Burning Down the Cost: A Study to Optimize Wildfire Expenses

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SIGNATURE PAGE

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Abstract

The cost of wildfires has been climbing drastically. In 2012, the total estimated cost for Montana wildfire suppression was $113.5 million. The goal of this research was to see if it was mathematically possible to minimize wildfire cost while ensuring that a fire is efficiently suppressed.

A linear program(LP) was designed to minimize suppression cost while allocating the required hand, air, and equipment crews to specific stages of a wildfire. Two scenarios are implemented into the linear program, where optimal solutions are found. First, a one wildfire scenario is simulated. Secondly, the most extreme fires of Montana's 2012 wildfire season are simulated. Finally, the LP's optimal results, are compared and analyzed with the actual 2012 fire results.

Based on the model's outcomes, it was found that dispatch centers with more available equipment, ready to suppress a wildfire, had a lower suppression cost. Although the model manages to meet management requirements, it doesn't account for intangible factors that go into decision making. In conclusion, the linear program provides an optimal solution for wildfire decision management, and under given constraints will efficiently determine the lowest cost while meeting suppression requirements.

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1 Introduction

Wildfires are becoming more severe and expensive. With increasing structures and temperature changes we can expect to see a growth in wildfire cost. From this growth, suppressing a fire efficiently and in a timely manner becomes vital.

In 2012, Montana experienced one of its worst wildfire seasons since 1904, the season ended with an estimated cost of $113.5 Million[1]. This cost includes management resources, fire crews, equipment, and aviation units. Although there are many factors in wildfire cost, suppression cost is vital in that it fluctuates depending on the size of the fire, structures threatened, and the fire condition. By analyzing the primary resources in suppressing a wildfire, it is possible to determine an optimal solution in regards to wildfire suppression. Based on the location of a fire, a dispatch unit will send hand, air, and equipment crews to initially attack the fire. The dispatch unit will continue to manage suppression units based on the type and condition of the fire if the initial attack fails. The key to lowering the suppression cost is to send in the units while meeting the constraints set by the fire.

This paper will use linear programming models to analyze and optimize the cost of wildfire suppression in Montana. Section 2 of this paper provides an in-depth literature review of wildfire suppression. Sections 3 and 4 give a brief understanding of linear programming and assumptions to the model. Then section 5 will describe the layout of the linear program. Estimated suppression costs that are connected with hand, air, and equipment crews will be implemented into the model. These crews will be modified as constraints, which will be based upon the stages of a fire. Then in sections 6 and 7, simulations will run that relate to wildfire scenarios for Montana. These simulations will then be compared to actual data from Montana's 2012 wildfire season.

2 Fire Literature

To develop a wildfire suppression model, multiple research sources were used to gain an idea of the tactics and costs it takes to suppress a Montana wildfire.

2.1 Increasing Wildfire Cost

According the National Inter-agency Fire Center in 2012, the total annual wildfire suppression cost was approximately 1.902 billion [2]. In 2001, the total suppression cost was 952 million which means that since 2012 the cost of wildfires has nearly doubled. Of course, the cost varies based on the severity of the wildfire, but the cost has steadily grown at an average of 3.5% per year since 2001. So why is the cost going up? Headwaters Economics, an independent nonpartisan research company, examined how residential development adds to the cost of fighting wildfires[3]. Their research in a Montana case study concluded that there was a strong correlation between the costs of fighting wildfires and the number of homes threatened. When more residence structures are built in rural areas, suppression costs increase. [3]. Since protecting homes is more important, the DNRC (Department of Natural Resources and Conservation) Fire and Aviation Management Bureau will spend more money and time suppressing a wildfire in close proximity to homes. It is estimated that if current rural residency developments continue in Montana, the cost associated with homes could cost $51 to $79 million per year or more by 2025 [3]. These future costs, adjusted with inflation, could be as high as $124 million per year.

2.2 Suppressing a Fire

Many resources are used to suppress a wildfire. Although there are numerous resources, the three primary types of suppression support are hand, equipment, and air crews. The way these type of units are deployed is based on the stage and situation of a wildfire.

