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A goal programming model for early evacuation of vulnerable people and relief distribution during a wildfire

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ABSTRACT

Wildfires generate many safety issues to population at risk areas. Sometimes, due to the proximity of a fire, it is necessary to carry out the evacuation of vulnerable people in order to protect them from heat, sparks or flames. To facilitate the evacuation planning, potential evacuees are classified according to their health condition, so that they are taken care of properly. Additionally, once they reach a safe area, basic supplies are crucial to ensure their welfare. In order to assure the proper coverage of the basic needs of the evacuees, supplies have been also classified according to their characteristics. Furthermore, not everybody decides to evacuate at the same time; on the contrary, vulnerable people affected by fires require assistance or go to the designated pick-up points according to their own susceptibility about the situation, leading to the dynamic arrival of potential evacuees along a certain time horizon. In the same way, dynamic arrival of potential supplies along time can be considered. All these factors define a real-life problem that can be formulated as a mixed integer optimization model that is dynamic, multi-modal and multicriteria. This model is more flexible than others available in the literature and allows for a joint approach to people evacuation and supply distribution. A case study regarding the Saddleridge Fire that hit San Fernando Valley in Los Angeles County, California, in October 2019, is introduced and used to validate the proposed model and evaluate its performance.

1. Introduction

Wildfires, bushfires or forest fires have an annual occurrence throughout the world, but their impact has historically been quite limited, mainly because they usually occur far from human settlements (CRED, USAID, UCLouvain, 2019) and hardly ever cause many casualties. However, several recent tragedies (Veeraswamy et al., 2018) have shifted the focus to this type of disaster (see Fig. 1), highlighting the need to improve safety issues of people affected by wildfires.

Fire seasons are lengthening and frequency of wildfires is increasing due to higher global temperatures, drier conditions and a larger vegetation land surface. According to CRED, USAID, UCLouvain (2019), 199 wildfires occurred worldwide between 2000 and 2016, resulting in 983 casualties and 2.9 million affected people. Some examples of more recent events are given in what follows. In Portugal, June 2017, a heat wave and a series of dry thunderstorms preceded a wildfire, resulting in 66 deaths and 204 injured people. Most of the people who died were trapped in their vehicles while trying to escape the fire. In October 2019, another series of wildfires outbroke in Portugal. According to the Australian Government, bushfires injured 8,000 people and caused 433 fatalities in Australia between 1967 and 2013. One of the deadliest events happened on February 7, 2009 in Victoria (Australia), where 173 people died in the wildfires known as Black Saturday, most of them inside their own homes. Moreover, the Black Summer (between September 2019 and March 2020) caused more than 450 casualties and the destruction of more than 9000 buildings all over Australia. Other severe fires occurred in Fort McMurray in Canada in May 2016, where more than 88,000 people were forced to evacuate with no fatalities (Veeraswamy et al., 2018). Another region with high wildfire risk is California, where 30 people died in 2017 and 88 in 2018 in 746 mayor incidents (>10 acres). In addition, more than 6,000 fires hit this region in 2019. A case study based on the Saddleridge Fire that hit California in October 2019 is presented later in this work.

Among the options to protect the population affected by wildfires, two of the most frequently used are evacuation and sheltering. Both strategies are analyzed in Cova et al. (2011), who conclude that, in

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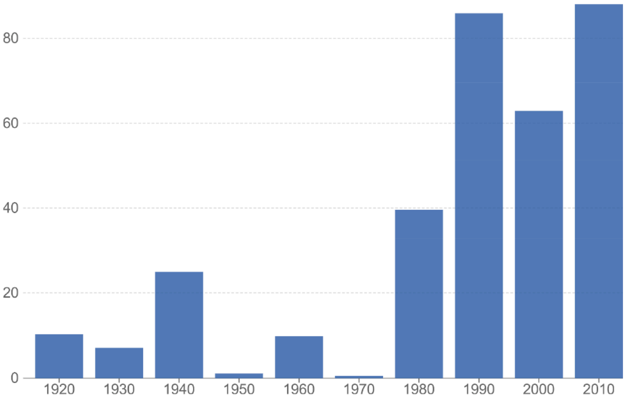

Fig. 1. Wildfire casualties worldwide. Decadal average (1920–2019).
Source: Ritchie and Roser (2021).

scenarios with enough time to decide, evacuation is a better option. On the other hand, in scenarios of urgency, particularly with a traffic delay component, sheltering is preferred in order to avoid potential exposure to the fire during evacuation.

The London Resilience Partnership (2018) consider three types of evacuation: self-evacuation, assisted evacuation and supported evacuation. Both self and assisted evacuation have been vastly studied in the literature, facing problems related to traffic congestion, bottlenecks, density waves, patterns, panic, etc. However, self and assisted evacuation are sometimes not an option, because individuals may require specific support (for example, an ambulance) to be transported from unsafe areas to safer ones, and thus supported evacuation, which is far less studied in the literature, is required. A very relevant problem connected with supported evacuation is shelter allocation and supply distribution to the shelters. A shelter is a facility where evacuated population can receive services and supplies to ensure their well-being. Supported evacuation and supply distribution to shelters, considered jointly in the presence of a wildfire, are the main object of this research.

Wildfire evacuation and supply distribution have been considered in the literature in different ways, but rarely in an integrated approach. Concerning evacuation, a multiobjective integer programming model showing that it could have been possible to evacuate all late evacuees during the Black Saturday wildfire events of 2009 is shown in Shahparvari et al. (2015). In Gama et al. (2016), a multi-period location-allocation approach is presented to identify where and when to open a predefined number of shelters, when to evacuate and how to assign evacuees to shelters over time. Zhao et al. (2015) present scenario-based multi-objective models for the allocation of residents to earthquake shelters. An iterative method to solve a multi-criteria constraint location model is stated in Xu et al. (2016). In Goerigk et al. (2014), a genetic algorithm to solve a multi-criteria optimization model to locate shelters and to determine the public transport and individual traffic routing simultaneously, considering time and evacuation risk, is developed. A mathematical optimization model that minimizes the number of people at risk and the cost of fire containment and property loses, considering the uncertainty inherent to the decision process, is presented in Zhou and Erdogan (2019). On the other side, a literature review on humanitarian supply distribution can be found at Vitoriano et al. (2013). Another model for a last-mile distribution problem in disaster relief operations, under insecure and uncertain conditions, is solved with a GRASP metaheuristic in Ferrer et al. (2016). An original scheduling and routing problem for a post disaster scenario with known number of evacuees is solved in Sabouhi et al. (2018) where, even though evacuation and distribution are taken into account, no interaction between them is considered. A two-stage mathematical model to improve post-earthquake self-evacuation can be found in Seraji et al. (2019).

According to California Governor's Office of Emergency Services (2015), the best practices while facing a wildfire need to be focused on the priorization of the mobilization and evacuation of people with disabilities and others with special access and functional needs. To this end, means of transport and shelter facilities are expected to be accessible and available for patients who would require additional assistance (Centers for Medicare & Medicaid Services, 2021). Furthermore, the number of evacuees to be received in different nodes and the way supplies are to be provided shall be planned previously in order to carry out a successful evacuation and supply distribution (California Governor's Office of Emergency Services, 2015). Finally, disorganized distribution systems may contribute to supplies shortages (World Health Organization & Pan American Health Organization, 2001), making it essential to coordinate evacuation and commodity distribution.

