A mixed integer programming approach for asset protection during escaped wildfires

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May 15, 2014

Abstract

Incident Management Teams (IMTs) are responsible for managing the response to wildfires. One of the IMT's objectives is the protection of assets and infrastructure. In this paper we develop a mathematical model to assist IMTs in assigning resources to asset protection activities during escaped wildfires.

We present a mixed integer programming model for resource allocation with the aim of protecting the maximum possible total value of assets. The model allows for mixed vehicle types with interchangeable capabilities, with travel times determined by vehicle specific speed and road network information. We define location specific protection requirements in terms of vehicles capabilities.

Computational testing shows that realistic sized problems can be solved within a reasonable time. The model capabilities are demonstrated using a hypothetical fire scenario impacting South Hobart, Tasmania, Australia.

Keywords: Forest fire; Emergency management; Integer programming; Orienteering; Wildland fire

1 Introduction

While fire is a natural component of many terrestrial ecosystems, uncontrolled wildfires occurring on populated landscapes can cause loss of life and damage to private property and community assets.

In many jurisdictions including Australia, Canada and the United States, *incident management teams* (IMTs) are responsible for coordinating, planning and managing wildfire response related activities (Australasian Fire Authorities Council 2013; ICS Canada 2012; US Department of Homeland Security 2008). IMTs dealing with large wildfires operate in high pressure environments where they must make complex, time critical decisions. The tasks that the IMT has to perform include assessing the merits of the available information, devising strategies for containing the fire, minimising the impact of the fire, managing fire fighting crews, managing resources, issuing warnings to the public, and evacuating people. Factors affecting decisions include weather conditions, fire spread predictions, fuel state, assets under threat, the value of assets and the location of vulnerable people. A strong need for decision support tools have been identified in the literature(McLennan et al. 2006; Omodei et al. 2005a,b). Challenges and difficulties faced include IMTs becoming overwhelmed with the volume of information, questionable accuracy of information and biases in human decision making. In this context, application of operations research and supply chain logistics tools such as assignment, routing and scheduling models could lead to enhanced management of large fires (Martell 2007).

The development of decision support tools to assist with the management of wildfires is an active field (Martell 1982; Martell et al. 1998; Minas et al. 2012). Published research to date largely focuses on long term planning, with considerably fewer studies concerned with short term IMT level decision-making (Minas et al. 2012). Models developed to support short term wildfire decision making have been concerned with the dispatch of resources to fires and with fire-line construction (Donovan 2003; Haight and Fried 2007; Lee et al. 2013; Pappis and Rachaniotis 2009). Alternative tasks, besides direct fire suppression, that fire agency resources can perform, such as asset protection, are not so well studied.

On days of extreme fire weather, when large fires are burning in hot, dry and windy conditions, active fire suppression may be both ineffective and unsafe. In these circumstances fire agency resources may be better utilised by assigning them to "defensive" tasks such as: asset protection, protecting vulnerable people in place, evacuating communities, collecting information and issuing warnings (CSIRO 2009).

In this paper we consider the problem of assigning resources to asset protection activities when large wildfires are burning out of control and direct suppression is not a viable option. We formulate a mixed integer programming model assigning resources to asset protection with the aim of maximising the total saved asset value. The model allows for mixed vehicle types with interchangeable capabilities with vehicle travel times determined by vehicle specific speeds and road network information. The protection requirements of locations are defined in terms of the vehicles' capabilities.

The remainder of the paper is structured as follows. A description of the wildfire asset protection problem is provided in the next section. Similarities of the wildfire asset protection problem to the team orienteering problem are discussed. A mixed integer programming formulation of the problem is presented and explained in §3. Computational testing of the model is done in §4 and its results discussed. This is followed by a discussion in §5 of the model parameters and how different conditions and scenarios could be parameterised. The models functionality is then demonstrated on a hypothetical wildfire scenario in South Hobart, Tasmania, Australia. The paper concludes with a discussion of the results and possible extensions to the model.

2 The wildfire asset protection problem

When escaped wildfires impact communities and infrastructure, it is often possible to carry out a number of steps to protect the assets being threatened. Wetting down structures, clearing gutters of combustible material and putting out spot fires are a few examples. The responding fire services need to decide how to best assign the available resources to these asset protection tasks at various locations.

To aid the IMT in their efforts, in some Australian jurisdictions the fire services prepare community protection plans. These plans, among other things, identify various community assets together with information pertinent to protecting those assets. The protection plans contain GPS coordinates, access information, number and type of resources required to protect the assets and importance of the assets to the community. Some examples of community assets are communication towers, hotels, historical significant buildings, schools, bridges, factories and hospitals.

