International Journal of Industrial Engineering & Production Research June 2020 Vol. 31, No. 2: 259- 267
DOI: 10.22068/ijiepr.31.2.259

RESEARCH PAPER

A Bi-Level Programing for Wildfire Self-Evacuation Network Design

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Received 18 April 2020; Revised 28 April 2020; Accepted 3 May 2020; Published online 30 June 2020

ABSTRACT
A non-linear bi-level problem is suggested in this paper for wildfire self-evacuation planning, the upper problem of which includes binary variables and the lower problem includes continuous variables. In this model, the upper problem selects a number of links and adds them to the available evacuation network. It predicts the traffic balance and the time window of the links in the lower problem. A part of the objective function in the bi-level problem is non-linearity and it is linearized with a linear approximation method which does not require binary variables. Then, the linear bi-level model is reformulated as a non-linear single-level problem. This model is linearized and transferred into Mixed Integer Programing. The model is then used for the real case study of the Beechworth fire in 2009. The final outputs of the model are beneficial in planning design schemes for emergency evacuation to use the maximum potential of the available transportation network.

KEYWORDS: *Bi-level programing; Wildfire self-evacuation; Linear approximation; Upper problem; Lower problem; Mixed Integer Programing.*

1. Introduction

Wildfire is free, uncontrolled, and unplanned fire and is usually dependent on different factors such as wind direction, ground slope, vegetation, temperature, and humidity. This catastrophe typically occurs in rural and regional areas, burning away almost anything on its way down, leading to extensive damage including mass human loss [15]. The Unites States, Canada, Russia, and several Asian and European countries have been constantly dealing with wildfires throughout history. As an example, the California wildfire in 2018 led to 85 deaths in one single day, making 40000 of the residents evacuate the area, and damaging 1000 buildings and 70000 hectares of land [16].

Evacuation planning is an extremely complicated and integrated procedure that requires both governmental and local decision-making at different local, federal, and non-governmental levels [15]. Evacuation is, furthermore, studied from different angles on different scales for a variety of purposes. Evacuation problems can be as large scale as an entire area or even as small scale as a single building with the aim of minimizing both risk and evacuation time and maximizing the number of evacuees. In addition, evacuation analysis is based on behavioral studies of evacuees [7,13-14,17]. Shahparvari et al. (2016) suggested a multi-objective mixed integer linear problem for late evacuees in areas affected by the Victoria wildfire in 2009 in Australia, where optimum evacuation solutions are proposed for complicated evacuation scenarios considering different objective functions, maximizing the transfer of evacuees, and minimizing the associated risk and the allocated resources [9-11].

A flow model was presented by Sherali et al. (1991) in which the evacuees were transferred to possible shelters of specific capacities via predetermined origins in a particular network. The objective function in their paper minimized the overall evacuation time for all evacuees, and the evacuation network was steady without decision-making coverage for shelter selection [12]. Sherali's model was further developed by Bayram et al. (2015) who proposed an alternative model that allowed for routing by the evacuees and ensured that they would be allocated to the nearest possible shelter. In other words, routing for the evacuees was not pre-determined [5]. Evacuation routing of a capacity network flow

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problem was formulated in a study by Lim et al. (2012) where a greedy approach was suggested together with a heuristic pattern based on the shortest routes [7]. Bish and Sherali (2013) studied a network flow problem to determine the evacuee flow in evacuation plans considering three objectives based on evacuation time [4]. In their paper, an individual evacuation route was considered for every node that needs to be evacuated. Apivatanagua et al. (2012) presented a bi-level evacuation problem with the aim of minimizing the travel time. Their model was designed for the evacuation problem of storm which decided on which people to evacuate based on the amount of risk associated with approaching the individuals [1]. In the suggested model of the present paper, the evacuation network includes pre-specified origins and pre-specified shelters with limited capacities. Two types of links are considered: links that are already available in the evacuation network and those with the potential of being constructed and added to the evacuation network, provided that a reasonable amount of budget and time is allocated. This ensures optimum use of the maximum capacity of the transportation network during the process of evacuation network design. In addition, the evacuation network is dynamic since all of the links have time windows and, with the expansion of wildfires, a number of roads become inaccessible, further shrinking the evacuation network. Herein, the problem is called a Self-Evacuation Capacitated Discrete Network Design with Time Window (SECDND-TW). The main objective of this study is to develop the fastest network flow so that the overall evacuation time can be reduced. The case study is focused on Beechworth wildfire.