2.2.1 Hand Crew

Hand crews consists of firefighters who suppress the fire on foot. The specialized hand crews consist of hot shots and smoke jumpers, which are considered to be the marines and green berets of firefighters, respectively. Smoke Jumpers can be flown into hard to reach spots, where they can set up fire lines and use their suppression skills to ideally stop the spread of a fire. Hotshots consist of 20 to 22 members and are expected to have a full range of training and expertise in fire suppression tactics. Other hand crews consist of fire line crews and even inmate crews. Smoke Jumpers and hotshots are preferred for initial wildfire attacks, since the fire is new and they have the tactics and tools to put it out as soon as possible. Table 1 displays several hand crews and their associated cost.

Hand Crew	**Estimated Daily Cost**
Hotshot Crew	$10,200
AD Crew	$5,500
Smoke Jumper Crew	$5,600

Table 1: Example Costs of Hand Crews

2.2.2 Equipment Crew

Equipment crews utilize mechanical equipment. Mechanical equipment is very effective in fire suppression and usually replaces fire line crews. Cost benefits can be realized through the use of machines when successful management practices are followed [4]. Several of the most important equipment tools that are utilized are dozers, engines, and water tenders. Dozers (Figure 1a[5]) are costly to operate, however in rocky areas and in dense timbers they can clear paths where crews can build fire lines and push further. Engines (Figure 1b[6]) are the most commonly used in that they aid the direct fire attack, supply water, and protect improvements already achieved that are threatened by a wildfire. Water tenders (Figure 1c[7]) are vital in that they carry water to the scene. They cost less, but the drawback is that they can only travel to the fire by roads.

(a) Dozer [5] (b) Engine [6] (c) Water Tender [7]

Figure 1: Pictures of Mechanical Equipment

Availability of mechanical equipment resources can at times be a problem. Each dispatch center has available equipment in the event of a wildfire. However, the majority of their equipment is privately owned. Construction agencies, ranchers, and other industries have equipment contracts with the DNRC. The equipment (dozers, engines, tenders) are usually called upon and deployed in the event of an initial attack on the new fire. As the fire stage increases the dispatch centers have the option to call in heavier support which is federally owned. Each unit for equipment is labeled by a type and how efficient it is in suppressing fires. Type 1 is considered the best equipment for high to extreme fires; type 6 equipment should be used for only low to moderate staged fires. Table 2 displays several equipment crews and their associated costs.

Equipment Crew	**Estimated Daily Cost**
Dozer	$3,000
Private Engine	$2,200
Water Tender	$1,480

Table 2: Example Costs of Equipment Crews

2.2.3 Air Crew

Air crews are often the most expensive units of the suppression resources. However, tactical air operations are considered to be highly effective and efficient. In decision management the operations chief not only must consider the cost of using aircraft, but also the cost of not using it [4]. The most expensive air craft are tankers which drop retardant. The daily cost for the use of a tanker with retardant is roughly $4,520 with retardant [9]. When firefighters or homes are threatened this equipment is ordered immediately. Helicopters are the least expensive of the aircraft suppression units. The majority of the time, helicopters deliver water to the fire, and can transport hand units. Aircraft can be ideal for an initial fire attack and it is used in extreme wildfire cases. Table 3 displays several air crews and their associated costs.

Air Crew	**Estimated Daily Cost**
2,450 gallon Tanker	$6,585
Kmax Helicopter	$4,200
212 Helicopter	$1,800

Table 3: Example Costs of Air Crews

3 Computational Method for Optimization

Linear programming will be used to determine the optimal resource allocation for Montana wildfire suppression. Since wildfire suppression is a complex multi-variable optimization problem, linear programming will be used to maximize an objective function. The objective function in this case will be to minimize the cost of a wildfire subject to the number of crews available and deploying required units based on the stage of the fire.

3.1 Linear Programming Method

The goal of linear optimization is to minimize cost while meeting wildfire suppression requirements. Linear programming offers the optimization of a linear objective function, subject to linear equality and inequality constraints. From the constraints and objective function, a convex polyhedron is created, better known as the feasible region. In a 2D model the inequality constraints, by intersections, form an enclosed area. This area is the feasible region, which can be represented in Figure 2.