2.1 Asset value and protection requirements

Each asset under threat is assigned a protection priority by the IMT either explicitly or implicitly. For modelling purposes, this protection priority is translated into a value, and the aim is to protect the maximum total value of assets with the available limited resources. The community protection plans identify the protection requirements for each asset. The protection requirement is the amount of each type of capability required to provide an adequate level of protection to the asset. For an asset to be protected, the resources with the required capability must arrive in a timely manner and remain at the asset for a sufficient period of time, called the service duration, to carry out the necessary protection tasks.

2.2 Resources

The typical resource units being assigned are fire trucks, commonly referred to as tankers. Besides tankers, various types of vehicles may be available to the incident management team to utilise in dealing with a fire threatening a community. As an example, the various vehicles and resources of the Tasmania Fire Service are shown in Table 1. The average travelling speeds of each vehicle type are summarised in Table 2.

2.3 Time windows

The advancing fire fronts imposes time constraints on protection activities. These time constraints can be translated into time windows during which asset protection tasks must commence in order to be successful. The time that a resource starts working on a task is called the service start time. The time windows are determined by the anticipated *time to impact*, this is the time remaining before the asset is impacted by the fire. The time to impact may be estimated using fire spread modelling. Extensive research has been carried out in the modelling and prediction of fire spread, which is summarised in a series of reviews undertaken by Sullivan (2009a,b,c).

Table 1: Vehicle types, their abbreviation, typical crew capacity and roles that the vehicle can perform.

Vehicle type	Abbreviation	Typical crew size	Capabilities and limits
Heavy pumper	HP	4	Asset protection; limited to formed roads, both sealed and ununsealed; limited to reticulated water
Medium pumper	MP	4	Asset protection; limited to formed roads, both sealed and unsealed; limited to reticulated water
Heavy tanker	HT	4	Suppression and asset protection; roads (formed/unformed and 4WD vehicular tracks)
Medium tanker	MT	4	Suppression and asset protection; roads (formed/unformed and 4WD vehicular tracks)
Light tanker	LT	2	Suppression and asset protection; roads (formed/unformed and 4WD vehicular tracks)
Aerial apparatus	Aer	2	Asset protection; limited to formed roads (sealed, unsealed) and reticulated water (*e.g.* Snorkel)
Transportation vehicle	Trans	< 10	Information gathering, firefighter transport (*e.g.* troop carrier)
Miscellaneous vehicle	Misc	-	Miscellaneous; limited to formed roads(*e.g.* canteen vehicle)
Fixed wing aircraft	-	-	Fire spotting, reconnaissance, air attack supervisor, fire command and control; can only operate during daylight
Rotary wing aircraft	-	-	Fire spotting, reconnaissance, air attack supervisor firefighter transport, water bombing, water delivery, aerial mapping, fire command and control; Can only operate during daylight
Dozer	-	-	Fire break construction
Excavator	-	-	Fire break construction

Table 2: The average travelling speeds of the different vehicle types.

Transport class	Surface type	Default	HP & MP	HT	MT	LT
National/State Highway	Sealed	100	90	80	80	90
Major arterial road	Sealed	80	75	75	75	75
Major arterial road	Unsealed	80	60	60	60	60
Arterial road	Sealed	80	70	70	70	70
Arterial road	Unsealed	60	60	60	60	60
Feeder	Sealed	80	60	50	60	60
Feeder	Unsealed	60	50	50	50	50
Access road	Sealed	60	40	40	40	40
Access road	4WD / Unsealed	20	-	20	20	20
Vehicular track	4WD / Unsealed	20	-	10	10	10

2.4 Related problems

The problem of assigning tasks to resources during large wildfires as described above has features in common with the *team orienteering problem with time windows* (TOPTW). In the TOPTW, a team of orienteerers have a limited time to collect rewards from various locations. The reward at each location is only available for a period of time specified by the location's time window.

The TOPTW is in the class of vehicle routing problems with profits and is closely related to the selective vehicle routing problem with time windows, which generalises the TOPTW by adding a capacity constraint to each vehicle (Feillet et al. 2005). Vehicle routing problems with profits have been reviewed by Archetti et al. (2013) and orienteering problems by Vansteenwegen et al. (2011).