Following these guidelines, in this work a new model enhancing the connection and interaction between evacuation and supply distribution to shelters is developed. The aim of the model is to evacuate the affected population that cannot do it by themselves from unsafe areas to shelters and, in a joint way, perform the required distribution of supplies (such as water, food, medicine, etc.) to ensure the well-being of evacuees. The transportation of both people and supplies can be performed by using the same vehicle fleet, allowing for a significantly greater planning flexibility. However, in return, this requires a coordinated approach, which is more complex to model and solve. As far as the authors are concerned, the connection and interaction of these two main logistic components has not been fully explored in the literature yet, leading to a research gap that this work tries to fill. The model we propose is based on sending a double flow (evacuees and supplies) through a logistic network by using a heterogeneous fleet of vehicles with the aim of evacuating as many affected people as possible while optimizing the evacuation cost and time and ensuring the required supplies are where they are needed. To the best of our knowledge, it does not exist in the literature any model with all these characteristics.

The aim of the proposed model is, thus, to help the designers of an emergency evacuation plan, in order to achieve a more precise and in time evacuation of vulnerable population during forest fires. The main contributions of the paper are the following: (1) A new and more flexible model allowing for a joint approach to people evacuation and supply distribution, in order to design coordinated operational plans. (2) The consideration of dynamic arrival of evacuees to the designated pick-up points according to their own susceptibility about the situation. (3) The consideration of dynamic arrival of supplies along time, coming from external shipments or donations. (4) The classification of potential evacuees according to their health condition, so that they can be taken care of properly. (5) The classification of available supplies according to the way they are used by the affected population and the inclusion of a detailed consumption control into the model according to the movement of evacuees. (6) The validation of the proposed model by means of a realistic case study based on the Saddleridge Fire, California, 2019.

The remainder of the paper is structured as follows. Section 2 describes in detail the problem to be solved. In Section 3 the mathematical formulation of this problem is introduced. Section 4 describes the application of this model to a case study based on the Saddleridge Fire, that hit California in October 2019. Section 5 presents the discussion, the main limitations of the model proposed and some ideas for future research. Finally, Section 6 draws some conclusions of this work.

2. Problem description

As mentioned before, the problem approached in the paper consists in creating a detailed plan for supported evacuation and supply distribution to aid vulnerable population affected by wildfires. The main assumptions made in order to define the problem rigorously are summarized next.

The problem concerns supported evacuation. When a wildfire strikes, some areas may have to evacuate for security reasons. While most people will evacuate by their own means, following authorities instructions, some may not be able to leave and will need assistance because of not having access to transportation, due to physical or emotional incapacity or because they require some special assistance. The latter are the object of this work.

The operational area is represented by a dynamic network composed by the region to be evacuated and the safe region to shelter the evacuees. The locations of the unsafe area represent pick-up points and those of the safe area are shelters, hospitals and depots. The streets or roads connecting these locations can be of different types (paths, local roads, highways, freeways, etc.), may present different states (blocked or shattered, seriously damaged, partially damaged, usable, etc.) and are characterized by their length and maximum speed.

Evacuees are picked up at specific locations and their arrivals are dynamic. The compromised population who cannot self-evacuate congregates at certain pick up points to wait for transportation to a shelter. At the beginning of the operation, while some people are already waiting at the pick up points, others may still be at home protecting or packing their assets. The latter may arrive at pick up points at a later time aided by different agencies, such as police, firefighters and/or Search and Rescue teams, or by themselves. The time when they get there depends on the time required by the involved agencies to provide the required aid and on their own risk perception, which, according to Özdamar and Ertem (2015), may be related to certain demographic characteristics. To represent this situation, it will be considered that evacuees arrive to the pick-up points dynamically. In addition, a classification of the affected population is performed, leading to different evacuation priorities. For example, people with disabilities or a bad medical condition must have a high priority (Houston et al. (2009)).

Evacuation to hospitals and shelters is combined with commodity distribution. People with critical medical needs are transported to hospitals, while the rest of the population goes to shelters. Both shall store commodities to fulfill the basic needs of the evacuees. Supply demand, which varies along time, is determined according to the number of evacuees staying at each location per time unit. The distribution of the supplies and their storage in shelters or hospitals must be organized with the aim of satisfying, in the best possible way, the basic needs of incoming evacuees.

The fleet of vehicles is used for both evacuation and relief distribution. A fleet of heterogeneous vehicles with certain space to transport passengers and load is used to transport both people and supplies, but those spaces are independent and cannot be shared. Important vehicle characteristics are capacity (different and independent for passengers and supplies), cost, speed and compatibility with each type of road (if they can fly, navigate or travel through highways, gravel roads, etc.). These vehicles are used jointly both for evacuation and relief distribution, making the operation planning significantly more difficult but, in return, increasing its flexibility significantly. The use of independent fleets for evacuation and relief distribution, which is more frequently found in the literature, is in fact a particular case of our problem.

The arrival of supplies is dynamic. At the beginning of the operation, medical supplies are mainly located at hospitals, while other supplies are at the depots. In some cases, there are not enough supplies to satisfy the demand of all evacuees, so donations are requested. They may come from neighbors, as well as from national or international humanitarian organizations, depending on several social cognitive issues (Oosterhof et al., 2009). Since they may arrive at any time, the availability of supplies is dynamic.

Available supplies are classified according to their usability. Supplies are classified according to their characteristics into consumable and non consumable. Non consumable supplies, such as blankets, tents, heating devices, electricity generators, etc., do not have a fixed daily consumption; however, while been used by one person, they cannot be used by another. On the other hand, consumable supplies, such as water, food or medicines, are periodically spent depending on the amount of people requiring them in a particular period. It may be the case of people arriving to temporary shelters before the needed supplies do, or not having enough supplies to cover the demand of every evacuee, but this unmet demand must be minimized.

Several criteria are considered jointly to decide how the evacuation and distribution plan is designed. First, the number of people evacuated successfully must be maximized, paying special attention to high priority evacuees; second, minimizing their evacuation time should be prioritized; and third, total operation time and cost and unsatisfied demand of supplies should also be taken into account.

Finally, it is important to highlight that the problem is defined in a generic way to widen the application range of the resulting model so that it could be applied to any type of disaster.

3. Mathematical modelling and formulation

To formulate and solve the problem described in Section 2, a mathematical programming model is constructed. A set of values for the decision variables of the model will define a way to move the evacuees and the supplies through the logistic network, providing an evacuation and distribution plan. Hence, the model is aimed to find appropriate values for these decision variables ensuring that all the relevant conditions regarding the vehicles (capacity, speed, etc.), the evacuees (when they arrive, what they need, etc.), the supplies (where they are available and required) and the network (which roads are available and in what condition, traversing times, etc.) are verified, so that a valid plan is provided, and at the same time maximizing the number of people evacuated successfully and minimizing evacuation time, operation cost and unsatisfied supply demand.

3.1. Model elements

Let (G,d) be the network of the problem, which we model as a graph $G(N,E)$, with set of nodes N, set of arcs or edges E, and let d be the distance function between any pair of nodes. There are different types of nodes, depending on their characteristics. Nodes at the unsafe area (pick-up points) are represented by NA and, at the safe area, by NS, NH and D, corresponding to temporary shelters, hospitals and depots, respectively. Finally, some transit nodes, NT, may also exist in the network. Nodes at the safe area are characterized by their capacity and nodes at the unsafe area by the number of people to be evacuated at each period of time. On the other hand, distance, velocity and required time to be traversed by each type of vehicle are characteristics of arcs/edges. In order to deal with the dynamic nature of the problem, time is discretized in T periods of equal length.

The objective of the model is to evacuate as many people as possible, as quickly as possible, while covering their basic needs. To achieve it, a Multicriteria Lexico- graphical Goal Programming Model is developed. This means that the objectives are organized according to a hierarchical order in three levels of decreasing priority: Objectives with highest priority (level 1) are those related to the amount of people evacuated successfully. Once the maximum number of people that can be evacuated verifying all constraints of the problem is obtained, it is fixed for the following levels. Level 2 comprises the evacuation time of high priority population, which, once calculated, is also fixed for level 3, which aggregates total operation cost, total evacuation time and unsatisfied coverage of basic supplies of evacuees. See Fig. 2 for a diagram of the 3-level optimization scheme.