In Section 2, the modeling of the problem is presented. In Section 3, a solution technique is proposed. In Section 4, a case study is conducted on which the proposed model is implemented, and the associated results are analyzed afterwards. The final section is dedicated to summarizing the results.

2. Problem Description

Self-evacuation endangers the evacuees in wildfire which has led to fatal consequences in some cases. Consequently, designing a safe evacuation network with the shortest possible travel time for individuals is one of the most significant objectives of an emergency management agency (upper-level decision-maker).

Such a network consists of origin nodes O, intermediate nodes K, and destination nodes (shelters) D. The link network L includes two sets, A and B, where $L = A \cup B$. A set of the existing links is called B; a set of new links capable of being built and added to the network is called A; the binary variable of Y_l is considered for the selection of these roads; and the upper problem is responsible for the selection of links. All links have time windows shown by m, and the network changes in each time window. The passing flow on each link at each continuous decision variable time window is shown by F_l^m, and G_l is an auxiliary continuous variable that actually shows the average flow on each link. The passing time on each link is determined by the time function: $T_l(G) = v_l(1 + e_l(\frac{G}{c_l})^4)$, where v_l, e_l, and c_l are the link parameters that will be explained in the following sections.

Symbol Description

Sets

N	set of all nodes, $N = O \cup K \cup D$
$O \subset N$	set of origin nodes
$K \subset N$	set of intermediate nodes
$D \subset N$	set of shelters
L	set of all links, $L = A \cup B$
$A \subset L$	set of all potential links
$B \subset L$	set of existing links
M	set of all time windows
$S_{.i}^t$	set of arrival links to node i at time window t, $i \in N$
$S_{i.}^t$	set of all the egress links from node i at time window m

Indices

i	index for origins

j	index for shelters
k, k'	index for intermediate nodes
l	index for roads
t	index for time window

Parameters

v_l	free travel time link l
e_l	congestion influence link l
c_l	capacity of link l
bu	total budget available
p_i	population of origin $i \in O$
q_j	capacity of shelter $j \in D$
h_l^t	if link l in time window t exists 1. Otherwise 0.
b'_l	construction cost for potential link $l \in A$
b_l	for existing link $l \in B$, 1. Otherwise 0.
$bigm_1$	big number

Decision Variables

F_l^t	continuous variable flow on each link $l \in L$ at time window t
Y_l	binary variable for potential link $l \in A$
G_l	continuous variable for average flow on each link $l \in L$

$$\text{(Upper) } \min \sum_{l \in L} G_l T(G_l) = \sum_{l \in L} G_l v_l + \frac{v_l e_l}{{c_l}^4} G_l^5 \quad (1)$$

s.t

$$\sum_{l \in A} b'_l Y_l \le bu \quad (2)$$

$$Y_l \in \{0,1\} \qquad \forall l \in A \quad (3)$$

$$\text{(Lower)} \min \sum_{l \in L} \int_0^{G_l} \left(v_l + \frac{v_l e_l}{{c_l}^4} G_l^4 \right) dG_l \quad (4)$$

s.t

$$\sum_{m \in M} \sum_{l \in S_{i.}^m} F_l^t = p_i \qquad \forall i \in O \quad (5)$$

$$\sum_{l \in S_{k.}^t} F_l^t - \sum_{l \in S_{.k}^t} F_l^t = 0 \quad \forall t \in M, k \in K \quad (6)$$

$$\sum_{m \in M} \sum_{l \in S_{.j}^m} F_l^t \le q_j \qquad \forall j \in D \quad (7)$$