Drawing the analogy to the TOPTW, fire tankers may be seen as members of an orienteering team. The assets requiring protection are equivalent to control points, each with an associated time window and value. However, in the wildfire asset protection problem multiple resources are often required to protect a single asset, whereas the TOPTW requires the visit of only a single team member to claim a reward from a location. In Van der Merwe et al. (2014) a new model, the *cooperative orienteering problem with time windows* (COPTW), was formulated to address this shortcoming.

The COPTW generalises the TOPTW to allow multiple resources to converge on a single location and cooperatively collect the associated reward. In this paper, we further extend the cooperative orienteering problem to allow for mixed resource types with different interchangeable capabilities, asset protection requirements defined in terms of those capabilities and vehicle specific speed and road networks determining the travelling time of each vehicle.

3 Model formulation

The resource units will be referred to as vehicles. Let $\mathcal{Q}$ be the set of vehicle types. There is a total of p_q of each type of vehicle $q \in \mathcal{Q}$ available for assignment. The value of the asset at location i is v_i. Let a_i be the service duration associated with location i, that is the duration vehicles are required stay at the location to protect the asset. Each asset i has an associated time window, the time window's opening time is o_i and it's closing time is c_i. The time window specifies the time during which protection activities must commence in order to be successful.

3.1 Depots

Initially the vehicles are located at one of m depots at locations $1, \ldots, m$. The depot may be a vehicle storage area, a fire station or a staging area. For brevity these locations will be referred to as depots. There are $stock_{iq}$ vehicles of type q stationed at depot i. The assets are located at locations $m+1, \ldots, n-1$. Note that location n is a dummy location representing the sink in the model formulation.

3.2 Asset protection requirements

Let $\mathcal{U}$ be the set of vehicle capabilities. Each vehicle type q has an associated capability vector $\boldsymbol{cap}_q$. The protection requirement for each location is defined in terms of the capabilities required to protect the assets at that location.

The protection requirement of an asset i is given by the protection vector $\boldsymbol{r}_i$ specifying the amount of each capability required. An asset is considered protected if the combined capabilities of the vehicles assigned to the asset meets or exceeds the capabilities required. Furthermore, the vehicles must arrive before or at the start of service time S_i and stay for the service duration a_i.

For example, one way of satisfying the protection vector $\boldsymbol{r}_i = (2, 3)$ is by combining the following three vehicles, one vehicle with $\boldsymbol{cap}_1 = (2, 1)$ and two vehicles with $\boldsymbol{cap}_2 = (0, 1)$.

3.3 Travel time

The time it takes for a vehicle to travel between two locations will depend on the vehicle type and the roads being used. Further, certain roads may only be accessible by some vehicle types, for example roads accessible only by four wheel drive vehicles. As a result each vehicle type will often have a unique travel time between two locations. Let t_{ijq} be the time it takes for vehicles of type q to travel from location i to location j.

3.4 Preprocessing

We eliminate those paths that are infeasible due to the time window constraints. This preprocessing approach is equivalent to that of Van der Merwe et al. (2014). Let $\mathcal{L}$ be the set of all possible location pairs. For vehicles of type q, consider two locations i and j chosen such that the earliest possible departure from location i results in an arrival at location j which is later than the closing time of location j. Since no feasible solution will contain the path i, j for vehicles of type q, it is possible to ignore this path. Let $\mathcal{E}_q$ be the index set excluding the infeasible paths, that is $(i, j) \in \mathcal{E}_q$ if and only if $(i, j) \in \mathcal{L}$ and $o_i + a_i + t_{ijq} \leq c_j$.

Two sets $\mathcal{F}_q^k$ and $\mathcal{G}_q^k$ are defined to simplify the model notation: $\mathcal{F}_q^k$ is the index set of locations adjacent *to* location k, that is $i \in \mathcal{F}_q^k$ if $(i, k) \in \mathcal{E}_q$, and $\mathcal{G}_q^k$ is the index set of locations adjacent *from* location k, that is $j \in \mathcal{G}_q^k$ if $(k, j) \in \mathcal{E}_q$.

3.5 The mixed integer programming model formulation

The following decision variables are used in the model formulation:

$Y_i = 1$ if asset i is protected, otherwise $Y_i = 0$;

X_{ijq} is an integer decision variable indicating the number of vehicles of type q travelling from location i to location j;

$Z_{ijq} = 1$ if a vehicle of type q is travelling from location i to location j, otherwise $Z_{ijq} = 0$; and

S_i is the start time of service at location i.