3.2. Sets, indices, parameters and variables

Let $G(N,E)$ be the representative graph of the problem, where.

N: Set of nodes or involved areas $(i, j \in N)$: $N = NA \cup NS \cup NT \cup NH \cup D$.

E: Set of edges or arcs, corresponding to roads or streets connecting nodes $((i, j) = (ij) \in E)$.

T: Discretized time periods $(t, t' \in \{1, \ldots, T\})$.

H: Set of types of people to be evacuated $(h \in H)$.

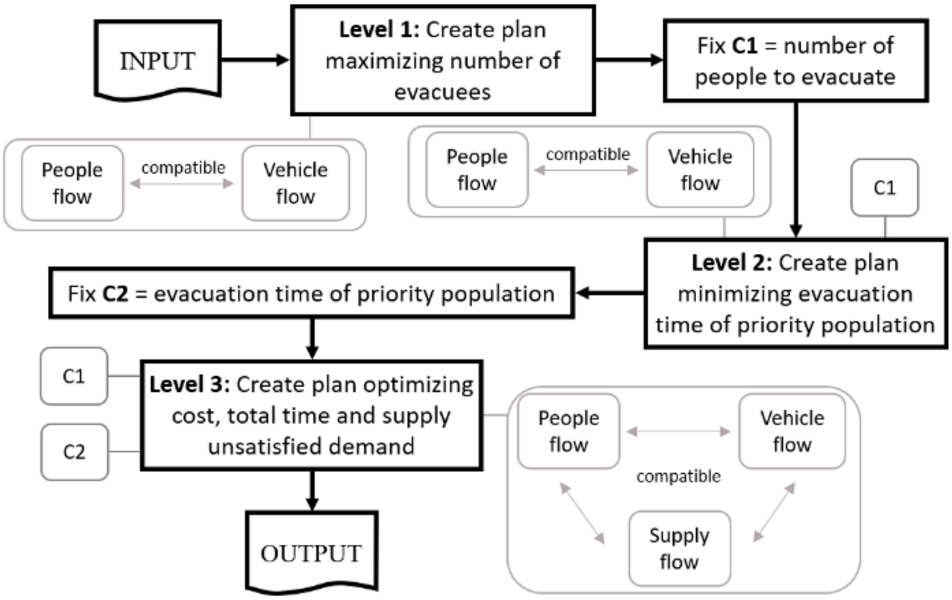

Fig. 2. Illustrative diagram of the 3-level lexicographical model.

C: Set of types of supplies to be distributed $(c \in C)$.

K: Set of types of vehicles available for the evacuation of the population and the distribution of supplies $(k \in K)$.

M: Set of goals to be achieved $(m \in M)$.

The model has the following **input parameters**, known or estimated.

I) Parameters related to the population to be evacuated:

qp^h_{it}: Amount of people of type $h \in H$ to be evacuated from node $i \in N$ A at the beginning of period $t \in T$.

typ^h: Priority of people of type $h \in H$ (high or normal).

wp^h: Space that a person of type $h \in H$ occupies in a vehicle to be transported or in a node of the secure area.

cp^h_i: Capacity for people of type $h \in H$ at node $i \in NS \cup NH$.

e, e': Upper bound of the total number of persons to be evacuated with high and normal priority, respectively.

II) Parameters related to the supplies to be distributed:

qs^c_{it}: Amount of supplies of type $c \in C$ available at the node $i \in NH \cup NS \cup D$ at the beginning of period $t \in T$, initial amount and donations.

tys^c: Typology of supply of type $c \in C$, consumable or non consumable.

wc^c: Space that a unit of supply of type $c \in C$ needs to be transported or stored.

cs^c_i: Capacity for supplies of type $c \in C$ that can be stored at node $i \in NS \cup NH \cup D$.

ps^{hc}: Standard average needed consumption of supplies of type $c \in C$ during a time period by a person of type $h \in H$.

β^c: Weight for the unsatisfied consumption of supplies of type $c \in C$.

III) Parameters related to the vehicles to be utilized at the operation:

vpc^k: Capacity of a vehicle of type $k \in K$ to transport the population.

vsc^k: Capacity of a vehicle of type $k \in K$ to transport supplies.

va^k_i: Number of vehicles of type $k \in K$ that are available at node $i \in N$ at the beginning of the operation.

fc^k_{ij}: Fixed cost to traverse arc/edge $(i, j) \in E$ with a vehicle of type $k \in K$, by unit of distance.

vc^k_{ij}: Variable cost to traverse arc/edge $(i, j) \in E$ with a vehicle of type $k \in K$, by unit of distance and cargo transported.

vv^k: Maximum velocity that a vehicle of type $k \in K$ may reach.

It is important to note that capacities cp^h_i and cs^c_i are independent, meaning that secure nodes have separated places for evacuees and supplies. On the other hand, this is not the case for the vehicles, which may transport people, supplies or both.

IV) Parameters related to the logistic network, available budget and objectives:

d^k_{ij}: Distance from node $i \in N$ to node $j \in N$ (or length of arc/edge $(i, j) \in E$) when traversed by a vehicle of type $k \in K$.

av^k_{ij}: Average velocity of arc/edge $(i, j) \in E$ for a vehicle of type $k \in K$.

τ^k_{ij}: Time required to travel arc/edge $(i, j) \in E$ with a vehicle of type $k \in K$.

b: Budget limitation.

α_m: Weight of goal $m \in M$.

tg_m: Aspiration level of goal $m \in M$.

The **decision variables** are listed below:

I) Variables related to the population to be evacuated:

P^h_{it}: Number of people of type $h \in H$ located at node $i \in N$ at the beginning of period $t \in T$.

PL^{hk}_{ijt}: Number of people of type $h \in H$ who started to be transported from node $i \in N$ to node $j \in N$ in a vehicle of type $k \in K$ at the beginning of period $t \in T$.

II) Variables related to the supplies to be distributed:

S^c_{it}: Amount of supplies of type $c \in C$ located at node $i \in NS \cup NH \cup D$ at the beginning of period $t \in T$.

SL^{ck}_{ijt}: Amount of supplies of type $c \in C$ that started to be transported from node $i \in N$ to node $j \in N$ in a vehicle of type $k \in K$ at the beginning of period $t \in T$.

QS^c_{it}: Amount of consumable supplies of type $c \in C$ that are consumed at node $i \in NS \cup NH$ during period $t \in T$.

NS^c_{it}: Amount of non consumable supplies of type $c \in C$ that are used at node $i \in NS \cup NH$ at the beginning of period $t \in T$.

U^c_{it}: Unsatisfied consumption of supplies of type $c \in C$ at secure *node* $i \in NS \cup NH$ during period $t \in T$.

III) Variables related to the vehicles used in the operation:

V^k_{it}: Number of vehicles of type $k \in K$ located at node $i \in N$ at the beginning of period $t \in T$.

VL^k_{ijt}: Number of vehicles of type $k \in K$ that started to move from node $i \in N$ to node $j \in N$ at the beginning of period $t \in T$.

IV) Variables related to the time required to evacuate the population:

BTH_t: 1 if population with high priority has been evacuated in period t.

BT_t: 1 if population with normal priority has been evacuated in period t.

V) Variables related to the optimization criteria:

DV_m: Deviation variable with respect to the aspiration level of goal $m \in M$.

PV_m: Slack variable with respect to the aspiration level of goal $m \in M$.

F_E: Number of people with high priority that are evacuated.

$F_{E'}$: Number of people with normal priority that are evacuated.

F_{US}: Weighted sum of unsatisfied consumption of supplies.

F_T: Total time required to evacuate evacuees with high priority.

$F_{T'}$: Total time required to evacuate the rest of affected population.

F_{Cost}: Total cost of the operation.