$$F_l^t \le bigm_1 h_l^t (b_l + Y_l) \qquad \forall l \in L, t \in M \quad (8)$$

$$G_l = \frac{1}{h_l^t} \sum_{m \in M} F_l^t \qquad \forall\, l \in L \quad (9)$$

$$F_l^t \ge 0 \qquad \forall\, l \in L, t \in M \quad (10)$$

$$G_l \ge 0 \qquad \forall\, l \in L \quad (11)$$

Constraint (1) indicates the objective function of the upper problem which minimizes the overall evacuation time for the maximum passing flow on each link based on the network generated at the same level. Constraint (2) guarantees that the sum of the costs of the links being added to the network does not exceed the budget. Constraint (3) determines the domain of the decision variable Y_l . Constraint (4) minimizes the maximum passing time on the links based on the evacuation network generated in the upper problem. Constraint (5) ensures that the demands of all origin nodes are met, and Constraint (6) is the flow balance restriction. Constraint (7) guarantees that the input flow to each shelter does not exceed its capacity. Constraint (8) maintains that flow can pass a link if TW is activated on that link. Restriction (9) defines the variable G_L to show the total flow of each link, and Constraints (11) and (12) represent the domains for decision variables F_l^m and G_L, respectively.

Solution Approach

In this study, the non-linear bi-level upper problem is first transformed into a linear model; then, the problem becomes a single-level problem using the Karuch-Kuhn-Tacher (KKT) [2].

3.1. Linearization of non-linear function

Given that there is a non-linear part $F = G_l^5$ in the objective function of the bi-level problem and since G_l^5 is a convex function, the problem can be linearized using a linear approximation without the need for a binary variable [8]. Let $R + 1$ be the number of approximation points $\{(z_0, F(z_0)), (z_1, F(z_1)), \dots, (z_R, F(z_R))\}$ and $\max G_l < z_R$ provided that $w_r = \frac{F(z_r) - F(z_{r-1})}{z_r - z_{r-1}}$.

Due to the fact that G_l^5 is an ascending function and a convex, $w_r - w_{r-1} \geq 0$, and the non-linear part of X_l^5 can be linearized as follows:

$$\min F(z_0) + w_1\, GG_l + \sum_{r \in R-\{1\}} (w_r - w_{r-1})\, GG_r \tag{12}$$

s.t

$$GG_1 \leq GG_r + z_{r-1} \qquad \forall r \in R - \{1\} \tag{13}$$

$$GG_r \geq 0 \qquad \forall r \in R \tag{14}$$

Since a new slope w_r is initiated at each point $(z_r, F(z_r))$, a $(w_r - w_{r-1})GG_r$ should be added from that point on with $GG_1 = GG_r + z_{r-1}$. It can be confidently said that GG_r takes the minimum value of $\min\{0, (GG_r - z_{r-1})\}$ as constraints (18) and (19) indicate the same. In the following, the non-linear bi-level problem for (SECDNPP-TW) is transformed into a linear problem:

$$\text{(Upper)} \min \sum_{l \in L} G_l v_l + \frac{v_l e_l}{c_l{}^4}\left(w_{l1} G_l + \sum_{r \in R-\{1\}} (w_{lr} - w_{lr-1})\, GG_{lr} \right) \tag{15}$$

s.t

constraints (2)- (3) &

$$G_l \leq GG_{lr} + z_{r-1} \qquad \forall l \in L, r \in R - \{1\} \tag{16}$$

$$\text{(Lower)} \min \sum_{l \in L} G v_l + \frac{v_l e_l}{5 c_l{}^4}\left(w_{l1} G_l + \sum_{r \in R-\{1\}} (w_{lr} - w_{lr-1})\, GG_{lr} \right) \tag{17}$$

s.t

constraints (5)- (11) &

$$G_l \le GG_{lr} + z_{r-1} \qquad \forall l \in L, r \in R-\{1\} \tag{18}$$

$$GG_{lr} \ge 0 \qquad \forall l \in L, r \in R \tag{19}$$

3.2. Single-level problem

The linear lower problem can be replaced by KKT condition, and the bi-level problem can be, thus, reformulated as a non-linear single-level problem [3,6].The dual variables α_{lr}, β_i, γ_k^t, θ_j, μ_l^t, ρ_l^t are associated with Constraints (18), (5), (6), (7) ,(8) ,(9), respectively.