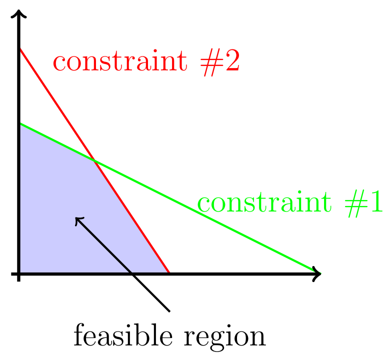

Figure 2: Diagram of Feasible Region and Constraints

In a linear program an algorithm is used. For this model, the interior-point algorithm is utilized, which finds a point in the feasible region where the objective function has the smallest or largest value. This determines the optimal solution for the model. An example of a linear program can be simply represented as

$$\text{Minimize } f(x) \text{ subject to : } \begin{cases} Ax \leq b \\ A_{eq} = b_{eq} \\ x \geq 0 \end{cases}$$

where A represents a matrix of the coefficients and $f(x)$ is the objective function. The variable x represents the vector of decision variables, while b is a vector of known coefficients. This vector creates the constraints of the model. In this case $f(x)$ would be the objective function that would be minimized based on the constraints given in the bracket; for example, one constraint is that all decision variables need to be greater than 0. A closer look at linear programming can be found on MathWork's official website [8].

4 Assumptions

Wildfire suppression management is complex and many factors are involved in decision making. Since there are so many factors, assumptions are made to ensure that the constraints will be created reflecting the largest influences that go into decision making. These assumptions are designed to neglect the minor and specific costs of wildfire suppression, and concentrate on the largest support expenses.

1. Suppression cost will only consist of the daily cost of hand, air, and equipment crews. The cost will not involve other factors such as management, feed crews, or camp crews.

2. The cost per unit will be an estimated daily cost that follows the DNRC quick cost estimator [9] .

3. If structures or residencies are threatened, then the wildfire type will be considered high and resources will increase to suppress the fire.

4. Low priority fires require less air crews and primarily consist of hand and equipment crews.

5. Each wildfire will be managed by its nearest dispatch center in Montana. (see Figure 3)

6. An initial attack will consist of resources available from the nearest dispatch center. Extended wildfire attacks will consist of federal aid support.

7. There are only 3 stages for a wildfire. (see Table 4)

The assumptions help generalize the decisions made in wildfire suppression management. A linear program (LP) was created to implement these assumptions and designed to adapt to multiple wildfire scenarios.

5 Wildfire Suppression Model

The linear program model is designed to minimize cost while allocating suppression units to the desired fire based on data provided by each dispatch center location (Figure 3)[11]. This way the dispatch center responds to the fire that is within its own area grid. To create a wildfire suppression model, several factors need to be considered.

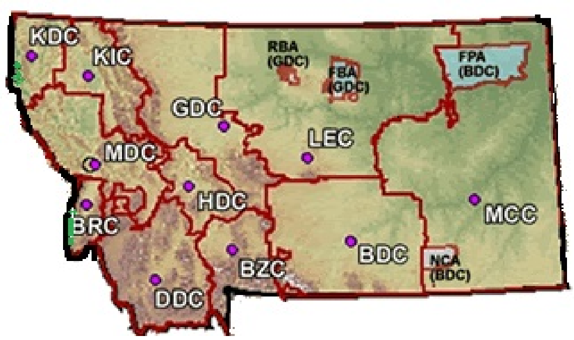

Figure 3: Location of Dispatch Units in Montana

5.1 Setup

There will be 3 stages for wildfires, low, moderate, and high. Table 4 displays a description of each wildfire type.

Stage	**Description**
Low	No structures or residencies threatened. Wildfire is controllable and is contained.
Medium	Possibility of structures being in danger. Wildfire is burning or smoldering. Moderate fuel danger.
High	Structures and residencies are threatened. Rate of wildfire growth is increasing and spreading quickly.

Table 4: Wildfire Type and Condition

Suppression resources will be allocated to the fire based on the stage. For a high stage fire the best equipment will be used first for the initial attack. Since it is assumed that each dispatch center will not have enough supplies for a high fire, then Federal resources will be dispatched to the fire in an high wildfire scenario. Table 5 outlines the different hand, air, and equipment crews along with a short description.The best equipment will be used for the extreme fire cases while the low priority fires will consist of low conditioned equipment. Some units will be separated by a type. This "type" measures the performance of the unit when suppressing wildfires, 1 being the best performance, and 6 being the least efficient in a high wildfire stage.