3.3. Mathematical model

The complete mathematical model is given in equations (1)-(31), followed by a brief explanation of how they work.

$$LexMin\left\{\left[\frac{\alpha_E DV_E}{tg_E}+\frac{\alpha_{E'}DV_{E'}}{tg_{E'}}\right],\ [DV_T],\ \left[\frac{\alpha_{T'}DV_{T'}}{tg_{T'}}+\frac{\alpha_{Cost}DV_{Cost}}{tg_{Cost}}+\frac{\alpha_{US}DV_{US}}{tg_{US}}\right]\right\} \tag{1}$$

In the objective function (1), LexMin stands for lexicographically minimizing the objective vector. There are three levels with no trade-off between them. First, the maximum number of people that can be evacuated successfully is calculated. Once this is determined, this is imposed as an additional constraint and level 2 starts, minimizing the evacuation time of high priority population. Again, once this is fulfilled, level 3 takes into account total operation cost, total evacuation time and unsatisfied coverage of basic supplies of evacuees.

1) Constraints related to the population to be evacuated:

$$\sum_{j|(ji)\in\varepsilon}\sum_k\sum_{t'\le t-\tau^k_{ji}} PL^{hk}{}_{jit'} + \sum_{t'\le t} qp^h{}_{it'} = \sum_{j|(ij)\in\varepsilon}\sum_k\sum_{t'\le t} PL^{hk}{}_{ijt'} + P^h_{it} \forall h,i,t \tag{2}$$

$$wp^h P^h_{it} \le cp^h_i \forall t,h,i \in NH \cup NS \tag{3}$$

$$\sum_h wp^h PL^{hk}_{ijt} \le vpc^k VL^k_{ijt} \forall i,j \in N|(ij) \in \varepsilon, \forall k,t \tag{4}$$

$$F_E = \sum_{h|typ^h=\max\limits_h\{typ^h\},i\in NH\cup NS} P^h_{iT} \tag{5}$$

$$F_{E'} = \sum_{h|typ^h=\min\limits_h\{typ^h\},i\in NH\cup NS} P^h_{iT} \tag{6}$$

Constraints (2) are the people flow conservation constraints, ensuring that, at any node and any time period, the number of the people arriving at the node plus the ones already there equals the number of people leaving the node plus the ones that stay there. Conditions (3) and (4) avoid the violation of the capacity of nodes and vehicles, respectively, while the maximum number of people of each category that can be actually evacuated under the conditions of the model is defined by constraints (5) and (6).

2) Constraints related to the supplies to be distributed:

$$\sum_{j|(ji)\in\varepsilon}\sum_k\sum_{t'\le t-\tau^k_{ji}} SL^{ck}{}_{jit'} + \sum_{t'\le t} qs^c{}_{it'} - \sum_{j|(ij)\in\varepsilon}\sum_k\sum_{t'\le t} SL^{ck}{}_{ijt'} \ge \sum_{t'\le t} QS^c{}_{ijt'} \ \forall t,c|tys^c = 1, i \in NH \cup NS \tag{7}$$

$$\sum_{j|(ji)\in\varepsilon}\sum_k\sum_{t'\le t-\tau^k_{ji}} SL^{ck}{}_{jit'} + \sum_{t'\le t} qs^c{}_{it'} - \sum_{j|(ij)\in\varepsilon}\sum_k\sum_{t'\le t} SL^{ck}{}_{ijt'} = NS^c_{it} \forall t,c|tys^c = 0, i \in NH \cup \ NS \tag{8}$$

$$\sum_{j|(ji)\in\varepsilon}\sum_k\sum_{t'\le t-\tau^k_{ji}} SL^{ck}{}_{jit'} = \sum_{j|(ij)\in\varepsilon}\sum_k\sum_{t'\le t} SL^{ck}{}_{ijt'} \ \forall c,t,i \in NA \cup NT \tag{9}$$

$$\sum_{t,h} ps^{hc} P^h_{it} = \sum_t \left(QS^c_{it} + U^c_{it}\right) \forall c|tys^c = 1, i \in NH \cup NS \tag{10}$$

$$\sum_{t,h} ps^{hc} P^h_{it} \le \sum_t \left(NS^c_{it} + U^c_{it}\right) \forall c|tys^c = 0, i \in NH \cup NS \tag{11}$$

$$F_{US} = \sum_{c,i,t} \beta^c U^c_{it} \tag{12}$$

$$S^c_{it} = \sum_{j|(ji)\in\varepsilon}\sum_k\sum_{t'\le t-\tau^k_{ji}} SL^{ck}{}_{jit'} + \sum_{t'\le t} qs^c{}_{it'} - \sum_{j|(ij)\in\varepsilon}\sum_k\sum_{t'\le t} SL^{ck}{}_{ijt'} - \sum_{t'\le t} QS^c_{it'} \forall t,c|tys^c = 0, i \in NH \cup NS \tag{13}$$

$$S^c_{it} = NS^c_{it} \forall t,c|tys^c = 0, i \in NH \cup NS \tag{14}$$

$$\sum_c wc^c S^c_{it} \le \sum_c cs^c_i \ \forall i,t \tag{15}$$

$$\sum_c wc^c SL^{ck}_{ijt} \le vsc^k VL^k_{ijt} \forall i,j|(ij) \in N, \forall k,t \tag{16}$$

Analogously to equations (2), the flow conservation of supplies is given by constraints (7)-(9), where (7) and (8) correspond to the flow conservation of consumable and non consumable supplies at the safe nodes, respectively, and (9) indicate that affected nodes are transshipment nodes for commodities. Real consumption of consumable supplies and real utilization of non consumable ones, in comparison with the needed consumption, are defined by (10) and (11), respectively, while the definition of the weighted insufficient consumption is given by (12). The amount of supplies of each type available is determined by (13) and (14). (15) and (16) are capacity constraints for nodes and vehicles, respectively.

3) Constraints related to the vehicles to be used at the operation:

$$\sum_{j|(ji)\in\varepsilon}\sum_{t'\le t-\tau^k_{ji}} VL^k_{jit'} + va^k_i = \sum_{j|(ij)\in\varepsilon}\sum_{t'\le t} VL^k_{ijt'} + V^k_{it} \ \forall t,i,k \tag{17}$$

$$\sum_i va^k_i = \sum_i V^k_{iT} \ \forall k \tag{18}$$

As done before with people and supplies, conditions (17) provide the vehicle flow conservation constraints, while (18) are the control constraints, ensuring no more vehicles than available are used.

4) Constraints related to cost and required time to evacuate the population:

$$F_{Cost} = \sum_{h,c,i,j,k,t|(ij)\in N} d_{ij}^{k}\left(fc_{ij}^{k} VL_{ijt}^{k} + vc_{ij}^{k}\left(PL_{ijt}^{hk} + SL_{ijt}^{ck}\right)\right) \tag{19}$$

$$F_{Cost} \leq b \tag{20}$$

$$F_T = \sum_t t\ (BTH_t - BTH_{t-1}) \tag{21}$$

$$F_{T'} = \sum_t t(BT_t - BT_{t-1}) \tag{22}$$

$$BTH_t \geq BTH_{t-1} \forall t \tag{23}$$

$$\sum_{h|typ^h=\max_h\{typ^h\}} \sum_{i,j|(ij)\in\varepsilon} \sum_k \sum_{t'|t'=\lceil t-\tau_{ij}^k\rceil} PL_{ijt'}^{hk} \leq e(1-BTH_t)\,\forall t \tag{24}$$

$$BT_t \geq BT_{t-1} \forall t \tag{25}$$

$$\sum_{h|typ^h=\min_h\{typ^h\}} \sum_{i,j|(ij)\in\varepsilon} \sum_k \sum_{t'|t'=\lceil t-\tau_{ij}^k\rceil} PL_{ijt'}^{hk} \leq e'(1-BT_t)\,\forall t \tag{26}$$

The operation cost is given by (19). There is a fixed cost of moving an empty vehicle and a variable cost for transporting people and commodities, and the maximum budget cannot be exceeded, as stated in (20). Constraints (21) - (26) are related to the operation time. The time required to evacuate the high priority population is given by equation (21), while the time required to evacuate all affected population is given by equation (22). To calculate them, binary variables BTH_t and BT_t are defined in (23)-(24) and (25)-(26), respectively.