(Upper) $\min \sum_{l\in L} G_l v_l + \frac{v_l e_l}{c_l{}^4}\left(w_{l1} G_l + \sum_{r\in R-\{1\}} (w_{lr} - w_{lr-1})\, GG_{lr}\right)$

s.t

Constraints (2)- (3),(5)-(11),(16)& (15)

$$\sum_{l\in L} G_l v_l + \frac{v_l e_l}{5c_l{}^4}\left(w_{l1} G_l + \sum_{r\in R-\{1\}} (w_{lr} - w_{lr-1})\, GG_{lr}\right) \ge \sum_{l\in L}\sum_{r\in R-\{1\}} z_{r-1}\alpha_{lr} + \sum_{i\in O} \beta_i p_i + \sum_{j\in D} \theta_j q_j + \sum_{l\in A}\sum_{m\in M} bigm_1 h_l^t (b_l + Y_l) \tag{20}$$

$$-\alpha_{lr} \le \frac{v_l e_l}{5c_l{}^4}(w_{lr} - w_{lr-1}) \quad \forall l \in L, r \in R-\{1\} \tag{21}$$

$$\beta_i - \gamma_k^t + \mu_l^t - \frac{1}{h_l^t}\rho_l \le 0 \quad \forall l \in S_{i.}^t, l \in S_{.k}^t, i \in O, k \in K, t \in M \tag{22}$$

$$\gamma_k^t - \gamma_{k'}^t + \mu_l^t - \frac{1}{h_l^t}\rho_l \le 0 \quad \forall l \in S_{k.}^t, l \in S_{.k'}^t, k, k' \in K, t \in M \tag{23}$$

$$\gamma_k^t + \theta_j + \mu_l^t - \frac{1}{h_l^t}\rho_l \le 0 \quad \forall l \in S_{k.}^t, j \in D, k \in K, t \in M \tag{24}$$

$$\sum_{r\in R-\{1\}} \alpha_{lr} + \frac{1}{h_l^t}\rho_l \le v_l + \frac{v_l e_l}{5c_l{}^4} w_{l1} \quad \forall l \in L \tag{25}$$

$$\alpha_{lr} \le 0 \qquad \forall l \in L, r \in R-\{1\} \tag{26}$$

$$\theta_j \le 0 \qquad \forall j \in D \tag{27}$$

$$\mu_l^t \le 0 \qquad \forall l \in L, t \in M \tag{28}$$

$$\rho_l \quad \text{free} \qquad \forall l \in L \tag{29}$$

For the dual variables GG_{lr}, F_l^t, and G_l, Constraint (21), constraints (22)-(24), and Constraint (25) are considered, respectively. Owing to the fact that part $\mu_l^t Y_l$ in Constraint (20) needs to be linearized, linearization is carried out in the following section by defining a new variable δ_l^t and $bigm_2$ as an extremely large positive number.

$$\sum_{l\in L} G_l v_l + \frac{v_l e_l}{5{c_l}^4}\left(w_{l1}G_l + \sum_{r\in R-\{1\}} (w_{lr} - w_{lr-1})\, GG_{lr}\right) \geq \sum_{l\in L}\sum_{r\in R-\{1\}} z_{r-1}\alpha_{lr} + \sum_{i\in O} \beta_i p_i + \sum_{j\in D} \theta_j g_j + \sum_{l\in L}\sum_{t\in M} bigm_1 h_l^t(\mu_l^t b_l + \delta_l^t) \quad (30)$$

$$\delta_l^t \leq \mu_l^t + bigm_2(1 - Y_l) \qquad \forall l \in L, t \in M \quad (31)$$