Hand	**Air**	**Equipment**
Hot Shots	Helicopter Type 1	Dozer
AD Crew	Helicopter Type 2	Federal Engine Type 1-6
Smoke Jumpers	Helicopter Type 3	Engine Type 3-6
State EFF	Tanker Type 1	Water Tender Type1-3
Inmate Crew	Tanker Type 2	
	Tanker Seat	

Table 5: Wildfire Suppression Resource List

Code was written in MatLab, which utilized the optimization toolbox to solve (using the interior point algorithm) for an optimal solution for dispatching resources to a wildfire.

5.2 The Linear Program

The objective is to minimize the cost of wildfire suppression. The linear program's objective function is the sum of the product of the cost c_i and decision variables x_i where each resource unit is represented by a number i. Equation (1) displays the layout of the linear program including the objective function along with constraints.This is the approximate model.

$$(LP)\begin{cases}\text{Minimize } c_1x_1 + c_2x_2 + \cdots + c_ix_i \\ \text{subject to the constraints} \\ x_i \leq b_i, \\ x_1 + x_2 + ... + x_5 \geq b_H \\ x_6 + x_7 + ... + x_{11} \geq b_A \\ x_{12} + x_{13} + ... + x_{19} \geq b_E \\ p_1x_1 + p_2x_2 + \cdots + p_ix_i \leq 0, \\ \text{where } x_i \geq 0 \end{cases} \tag{1}$$

x_i = Resource unit i
c_i = Cost coefficient for unit i
b_i = Resources available for x_i
b_H = Constraints value for required number of hand crew units
b_A = Constraint value for required number of air crew units
b_E = Constraint value for required number of equipment crew units
p_i = Percentage coefficient that requires unit i to be used in wildfire stage

Data from the DRNC priority reports, showed the availability of equipment resources within each dispatch center [12]. Many resources such as dozers, engines, and water tenders are privately owned, but if they are contained within the dispatch unit's area boundaries and are contracted by the owner, then they can be called upon to suppress an initial wildfire attack. This data will be used as a constraint for acquiring equipment resources for low and medium wildfire attacks. In a high stage wildfire, it is assumed that the dispatch unit will call in federal equipment resources because more equipment units will be required.

Stage	Resource	Constraint
Low	Hand Crew	At least 40% must be hand crew Smoke Jumpers or Hotshot are 40% of crew Deploy at least 2 hand crews
	Air	No more than 10% air crews
	Equipment	Have at least 6 Equipment Crews No more than 50% of Equipment Crew will consist of water tenders
Medium	Hand Crew	At least 35% must be crew Smoke Jumpers or Hotshot are 40% of crew Deploy at least 6 hand crews
	Air	At least 10% must be air crews Deploy at least 2 air crews
	Equipment	40% of equipment must be low types No more than 50% of equipment will consist of water tenders Deploy at least 10 equipment crews
Large	Hand Crew	At least 30% must be hand crew Smoke Jumpers and Hotshots are 40% of crew Deploy at least 10 hand crews
	Air	At least 20% must be air crews Deploy at least 6 air crews
	Equipment	Majority of equipment must have high type Federal engines and equipment are called in Deploy at least 35 equipment crews

Table 6: Constraints of Resources Compared with Wildfire Type

Based on the fire type, the model requires that the correct resource type (i.e. best equipment in regards to fire) be used given characteristics of the fire. Table 6 displays the verbal interpretation of the constraints used for each wildfire stage. Within the model the user can increase the required number of crews by a fixed percentage. By doing so, cases can be created where we can analyze if increasing/decreasing a suppression resource will derive a smaller cost and maintain efficiency.

6 One-Wildfire Model

The linear program was adjusted to model one wildfire, the Montana Chrandal Creek fire in 2012. First, the linear program finds the optimal solution for one dispatch center. Secondly, the same wildfire scenario was implemented for each dispatch center. The optimal results for each dispatch center were then analyzed. Finally, the actual Chrandral Creek historical data was analyzed and compared with the linear program's results.