5) Constraints to define the deviations from the objective goals:

$$F_m + DV_m - PV_m = tg_m \forall m \in \{E, E^{'}\} \tag{27}$$

$$F_m - DV_m + PV_m = tg_m \forall m \in \{T, T^{'}, US, Cost\} \tag{28}$$

6) Constraints related to the domain of variables (continuous, integer and binary):

$$S_{it}^{c},\ SL_{ijt}^{ck},\ QS_{it}^{c},\ NS_{it}^{c},\ U_{it}^{c}, F_{US},\ F_{Cost} > 0\,\forall i,j,c,k,t \tag{29}$$

$$P_{it}^{h},\ PL_{ijt}^{hk},\ V_{it}^{k},\ VL_{ijt}^{k},\ F_E,\ F_{E'},\ F_T,\ F_{T'} \in \mathbb{Z}^{+}\,\forall i,j,h,k,t \tag{30}$$

$$BT_t,\ BTH_t \in \{0,1\}\forall t \tag{31}$$

Once a wildfire happens, affecting population that requires to be evacuated, the proposed mathematical model (1)-(31) is intended to create an emergency plan to respond to the current situation by taking the available information as input data. As a result, for a particular situation, the model provides one single plan, which is supposed to be the optimal response to the considered parameters. Nevertheless, if updated or additional information is received later, the model could be run again to obtain a new plan better suited for the new situation.

4. Case study

According to National Geographic (2018), the hottest and driest summers since 1895 in California have all occurred in the last 20 years. Drought, dry vegetation and extreme winds enhance wildfires and the fire season starts earlier and ends later each year. The Governor of California (2019) declared the state of emergency for Los Angeles and Riverside counties in October 11, 2019, due to the effects of several fires, including Saddleridge, Eagle, Sandalwood, Reche and Wolf fires. The consequences of these fires were the destruction of structures, both homes and critical infrastructure, and the evacuation of residents.

This section describes the case study used to evaluate the performance of the proposed model, which is based on the Saddleridge Fire. It broke out in California between October 10, 2019 and October 31, 2019. In particular, the burned area, around 8,799 acres (3,561 ha), started in Sylmar, San Fernando valley, north to Los Angeles, and quickly spread west. There were one warning evacuation area (WE) and several mandatory evacuation areas (ME), as illustrated in Fig. 3. The number of homes at mandatory evacuation areas was estimated in 23,000 and the number of people forced to evacuate rose to 100,000. Although most of them evacuated by their own means, at least 25 rescue ambulances were working to help people evacuate, especially the elderly and disabled (see LA ist (2019)). The safe centers for people were established on Lanark Park, Sylmar, Granada Hills, Mason, Northridge Recreation Centers and Brandford Recreation Center, according to LAFD (2019).

4.1. Assumptions and data collection

The logistic network of the case study contains 26 nodes representing locations of San Fernando Valley, California, as depicted in Fig. 4, which are classified according to their characteristics as:

- 17 pick up points located at the unsafe areas, according to LAFD (2019).
- 6 temporary safety nodes representing real evacuation sites enabled, see LAFD (2019).
- 1 hospital node that corresponds to the location of the Pacifica Hospital of the Valley.
- 2 depots located in the safe area, which have supplies to be distributed to other nodes: California State University, Northridge, had mainly water, food and long stay supplies, while the Sepulveda Ambulatory Care Center had medicines and other long stay supplies.

The nodes are connected by edges, that represent roads, streets or tunnels for terrestrial vehicles. Lengths or distances between nodes are determined by using GoogleMyMaps technology. The maximum velocities of the roads have been set out according to the speed limit of the government of California, except on those that, according to Red Cross (2019b), were closed or congested due to the wildfire, which have been penalized by 100% and 50%, respectively. Aerial vehicles are considered to follow a straight line connecting any pair of locations with available heliport and are not included in Fig. 4.

Target population includes those who cannot evacuate by themselves due to phys ical or emotional incapacity or due to failure or lack of equipment, and ask for support to be evacuated. According to Healthy Western Australians (2019) Healthy Western Australians (2019), people with breathing or respiratory problems (BP), pregnant women (PW) and people with heart disease, elderly people and those with reduced mobility (considered together as EI) are considered as sensitive population. Those groups at mandatory evacuation areas are classified as high priority population. Children are assumed to travel with their families (FM), which are classified as normal priority population, together with the rest of the people from the mandatory evacuation (OM) areas and the population at the warning evacuation area (OW). Most of the evacuees are assumed to require one standard unit of space at any shelter or vehicle. Some exceptions are pregnant women and the elderly and injured in need of a wheelchair, who may need additional space. Families of at most 3 members are considered for transportation (if larger, they are split into smaller groups).

People arrivals to the pickup nodes are estimated emulating other evacuation behaviours in disasters (see Goudie (2009) and Schadschneider et al. (2008), distinguishing between early adopters, majority and laggards). Furthermore, and according to LAFD (2019), evacuation warnings changed over time and did not affect equally to the whole territory, leading to three groups of locations: *NA1*, representing early adopters; *NA2*, representing the majority of the population; and *NA3*, representing the laggards. The functions shown in equations (32), (33)

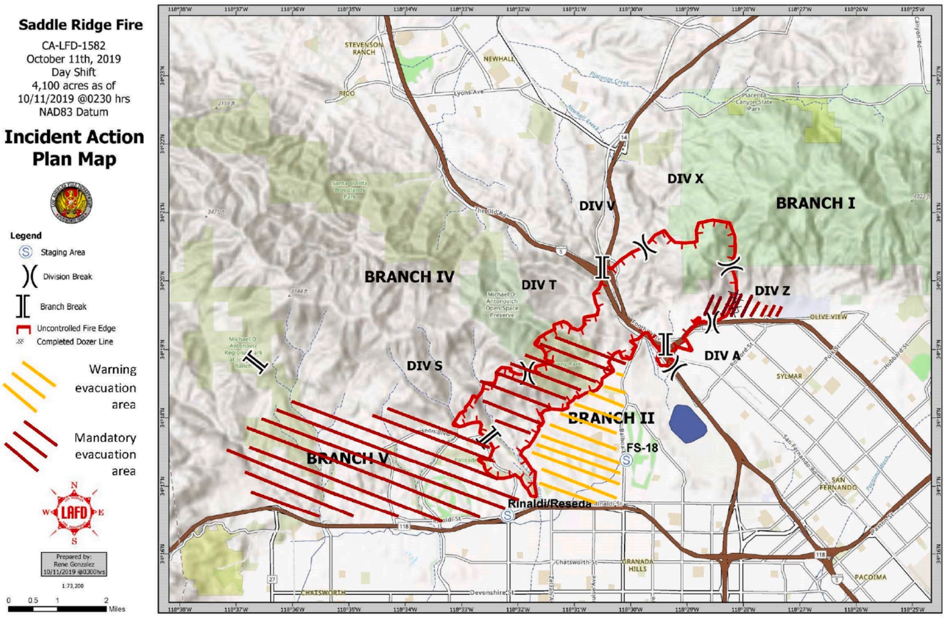

Fig. 3. Final Fire Perimeter and ME & WE Areas.
Source: LAFD (2019).