Based on the notation introduced above, the problem being considered may be formulated as a mixed integer program:

$$\text{Maximise} \sum_{i=m+1}^{n-1} v_i Y_i \tag{1}$$

subject to

$$\sum_{j \in \mathcal{G}_q^k} X_{kjq} = stock_{kq} \quad \forall\ k = 1, \ldots, m,\ q \in \mathcal{Q}; \tag{2}$$

$$\sum_{i \in \mathcal{F}_q^k} X_{ikq} = \sum_{j \in \mathcal{G}_q^k} X_{kjq} \quad \forall\ k = m+1, \ldots, n-1,\ q \in \mathcal{Q}; \tag{3}$$

$$\sum_{q \in \mathcal{Q}} \sum_{i \in \mathcal{F}_k^q} X_{ikq} cap_{qu} \geq r_{ku} Y_k \quad \forall\ u \in \mathcal{U}, k = m+1, \ldots, n-1; \tag{4}$$

$$X_{ijq} \leq p_q Z_{ijq} \quad \forall\ (i,j) \in \mathcal{E}_q,\ q \in \mathcal{Q}; \tag{5}$$

$$S_i + t_{ijq} + a_i - S_j \leq M(1 - Z_{ijq}) \quad \forall\ (i,j) \in \mathcal{E}_q,\ q \in \mathcal{Q}; \tag{6}$$

$$o_i \leq S_i \quad \forall\ i = 1, \ldots, n; \tag{7}$$

$$S_i \leq c_i \quad \forall\ i = 1, \ldots, n; \tag{8}$$

$$X_{ijq} \in \{0, 1, 2, \ldots, p_q\}, Z_{ijq} \in \{0, 1\} \quad \forall\ (i,j) \in \mathcal{E}_q,\ q \in \mathcal{Q}; \tag{9}$$

$$Y_i \in \{0, 1\} \quad \forall\ i = m+1, \ldots, n-1. \tag{10}$$

The objective function (1) is to maximise the total protected asset value. Constraints (2) enforce the starting position of vehicles to depots. The vehicle flow to and from each location is balanced by constraints (3). Constraints (4) enforce the condition that an asset is protected only if the vehicles assigned to the asset collectively meet the protection requirement. Constraints (5) and (6) ensure that service at a location may only start after protection activity at a previously visited location has been completed and sufficient time for travel has been allowed, with M representing a large constant. Setting $M = \max(o_i) + \max(t_{ijq}) + \max(a_i) - \min(c_i)$ is sufficiently large for this purpose. The start of protection activities at locations are limited to their respective time windows by constraints (7) and (8). Constraints (9) and (10) enforce the integer and binary conditions on the appropriate decision variables.

4 Computational study

Computational testing was carried out on a single node of a computer cluster. The node has two Intel Xeon E5-2670 processors and 64GB of RAM. CPLEX 12.6 was used to solve the problem instances and performance was measured in CPU time. The solver's parallel optimisation mode was set to deterministic while all the remaining CPLEX solver parameters were left at their default values.

Ten problem instances with 60 locations each were generated. The assets of each instance are uniformly distributed in a 80km by 80km square region. The travel time is directly proportional to the distance between locations. The opening time of each time window is correlated to the x-coordinate of it's location. This was done to capture the spatially correlated property of time windows in wildfire scenarios. It is assumed that all the time windows have the same length w, the closing time of each window is thus given by $c_i = o_i + w$. Random asset values and protection requirements were generated. The smaller problem instances (30,40 and 50 locations) are subsets of the 60-location instances.

Our first set of experiments consider only two entries in the vehicle capability vector and four vehicle types. The rest of the parameters are set as summarised in Table 3. The results of these experiments are contained in Table 4(a). The problems generally become harder as the number of locations and vehicles increase. Problems of size 30 are generally quick to solve, while larger problems depend on the properties of the problems. Longer time windows result in harder problems.

The second set of experiments consider three entries in the vehicle capability vectors. The rest of the parameters are set as summarised in Table 3. The results of these experiments are available in Table 4(b). Although all the problems of size 30 considered could be solved within the time limit, increasing the number of elements in the vehicle capability vector increased the solution times.

These results indicate that problems containing 50 locations or more are very hard to solve with this integer programming approach.

5 Model demonstration

In this section we demonstrate how the model could be used in practice. The modelling approach's flexibilities are discussed with regards to protection activities and interchanging or combining resources to protect assets. Finally a case study is considered using assets located in South Hobart, Tasmania, Australia.