$$\delta_l^t \geq \mu_l^t \qquad \forall l \in L, t \in M \quad (32)$$

$$\delta_l^t \geq - bigm_2 Y_l \qquad \forall l \in L, t \in M \quad (33)$$

$$\delta_l^t \leq 0 \qquad \forall l \in L, t \in M \quad (34)$$

4.Case Study

Beechworth- Mudgegonga district is 316 kilometers northeast of the state capital, Melbourne. On Saturday, 8th of February 2009, a wildfire ignited and could not be extinguished until the 16th of February. Two fatalities were reported, 38 homes destroyed, and 33.577 hectares of lands burnt away by the fire (Figure 1) [15].

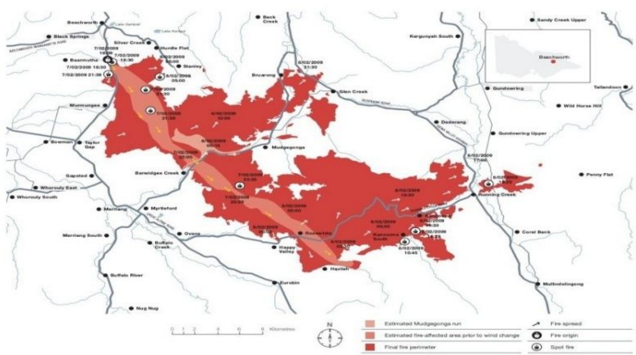


Fig. 1. At 00:20, on 8th of February 2009, it was warned that P-ire storm was approaching Mudgegonga. At 2:15 AM, the fire reached Pinnacles via the Kancoona fissure. At 3:40 AM, blast in Mudgegonga decreased and, by 5:10 AM, fire had reached both sides of Running Creek road. At 6:30 AM, about 20000 hectares of lands had been burnt away. The northern fire had been partly controlled [15].

In this case study, 3 origins and 2 shelters with specified capacities are considered. The number of available roads is 12, and 4 potential links are considered. The total budget is 20000 (Table 1). It is assumed that 80% of the population attempt self-evacuation, and the traffic load for each car is considered 1.9. The number of time windows (TW) is considered to be 3. Figure 2 shows the available network.

Tab. 1. Key information

origins	p_i	Shelters	g_j
i1 Mudgeonga	90	$j1$ Beechworth	170
i2 Kancoona	110		
i3 Murmungee	88	$j2$ Dederang	150

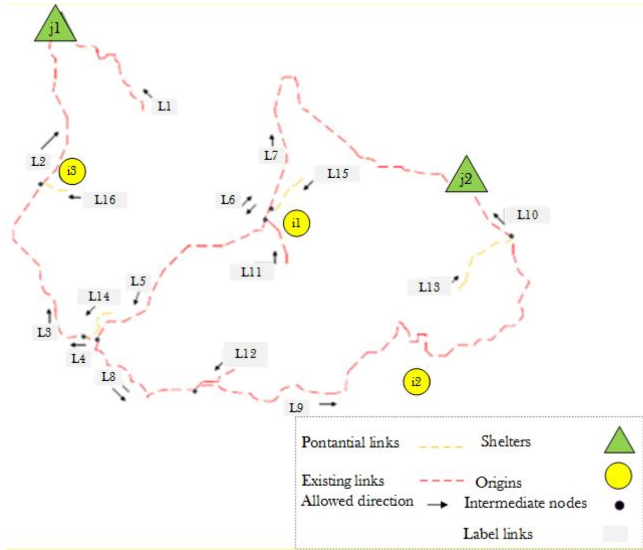
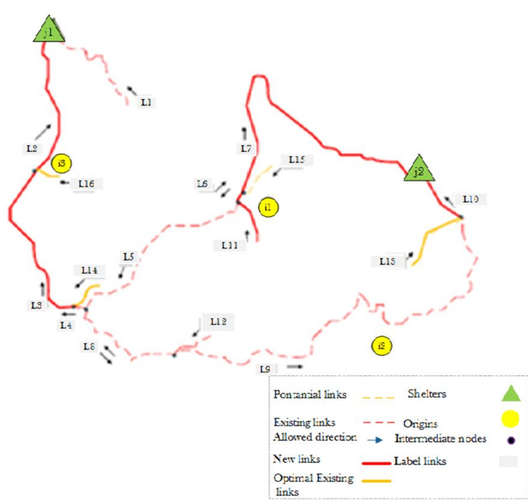