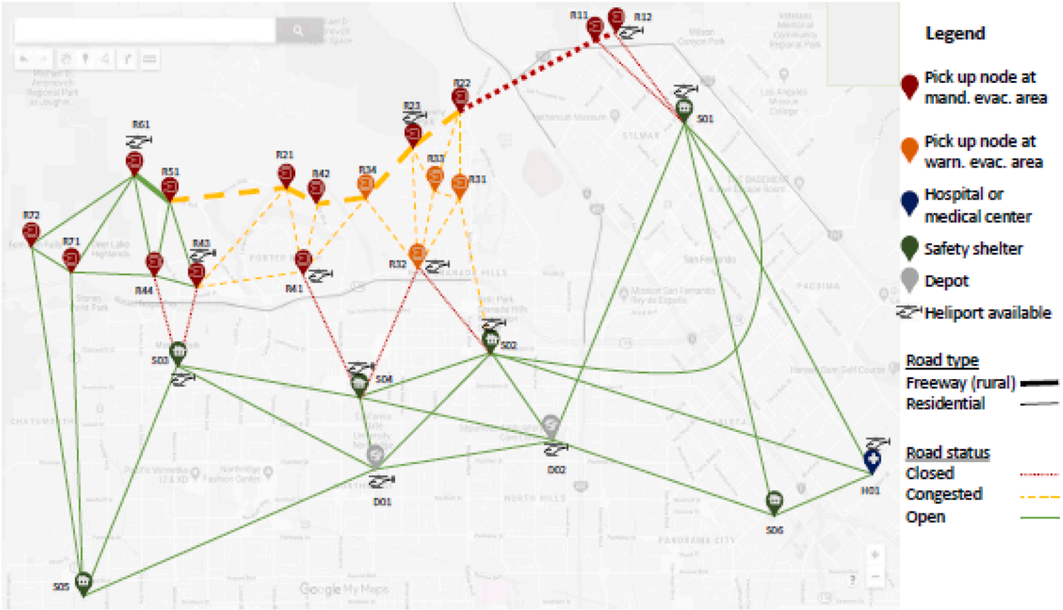

Fig. 4. Logistic network.

and (34) have been defined with the aim of modeling the arrival of people over time to the pick up points as described earlier: increasing for early adopters in *NA1* for time periods up to one sixth of the planning horizon; constant in *NA2* for time periods between one sixth and one third of the planning horizon; and decreasing in *NA3* for time periods between one third and half of the planning horizon representing the laggards. Note that exponential and logarithmic functions are used to achieve a smooth increasing or decreasing behaviour in each case. Finally, the number of people already waiting at the pick-up points at the beginning of the operation is denoted by qp_{i0}^h.

$$qp_{it}^h = \left\lfloor \frac{qp_{i0}^h}{T/6} \exp\left(\frac{\log(t)}{\log(pq_{i0}^h)+1}\right) \right\rfloor \forall t \leq \frac{T}{6}, \forall i \in NA1 \tag{32}$$

$$qp_{it}^h = qp_{i0}^h, \ \frac{T}{6} < t \leq \frac{T}{3}, \forall i \in NA2 \tag{33}$$

$$qp_{it}^h = \left\lfloor qp_{i0}^h \exp\left(\log\left(qp_{i0}^h\right)\frac{1-t}{T}\right) \right\rfloor, \ \frac{T}{3} < t \leq \frac{T}{2}, \forall i \in NA3 \tag{34}$$

According to Los Angeles Daily News (2019), the capacity of each Red Cross safety shelter was 100 evacuees, with the possibility to shelter up to 140 people in extreme circumstances. The capacities of the remaining shelters were estimated accordingly. The main data regarding the different types of evacuees are collected in Table 1.

Regarding supply availability, since only monetary donations were requested, donations of supplies were not considered in the case study, and thus it has been assumed that supplies are stored at the depots and/

Table 1
Characteristics of the population to be evacuated.

	qp^h_{i0}	typ^h	wp^h	cp^h_i
EI	82	High priority	2	180
PW	19	High priority	1.5	45
BP	36	High priority	1	90
FM	72	Normal priority	3	180
ME	86	Normal priority	1	80
OW	59	Normal priority	1	220

or the hospital at the beginning of the op eration. According to Red Cross (2019a), four shelters were opened, where more than 3,200 meals and snacks and 1,500 units of basic medicines, both considered as consumable, and 440 longer stays and 490 comfort kits, as non consumable, were provided. The required space for every type of supply has been estimated according to usual measures of humanitarian logistics. The assumed consumption is about two meals and one snack in the first 12 h for every type of person. Two units of basic medicines in this period are delivered for the elderly, people with reduced mobility and pregnant women, four for people with breathing problems, as they need more specific medicines, and three for families. For the definition of the unsatisfied consumption, as stated in (12), we use $\beta = (3, 1, 3, 1)$.

The vehicles considered for transportation are helicopters (H), army trucks (T), buses (B) and ambulances (A). Terrestrial vehicles cannot traverse closed roads. Ini tially, all ambulances and most helicopters are located at the hospital, while buses are at several locations of the mandatory and warning evacuation areas and trucks are at the depots and at some safety shelters. The availability of the vehicles, together with their capacities, velocities and costs are presented in Table 2.

The time horizon considered spans between 10.10.2019 at 10:55PM and 11.10.2019 at 10:55AM and is discretized into 24 half-hour periods. As an estimation for the operations and scope included in our case study, an available budget of $75,000 has been considered.

4.2. *Numerical results*

In this section, the numerical results obtained by solving the case study introduced earlier and certain variations of it are presented and analyzed. The resulting models are solved by GAMS 23.7 with an integrality gap of 5% on an Intel(R) Core(TM) i7-8565U CPU 1.80 GHz with 16.00 GB RAM running Windows 10. The number of variables of the complete model exceeds 125,000 for the first and second levels and 130,000 for the third one, among which around 84,000 are discrete.

First, the original model is solved by optimizing each objective independently of the others in order to obtain their optimal values. As a result, we know that the maximum high and normal priority population that can be evacuated are, respectively, 306 and 480 people, and the fastest way to evacuate them takes 5 and 6.5 h, respectively. The cheapest evacuation operation requires $38,865.92, and it is possible to fulfill the needs of all evacuees, leading to an optimal unsatisfied consumption of.

0. However, as expected, these optimal values cannot be reached together with a single solution, showing the conflict among the different objectives considered. As a result, from now on we will consider the 3-level lexicographical goal programming model, in order to take into account all criteria jointly: evacuated people (first level), evacuation time of high priority population (second level) and total evacuation time, cost and unsatisfied supply consumption (third level), as stated in equation (1).

Table 2
Characteristics of vehicles.

	va^k_i	vpc^k	vsc^k	vv^k	fc^k_{ij}	vc^k_{ij}
H	18	6	2	153	1.20	0.50
B	30	30	8	80	0.80	0.20
A	25	6	0	80	0.80	0.20
T	30	0	15	60	0.50	0.10

4.2.1. *Results on the original case study*

Each goal requires an aspiration level, which is determined as follows. The aspiration levels for the amount of people to be evacuated, with high or normal priority, are set as the total number of people of each type that arrive to the pick-up points along the time horizon. The aspiration levels for the evacuation time of high and normal priority population is 5 h (10 periods) and 7 h (14 periods), respectively, while the aspiration levels for the operation cost is 75% of the available budget ($56,250) and 0.05 (a very small amount) for the unsatisfied consumption.

The resolution of the first two levels of the model, considering $\alpha_E = {}^{5}\alpha_{E}'$, provides a plan able to evacuate all high priority population in 5 h and 91.77% of the normal priority population. Since the third level aggregates three criteria, different weight combinations $\gamma = (\alpha_T', \alpha_{Cte}, \alpha_{US})$ have been tested, obtaining a variety of solutions. For example, giving the same importance to all criteria (γ =(1/3, 1/3, 1/3)), a $73,377 plan with a total evacuation time of 8.5 h is obtained; however, if the cost is considered more important (γ = (¼, ½, ¼)), a cheaper $57,054 plan is obtained, but requiring 11 h to complete the operation. Increasing the weight assigned to the total evacuation time does not provide times shorter than 8.5 h, while the unsatisfied supply consumption aspiration level is always achieved, meaning that the needs of all evacuees are always fulfilled. The running time to solve the model varies along different γ combinations, taking between several minutes to 1–2 h. Choosing one solution or another depends on the preferences of the decision maker and the trade off between the involved criteria.