5.1 Time windows

Parameterising two types of asset protection tasks and how this influences the time windows are considered next. The two tasks are active defence tasks and strategic defence tasks. Active defence tasks are those tasks that take place during the time that a fire is actively impacting the assets, either through direct flame contact or embers. Examples of active defence tasks are putting out spot fires near assets and wetting down structures. The duration of active tasks depend on the intensity of the fire, the structure being threatened and the fuel surrounding the asset, but typically have a duration between fifteen minutes and six hours. To ensure active protection activities commence at the time of impact, the times window's opening time equals its closing time.

Strategic defence tasks are preparatory tasks that can be carried out before a fire impacts an asset. Examples of strategic defence tasks include: clearing fuel around a structure, wetting down the roof, setting up a sprinkler system and applying fire retardant expansion foam to a structure. The time windows associated with strategic defence tasks start some time before the anticipated time to impact and end close to the time of impact, depending on the activity.

5.2 Interchanging resources

The model allows for combining and substituting resources to meet a given location's protection requirements. Although a myriad of possibilities of interchanging and combining resources to meet protection requirements exist, three cases are discussed next as an illustration.

Possibly the simplest case is when there is no overlap in the capability of vehicle types. Consider the following example, two vehicles with capabilities $\boldsymbol{cap}_1 = (1, 0)$ and $\boldsymbol{cap}_2 = (0, 1)$, respectively. These vehicles are not substitutable.

The second case is where vehicles can perform the same task, but some vehicles can provide more of a required capability than others. In this case the vehicle capability vectors are a scalar multiple of each other. As an example, assigning a vehicle with $\boldsymbol{cap}_3 = (2, 4)$ to protect an asset, is the same as two vehicles with $\boldsymbol{cap}_4 = (1, 2)$.

The third case is where one vehicle can perform the role of another, but not vice versa. For example, tankers can replace pumpers, but since pumpers do not carry their own water supply, they cannot always replace tankers. Pumpers can only operate where a water source is available, tankers on the other hand, do have their own water supply and are not limited by the availability of water. To illustrate how this would be handled in the model, consider the vehicle capabilities contained in Table 5.

Consider an asset i, which has no water source, that has a protection requirement of $\boldsymbol{r}_i = (2, 2)$. The first entry indicates that the location requires tankers and the second entry indicates that a heavy vehicle (or equivalent) is required. The protection requirement of asset i can be met by either one heavy tanker, since $\boldsymbol{cap}_{HT} = (2, 2) \geq (2, 2) = \boldsymbol{r}_i$, or two light tankers, since $2 \cdot \boldsymbol{cap}_{LT} = 2 \cdot (1, 1) \geq (2, 2) = \boldsymbol{r}_i$. Note that no combinations of pumpers can satisfy the protection requirement.

Next consider a location at location j that has an articulated water source and a protection requirement of $\boldsymbol{r}_j = (0, 2.5)$. The protection requirement of location j may be met by two medium pumpers, since $2 \cdot \boldsymbol{cap}_{MP} = 2 \cdot (0, 4/3) \geq (0, 2.5) = \boldsymbol{r}_j$, a medium pumper and a heavy pumper $\boldsymbol{cap}_{MP} + \boldsymbol{cap}_{HP} = (0, 4/3) + (0, 2) \geq (0, 2.5) = \boldsymbol{r}_j$, or two heavy pumpers, $2 \cdot \boldsymbol{cap}_{HP} = 2 \cdot (0, 2) \geq (0, 2.5) = \boldsymbol{r}_j$. The protection requirement can also be met by the appropriate combination of tankers. For example, a heavy tanker and a light tanker would meet the protection requirement, since $\boldsymbol{cap}_{HT} + \boldsymbol{cap}_{LT} (1, 1) + (2, 2) \geq (0, 2.5) = \boldsymbol{r}_i$.

The entries in the capability vectors may be viewed as resources being delivered to a location by the vehicle. For example, the vehicle capacity vector could specify the number of people and litres of water each vehicle can deliver. Each location's protection requirement specifies how much of each resource (i.e. people and water) is required to protect the assets at that location.

5.3 Case study: South Hobart

Fire stations located in Hobart and assets specified in the South Hobart protection plan are used in the demonstration. The location of these fire stations and assets are shown in Figure 1 which also contains the parameter values for these locations.

In January of 2013, numerous fires burned out of control in Hobart with devastating consequences. Among the losses were 203 residential buildings, approximately 662kms of commercial fencing and 10 000 head of livestock, mainly sheep. The estimated cost of the losses was in the order of AUD100 million, not taking into account the cost of emergency response and recovery operations and the longer term economic impact (Hyde 2013).