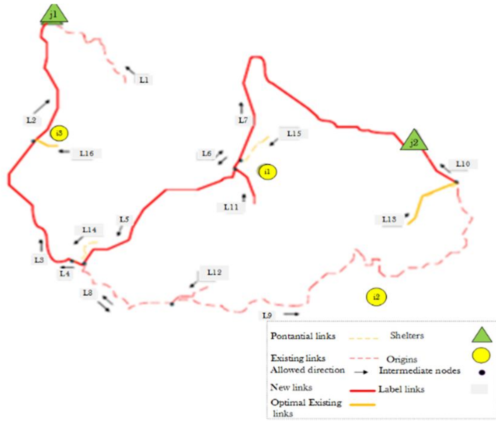
Fig. 2. Basic evacuation network

4.1. Results and discussion

In this section, the proposed model is introduced. In order to improve both the planning procedure and the Self-Evacuation performance, the generated network is suggested to minimize the evacuation time, hence reducing the effects of the wildfire on the evacuees. As can be seen in Figure 3, changes in the amount of budget significantly affect both the evacuation performance and the evacuation network. As can be observed, such changes even affect the use of the available links; therefore, this factor is a great influence on the evacuation network. It is also seen in Figure 4 that increasing the budget reduces the evacuation time since a considerable budget rise increases the number of links that can be constructed, thus shortening the travel time. This is a crucial subject since by declining the evacuation time, crisis managers and network designers will benefit from extra time for the preparedness of the network and to provide further network safety. Besides, individuals will experience a shorter travel time between the endangered points and the shelters which noticeably reduce the mental pressure they would suffer from. This model is performed using the CPLEX Solver 12.8.0.0 on a PC with 4.00 GB Ram and 2:67 GHz. The size of the case study is kept on an intermediate scale; yet, the selected parameters are proper for verifying the performance of the proposed model.



(a)



(b)

Fig. 3. Figure 3(a) optimal evacuation network design with budget 30000; Figure 3(b) optimal evacuation network design with budget 50000

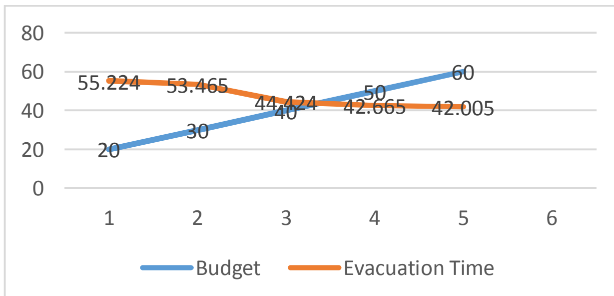


Fig. 4. Impact of Budget on total Evacuation Time

5.Conclusions

This paper proposed a self-evacuation network design model considering the expanding nature of wildfires over time. All of the links were considered to have TWs. Taking into consideration different decision-making levels in order to facilitate the complete use of resources of the link system for evacuation, a non-linear bi-level model called self-evacuation capacitated discrete network design with time window (SECDND-TW) was presented which transformed the problem into a linear bi-level problem via an algorithm without binary variables, which then turned into a single-level problem using the KKT condition only to be ultimately transformed again into a Mixed Integer Problem (MIP). Results of implementing the model on the case study of Beechworth wildfire, 2009, indicated how an optimum evacuation network can be designed by a limited budget, and the effects of this type of network on decreasing the evacuation time were witnessed. The associated risks of each link and the possibility of destruction of the shelters need to be considered as future research focus.

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