decision postpones the flooding time, both coming at a cost. These decisions can be incorporated in the tree design problem, which is also the master problem of a Benders decomposition method. The objective is still to maximize the number of evacuated people under a budget constraint that limits the infrastructure upgrades. The maximum flow subproblem is used to obtain a feasible flow schedule and also to generate optimality cuts that are reinjected in the master problem. To increase the performance of the Benders method, pareto-optimal cuts are generated.

All previous approaches assumed that each individual vehicle of an evacuation (flow unit) moves independently from the other vehicles of the same zone, and exactly as prescribed by the maximum flow model. Pillac *et al.* [8] propose to use the concept of response curves to incorporate behavioral models in the problem. In practice, instead of assigning a start time to each evacuee, the authorities can influence the evacuation start time of a zone and the level of resources mobilized to increase the evacuation rate (e.g. number of agents knocking on people's door), to which people answer according to a behavioral model abstracted by a response curve. It follows that to each evacuation zone $k \in \mathcal{E}$, a set of response curves \mathcal{F}_k is given. For each evacuated zone, a start time δ_k and a response curve $f_f \in \mathcal{F}_k$ has to be assigned such that the flow of evacuees leaving zone k at time t is given by

$$\phi_k^t = \begin{cases} 0 & \text{if } t < \delta \\ f(t - \delta) & \text{if } t \geq \delta. \end{cases}$$

A column generation approach is proposed where the set of all evacuation

plans of a zone is considered, where a evacuation plan is a path from the evacuated zone to a safe node, the start time and the response curve. The master problem selects a plan for each evacuation zone in such a way that the network capacity is satisfied and the total cost of the plans is minimized (without ensuring that a convergent is obtained). The plan generation sub-problem is solved either via a MIP or via a shortest path approach. The methods experiences difficulties is solving realistic instances due to a long-tail effect.

Another drawback of the flow model is that it generated preemptive evacuation plans. As flow units are routed independently there are time periods in which the evacuation of a zone may be stopped and reinitiated later. Even *et al.* (2015) [4] report that this creates serious implementation issues for the evacuation plans. They propose another model in which the evacuation rate is a decision variable that remains fixed as soon as the evacuation starts and as long as the zone is not fully evacuated or the time horizon is reached. They assume that the evacuation path of each evacuation zone is already determined and concentrate only on the scheduling problem. We present this model in the case that all people must be evacuated and the objective is to minimize the clearance time. Let δ_k denote the start time of evacuation of zone k and let λ_k denote the evacuation rate of zone k . Let $\mathcal{A}_k = (e_k^1, \dots, e_k^{|\mathcal{A}_k|})$ the evacuation path of zone k given as its list of edges. An evacuation plan defines a task J_k^i for each edge e_k^i with a start time $S_k^i = \delta_k + \sum_{q=1}^{i-1} t_k^q$ where t_k^i is the travel time of edge e_k^i . The evacuation has a variable duration p_k and the total number of evacuees is $p_k \lambda_k$ with $p_k \lambda_k = d_k$ since all people must be evacuated. Each edge task $e_k^i \in \mathcal{A}_k$ has duration p_k . Let \mathcal{J}_e the set of tasks that use edge $e \in \mathcal{A}$. The model can be

written as follows :

$$\min C_{\max} \tag{1}$$

$$C_{\max} \geq S_k^{|\mathcal{A}_k|} + p_k \quad \forall k \in \mathcal{E} \tag{2}$$

$$S_k^i + p_k \leq b_{e_k^i} \quad \forall k \in \mathcal{E}, \forall i = 1, \dots, |\mathcal{A}_k| \tag{3}$$

$$p_k \lambda_k = d_k \quad \forall k \in \mathcal{E} \tag{4}$$

$$S_k^i = \delta_k + \sum_{q=1}^{i-1} t_k^i \quad \forall k \in \mathcal{E}; \forall i = 1, \dots, |\mathcal{A}_k| \tag{5}$$

$$\sum_{J_k^i \in \mathcal{J}_e, S_k^i \leq t < S_k^i + p_k} \lambda_k \leq u_e \quad \forall e \in \mathcal{A}, \forall t \geq 0 \tag{6}$$

This is a no-wait total work- and resource-constrained project scheduling problem where (4) are the total work constraints, (5) are the no-wait constraints and (6) are the cumulative constraints. The problem was efficiently solved via constraint programming for both the clearance time minimization version and the maximization of the number of evacuated people variant.

4 New problems

In this section we identify possibly relevant problems that were not addressed in the literature.