In our scenario a simple fire spread, radiating outwards at rate of 3km/h from a single point of origin in a circular fashion impacting South Hobart, is assumed. Each asset requires 30 minutes of active protection commencing at the time of impact. The travel times between assets were calculated using Google Maps' Distance Matrix service. We assume that there are four vehicle types. The capability of each vehicle is shown in Table 5. A total of 14 vehicles are available for assignment: 5 light tankers, 2 heavy tankers, 5 medium pumpers and 2 heavy pumpers.

The scenario is solved for two variations considering different starting locations of vehicles. In the first, all vehicles are located at a fire station on the eastern side of the Derwent river. The optimal assignment of vehicles is shown in Figures 2 and 3. In the second variation, vehicles are distributed among the various fire stations. An optimal solution is shown in Figures 4 and 5. In the second variation considered a total value of 270 is protected, compared to 240 in the first variation.

Table 3: The parameter values used for computational testing.

Parameter	Value			
	$q = 1$	$q = 2$	$q = 3$	$q = 4$
$\boldsymbol{cap}_q$ ($\lvert\mathcal{U}\rvert = 2$)	$(1, 1)$	$(2, 1)$	$(0, 2)$	$(1, 0)$
$\boldsymbol{cap}_q$ ($\lvert\mathcal{U}\rvert = 3$)	$(1, 1, 2)$	$(2, 1, 0)$	$(0, 2, 1)$	$(1, 0, 1)$
p_q ($p = 6$)	2	1	2	1
p_q ($p = 10$)	3	2	3	2

Table 4: The solution times for test instances in seconds. The number of unsolved problems after three hours is indicated in parenthesis while a dash indicates that none of the problems in could be solved within the three hour time limit.

(a) $\lvert\mathcal{U}\rvert = 2$

	$p \rightarrow 6$	10	6	10
n	$w \rightarrow 20$	20	40	40
30	9	3	540	460
40	45	59	(1) 1 800	(7) 8 952
50	87	544	(5) 8 500	-
60	287	(3) 4 467	-	-

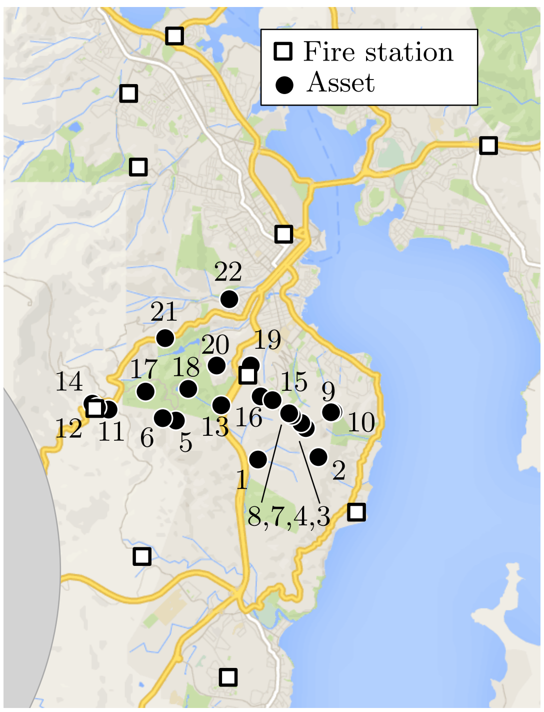
(b) $\lvert\mathcal{U}\rvert = 3$

	$p \rightarrow 6$	10	6	10
n	$w \rightarrow 20$	20	40	40
30	18	16	436	1455
40	53	140	(1) 2 262	(8) 10 065
50	168	1 280	-	-
60	310	(5) 6 621	-	-

Table 5: The capability vectors for each vehicle type to demonstrate how resource substitution may occur.

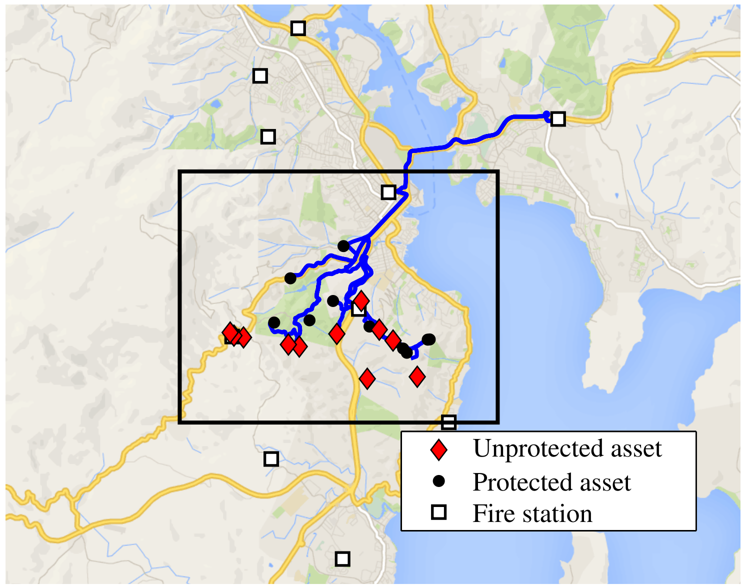
Vehicle type (q)	$\boldsymbol{cap}_q$
Light tanker (LT)	$(1, 1)$
Heavy tanker (HT)	$(2, 2)$
Medium pumper (MP)	$(0, 4/3)$
Heavy pumper (HP)	$(0, 2)$