The final distribution of the population obtained by assigning equal weights to all criteria considered at level 3 is illustrated in Fig. 5. It can be observed that evacuees are distributed more or less evenly among the different shelters and the hospital, while very few people stay at the unsafe area. To complement this information with routing details, Fig. 6 shows, as an example, the period (or periods) in which people with breathing or respiratory problems (in blue) and meals and snacks (in yellow) start being transported from one node to another, the type of vehicle used for transportation and the number of people (or supplies) that are being moved. If the same path is followed by the same type of vehicle at different periods, square brackets are used. It can be seen how buses are mostly used for the transportation of people (from the unsafe area to the shelters and the hospital) and trucks for the transportation of meals and snacks (from the depots to the shelters).

4.2.2. *Sensitivity analysis*

Taking the case study as a base case, several variations have been considered in order to analyze how the model responds to different situations that may appear during a wildfire. First, different budgets have been considered in order to test how the operation may be affected by money availability. Considering that only 90% of the original budget is actually available, the same number of people can be evacuated, but it takes one additional hour to complete the operation. On the other hand, increasing the budget up to $100,000, the operation can be finished one and a half hours earlier and with no deviations from the aspiration levels.

The second experiment regards the possibility of certain shelters being damaged by the fire and thus becoming unavailable. Following this idea, we modified the base case by disabling the Sylmar Recreation Center (S01 in the original graph), which was the closest shelter to the fire. This node remains as part of the graph as a transshipment node, in order to keep the network structure, but it cannot host evacuees nor store supplies or vehicles. Adding both the capacity of the disabled node and the available vehicles to another node results in a significant 3-hour delay to evacuate the same number of people. On the other hand, if both the capacity and the vehicles of the shelter are removed directly from the

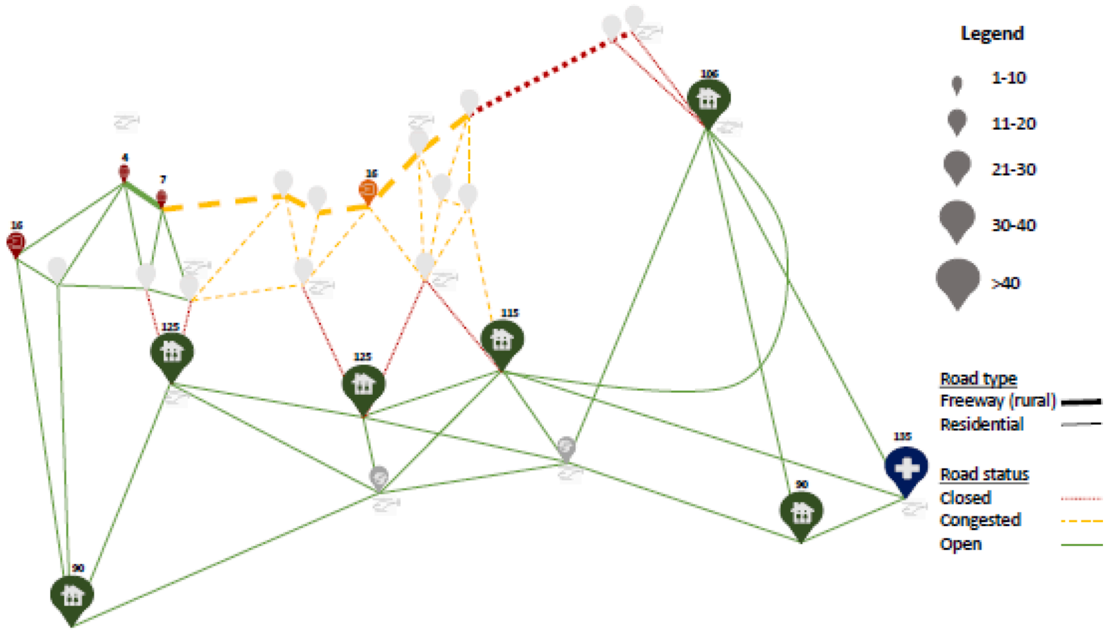

Fig. 5. Final distribution of the evacuees.

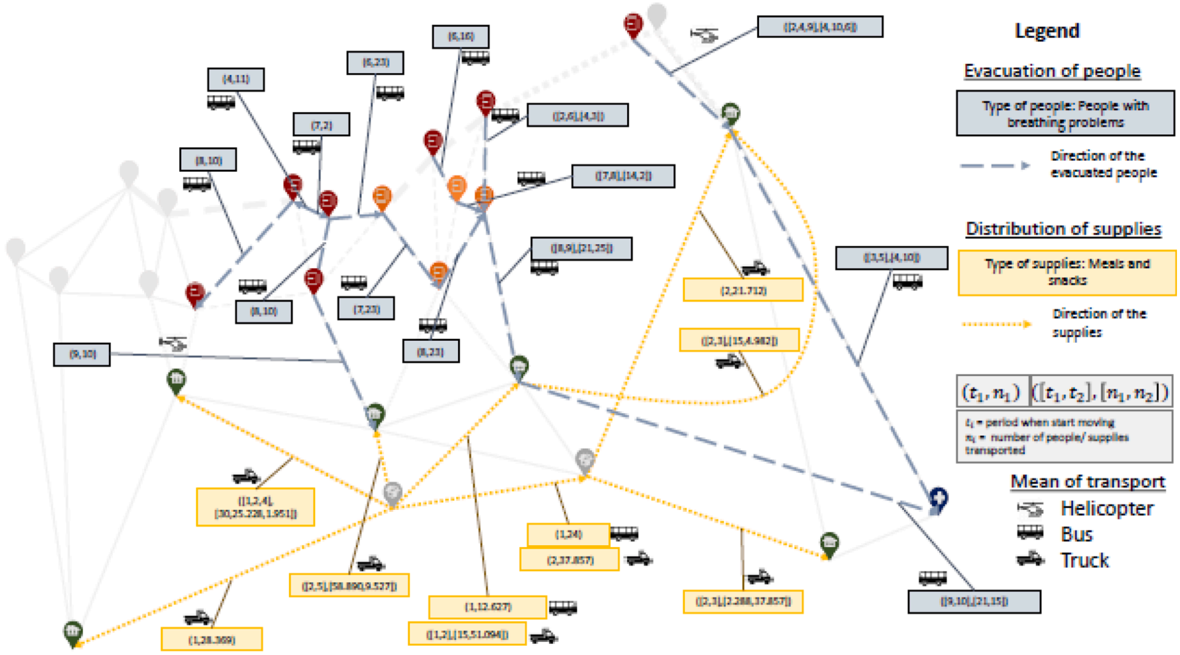

Fig. 6. Representation of routing of people with breathing or respiratory problems.

base case, a much more difficult situation arises, because only 88.24% and 78.39% of the high and normal priority population, respectively, can be evacuated. It seems clear how the loss of a shelter may prevent many people from being evacuated successfully.

In order to simplify the planning of the operation and also reducing the running time required to solve the model, it could be interesting to divide the original problem into two or more subproblems, which could be solved independently. In order to evaluate how this could be done in our case, the graph of the base case has been partitioned into two subgraphs, as shown in Fig. 7, where 12 nodes compose the first area, 11 the second one, and the depots are shared by both. People to be evacuated are located only at the affected nodes of each particular partition and available supplies at the depots are divided evenly between the two partitions. At the beginning of the operation, vehicles are located separately, forming two groups according to the nodes of each particular partition, and the budget of each partition is proportional to the people to be evacuated (60% for the first partition and 40% for the second one). The sum of the running times required to solve the two subproblems adds up to less than one third of the running time to solve the original problem, showing how the partitioning of the network clearly leads to a simpler problem. However, solving each subproblem independently prevents an adequate coordination of the operations: by merging the solutions of the two partitions only 89.22% and 47.8% of high and normal priority population can be evacuated, instead of 100% and 91.78%, as in the original approach.