4.1 Integrated evacuation routing and non preemptive scheduling

The CP approach [4] was limited to the flow scheduling part. Consequently, it could be integrated as the subproblem solver in the benders method proposed in [6]. This would allow the integrated generation of convergent evacuation routes and non preemptive schedules. However the subproblem would become a combinatorial optimization problem, which raises the question of generating combinatorial benders cuts.

4.2 Objective function

The time b_e at which arc e becomes unavailable comes from a fire/flood propagation model. In the case of fire, even if precise propagation models

can be obtained, they depend on multiple parameters. Among them, the wind has a great variability. An alternative to modeling uncertainty of the unavailability dates would be to consider an objective function that seeks to maximize the length of the time interval $[C_e, b_e]$, where C_e is the completion time of the last task using edge e . We can also consider the weighted case, which could allow to model the risk associated to a particular edge. Note that the objective would be to maximize $\sum_{e \in \mathcal{A}} w_e (b_e - C_e)$, which amounts to minimizing the weighted resource disposal time $\sum_{e \in \mathcal{A}} w_e C_e$. A question arises about the complexity of this objective for preemptive evacuation. The preemptive scheduling problem (probably) becomes NP-hard but that has to be checked, for particular networks. For non-preemptive evacuation, it is not clear whether the CP method would remain efficient because of the objective change from a max to a sum. It could be interesting to design a hybrid MILP/CP method.

Another question raised would be how to incorporate the smoke problem in the model constraints and objective. May we have two values on the arcs: one for the burning time and another one for the presence of smoke that can be earlier?

4.3 Uncertainty

We could introduce an explicit modeling of uncertainty either in the arc unavailability dates, and/or in the evacuation rate and/or in the numbers of evacuees. Discrete scenarios could be considered with the objective to find a robust evacuation plan. A complexity question, still for preemptive evacuation scheduling, is it easy to find the best schedule that maximizes the worst number of evacuated people (or minimizes the worst clearance time) on the set of discrete scenarios? Can we propose an efficient robust optimization algorithm in the general non-preemptive case with integrated routing? In a two-phase method the uncertainty would be tackled in the sub-problem (to find a schedule feasible in the worst case). A certain number of approaches tackling uncertainty in evacuation planning are reported in [1], namely robust optimization, stochastic optimization and chance constrained programming. Note that in case of uncertainty in the unavailability time of an arc, the chance constraint

$$\mathbb{P}[C_e \leq \tilde{b}_e] \geq \alpha \tag{7}$$

where \tilde{b}_e is the stochastic unavailability time variable for arc e and α is the desired guarantee has a deterministic expression provided that the inverse of cumulative distribution function F has an analytical expression. $\mathbb{P}[C_e \leq \tilde{b}_e] = 1 - P[\tilde{b}_e \leq C_e] = 1 - F(C_e)$. It follows that (7) is equivalent to $1 - F(C_e) \geq \alpha$ and so

$$C_e \leq F^{-1}(1 - \alpha) \quad (8)$$

This means that the deterministic constraints also offers a probabilistic guarantee in case of a stochastic unavailability date.

4.4 Evacuation rates

In non preemptive evacuation schedule, a variable evacuation rate could be introduced. We can imagine a situation where the authorities may regulate the rate of the vehicles that exit the evacuation area. This would allow to find a better compromise between congestion and evacuation speed. The energy (or total work) constrained scheduling model, that allows to define for each task a variable rate from a minimum value $\lambda_k^{\min} > 0$ to avoid preemption to a maximal value λ_k^{\max} . The rate function is a decision variable. Note that considering such variable rates can be used when the decision maker has actually the control on the rate but also in the case that the rate is an uncertain parameter, whose lower and upper bounds are known. In that case constraint propagation on the total work can be used in a search tree to establish that there no feasible scenario according to the current search status. The cumulative constraint with variable resource usage model proposed in [7] and the associated constraint propagation algorithm could be used. Already established results that state that is is dominant to consider rate changes only at the start and completion time of tasks, will probably be transposable here.

4.5 Evacuation vehicle routing, location of evacuation and safe nodes

The models presented above implicitly considered that each evacuee uses its own vehicle but we could also consider that some evacuees need to be evacuated in shuttles available in a limited number and with a limited capacity that have to travel back and forth from the evacuation node to the safe nodes, (or even using more complex routes that have to be determined but this will

conform no more to the hypothesis of a single path from an evacuation node to a safe node). Another decision level is to decide the location of evacuation and safe nodes. This is mentioned in the survey [1] as the Shelter location problem also studied by several authors.

5 Data instances

A crucial issue is the generation/obtention of realistic data instances. The ones used in the NICTA papers are not available. One possibility is to use the SPARK toolkit developed at CSIRO to generate instances [12].

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