Figure 1: Assets located in South Hobart and Hobart fire stations (Map data ©2014 Google).



i	v_i	$o_i = c_i$	$\boldsymbol{r}_i$
1	10	91	(2, 2)
2	10	126	(3, 2)
3	30	119	(1, 1)
4	30	117	(2, 3)
5	20	45	(3, 1)
6	10	38	(3, 1)
7	30	112	(2, 3)
8	10	110	(3, 2)
9	20	134	(2, 3)
10	10	136	(1, 1)
11	30	8	(1, 3)
12	30	2	(1, 1)
13	10	72	(3, 3)
14	10	0	(2, 2)
15	10	102	(2, 3)
16	10	95	(1, 2)
17	20	31	(1, 2)
18	20	55	(2, 3)
19	10	93	(2, 1)
20	20	75	(1, 1)
21	20	51	(3, 1)
22	30	94	(2, 2)

Figure 2: An optimal solution for the first scenario described in the text. All of the vehicles are located at a fire station on the eastern side of the Derwent river (Map data ©2014 Google).



6 Discussion

In this paper we presented a mixed integer programming approach to the problem of protecting assets during escaped wildfires. This research is a step towards providing IMTs with tools that may be used in real-time to reduce the impact of escaped wildfires on communities.

The mixed integer programming model presented here is a generalisation of the COPTW. The COPTW is generalised by allowing mixed vehicle types, introducing a vector specifying the protection requirement for each location and allowing each vehicle type to have a unique travel time between two locations.

Testing of the asset protection model formulation demonstrated that it is computationally feasible to apply the model to real life asset protection problems.

The working of the model was demonstrated using the locations of asset and fire stations in Hobart, Tasmania, Australia. Although the data used to demonstrate the model was sourced from Tasmania Fire Service, the modelling approach is general and the model could be applied to other locations.

Future work may consider modification to the model presented here to account for certain wildfire management cases. For instance, saving lives is considered the top priority by fire agencies. In the case where lives are at risk, the evacuation and protection of vulnerable people in place would need to be carried out before any asset protection is considered. This may be accounted for in the model by the addition of constraints. Other extensions may require more in-depth reformulation of the model. As an example, when its not possible to protect an asset completely, it may still be possible to partially save or reduce the damage to an asset. In the model this would translate to

Figure 3: The solution in Figure 2 shown by vehicle type. The map has been cropped to the area highlighted by the rectangle in Figure 2 (Map data ©2014 Google).