The types of vehicles available for transportation may also influence

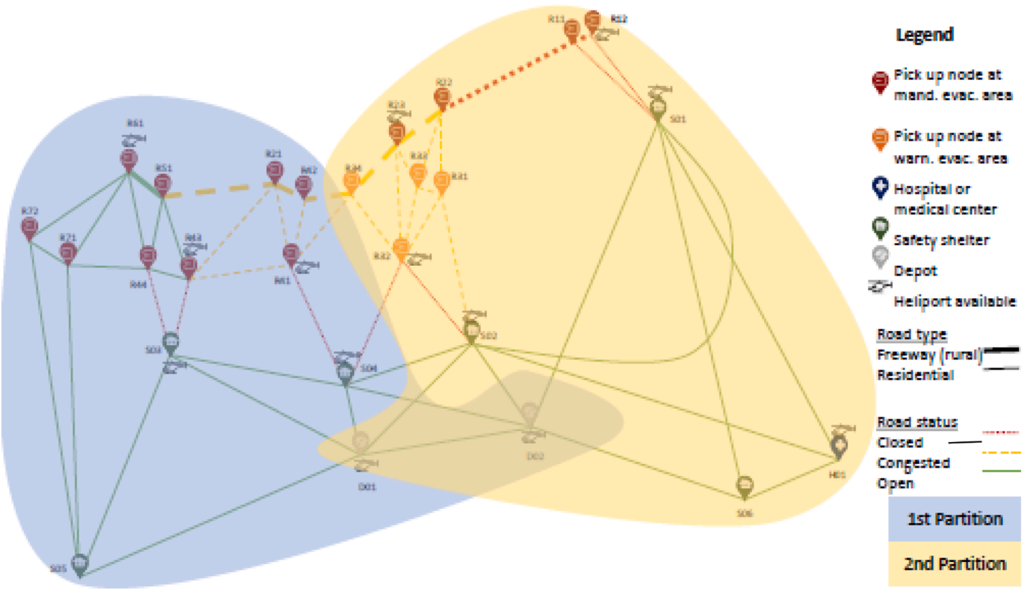

Fig. 7. Partition of the graph.

significantly the performance of the operation. In order to evaluate the effect of this, we have solved the base case by assuming, in turn, that no helicopters, trucks or buses are available. Without helicopters, it takes one hour longer to evacuate only 63.40% of high priority population, highlighting the importance of this kind of transportation mode to rescue the most vulnerable people. The absence of trucks or buses provide similar results: high priority population is not affected, but slightly less normal priority people can be evacuated and the operation is 3 h longer. This shows that trucks or buses are not essential for an effective operation but are important to achieve a timely evacuation.

5. Discussion, limitations and future work

Certain novel elements of the model are specifically included in order to represent as faithfully as possible the real situations that usually arise during wildfires: the joint approach to people evacuation and supply distribution, the dynamic arrival of people and commodities to the pickup nodes and the depots, respectively; the classification of evacuees and supplies, according to their special needs and their usability, respectively; the use of the same fleet of vehicles for transportation of both people and supplies, even though it complicates the planning significantly; the joint consideration of multiple conflicting attributes which are relevant in real operations and must be dealt with. We believe all these elements characterize the proposed model, make it realistic and are an important contribution to the state of the art.

The model is able to provide a variety of detailed evacuation and supply distribution plans optimizing several criteria related to the number of evacuees, operation time and cost and unsatisfied supply consumption. By choosing appropriate criteria weights, the decision maker can introduce his/her preferences into the model in order to determine the solution and fits his/her interests in the best possible way. The model can be solved iteratively with varying weight configurations (or any other parameter changes) until the decision maker is satisfied with the proposed solution.

The case study analyzed in the paper illustrates how a real operation could be managed by using the model: required input (data), produced output (detailed plan), resolution performance, etc. The sensitivity analysis shows how solutions with very different characteristics can be achieved by varying the attribute weights, balancing the number of people evacuated, operation cost and evacuation time according to the decision maker's preferences. Furthermore, the impact of key elements of the infrastructure can also be evaluated through the model, concluding, for example, that a certain shelter is essential for a successful evacuation or a certain type of vehicles are required for a timely operation.

The model has some limitations that is important to bear in mind:

- We opted for an optimization model because it is able to build, from scratch, the optimal plan regarding the considered criteria based on the available data, as opposed to what it could be done with simulation models, for example, that could be used to evaluate the performance of a given plan in different situations by trying to emulate the real operation, but it would not be able to create such a plan. The main limitation of an optimization model like this one when compared to other possibilities such as a simulation model is the complexity of the solution methods needed to solve it, which may require more computational effort.
- Certain aspects related to the movement of vehicles and people during evacuation, such as traffic congestion, clogging, bottlenecks or panic, are only considered implicitly by reducing the travel times on the roads. This is so mainly because of their non-linear nature, that would complicate significantly the res olution of the model. One possible future research line would be to include explicitly some of these aspects into the model and devise an efficient solution method to solve the resulting non-linear model.
- The locations of shelters and depots and where the available supplies are prepositioned are part of the logistic network and thus cannot be modified. However, it could be useful to have an additional model to locate optimally shelters, depots and supplies, or extend the current model to include these decisions. Any of these alternatives would again increase the computational complexity of the problem and it is important to find a compromise between complexity and usability.
- Even though the arrival of people and supplies to the system are considered dynamic and may vary over time, in real life this might not be known with cer tainty. In addition, the state of the infrastructure or the availability of vehicles may also be unknown. In order to consider this, certain stochastic elements could be added to the proposed model. However, stochasticity is another source of increased complexity for the model, probably even more difficult to deal with than the other extensions mentioned above.
- As shown in the case study, it is possible to solve the model to optimality within reasonable running times for realistic instances of the problem. However, if significantly larger networks are considered, the required resolution time may be too long for a practical use.

To overcome this limitation, sub-optimal solutions obtained by running an exact method only for a limited time or by solving the model with heuristics could be used as well. These solutions may not be optimal but could provide very good evacuation and distribution plans in much shorter running times.

6. Conclusions

In this work a new model to palliate the effects of wildfires on vulnerable people, enhancing the connection and interaction between evacuation and supply distribution, has been proposed. The model aims to evacuate the affected population that cannot leave unsafe areas by themselves and perform the required supply distribution to ensure the satisfaction of their basic needs. Furthermore, the connection and interaction of these two main logistic components had not been fully explored in the literature yet, leading to a research gap that this work has tried to fill.

The real-life problem defined in this work has been formulated as a dynamic multi-criteria mixed integer programming model. No trade-off is allowed between evacuating as many people as possible, evacuating the most vulnerable as fast as possible, and the other criteria, and as a result lexicographical goal programming has been used to deal with 6 different criteria.

The proposed model has been validated on a case study regarding the Saddleridge Fire that hit San Fernando Valley in Los Angeles County, California, 2019. It has shown that, by organizing evacuation and supply distribution operations in a joint way, practical and efficient coordinated plans can be obtained. The model provides detailed information so that practitioners can implement the proposed plans easily in real operations. The coordination between people and supply itineraries allows for a better and more rational use of the available resources, so that evacuees are looked after in the best possible way.

Even though the description of the model has been focused on wildfires, it could actually be applied to any kind of disaster requiring supported evacuation and supply distribution.

CRediT authorship contribution statement

Inmaculada Flores: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **M. Teresa Ortuño:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Gregorio Tirado:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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