(a) Light tankers (b) Heavy tankers

(c) Medium pumpers (d) Light pumpers

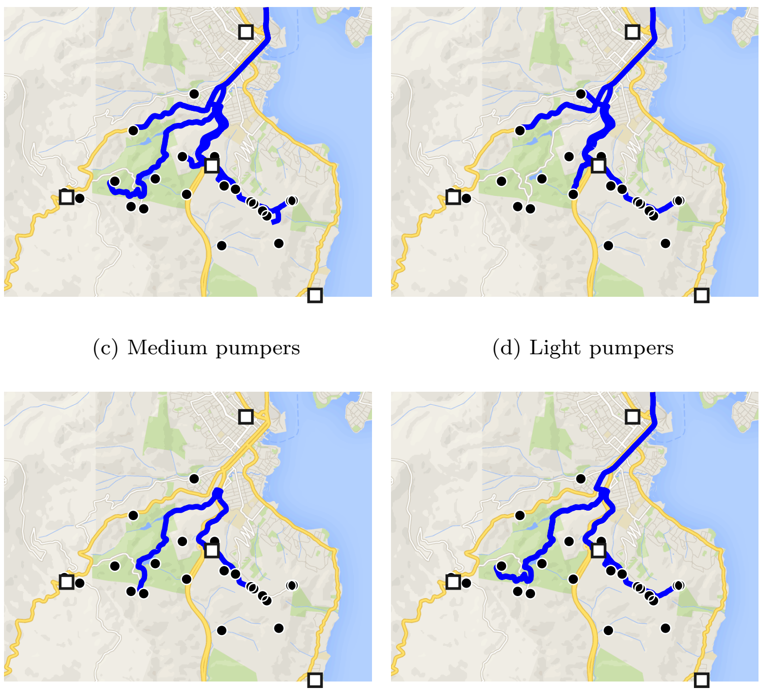
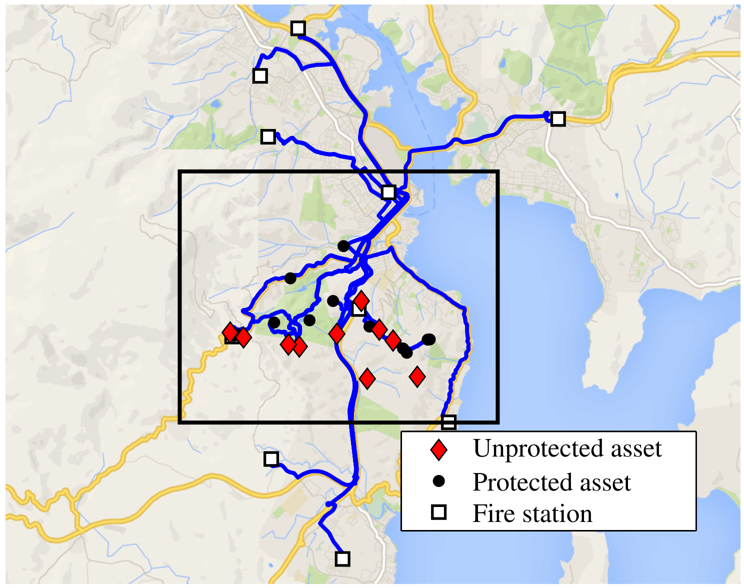


Figure 4: An optimal solution for the second scenario described in the text. The vehicles are located at various fire stations across Hobart (Map data ©2014 Google).



collecting partial rewards from locations. Another important area for future research is accounting for uncertainty in parameter values and the consequences of uncertainty in decision making when assigning resources to asset protection.

Acknowledgements

We would like to thank Damien Killalea from the Tasmanian Fire Service for providing valuable information on wildfire incident management. This work was supported by the Bushfire CRC in the form of scholarship funding to Martijn van der Merwe. The third author is supported by the Australian Research Council under the Discovery Projects funding scheme (project DP140104246).

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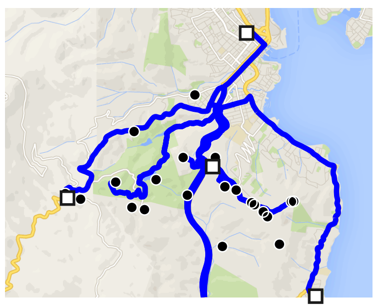
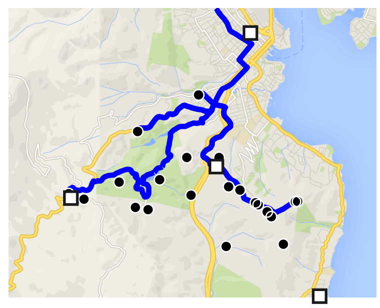
Figure 5: The solution presented in Figure 4 shown by vehicle type. The map has been cropped to the area highlighted by the rectangle in Figure 4 (Map data ©2014 Google).

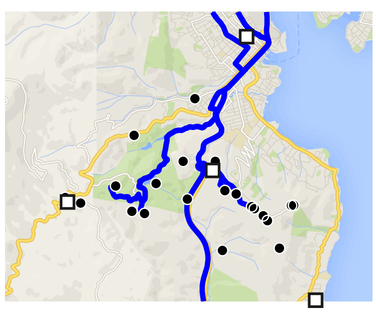
(a) Light tankers



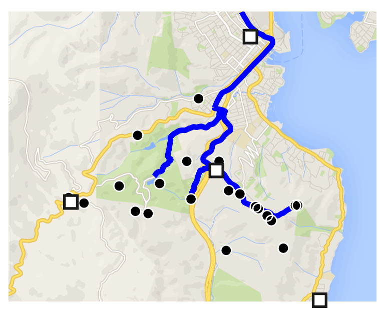
(b) Heavy Tankers



(c) Medium pumpers



(d) Heavy pumpers



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