The actual Chrandal fire's timespan was a month. Over a month the fire went through three stages. The fire started off as a low priority and then increased to a high priority fire. By the end of the month the wildfire decreased back into a low priority stage.Table 7 displays the stages of the fire. The linear program was changed to represent this same time frame.

Stage	Duration (days)	Description
Low	1-10	Mild Wildfire, no structures at risk, smoldering
High	11-20	High to Extreme wildfire, Structures threatened
Medium	21-25	Fire decreases
Low	26-31	Low priority

Table 7: One Wildfire Scenario Duration and Stages

6.1 Results of the One Wildfire Simultaion

The actual Chrandal wildfire was managed by the BRC (Bitterroot Dispatch Center). Since this was the case, this particular dispatch center was used for this simulation. Under the given constraints Figure 4 displays the LP's optimal daily and running cost results of the wildfire, which occurred under the BRC dispatch unit.

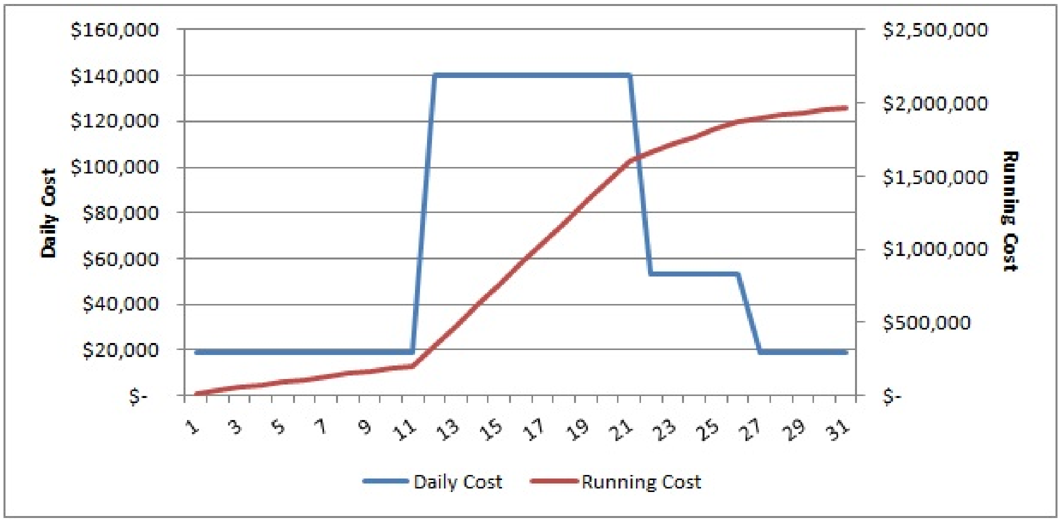

Figure 4: LP Results for Daily and Running Cost for Month Scenario

The model's total cost result after 31 days was $1,969,306. The same optimal results occurred each day of the fire based on the stage the fire was in (i.e. low,medium, and high).

6.1.1 Increasing/Decreasing Crew Units

To get a better understanding of how the model optimally minimizes cost in regards to allocating suppression resources, several simulations were made in which the required unit constraints were altered. Table 8 displays the optimal results based off of the changes (i.e. increases/decreases of crew units) to the constraints of the linear program. It is also important to realize the total cost of the actual fire differs from the model's fire since it accumulates many other suppression costs as well.

		Dispatch Resources		
Simulation/Constraint Changes	**Total Cost**	**Hand**	**Air**	**Equipment**
Original Simulation	$1,969,306	162	103	510
Increase Hand,Equipment,and Air Crew by 50%	$3,375,922	243	154	765
Only Increase Equipment and Hand Crew by 50%	$3,367,362	243	153	765
Only Increase Air Crew by 50%	$1,996,634	165	110	510
Only Increase Equipment Crew by 50%	$2,723,903	178	143	765
Only Increase Hand Crew by 50%	$2,620,488	233	113	510
Use Type 1 Resources for Initial Attack	$1,985,475	162	103	510

Table 8: Total Cost and Resources with New Constraint Changes

When the constraints were changed, the simulation with the lowest cost occurred when the air crew was increased by 50% while the hand and equipment crew remained unchanged. Increasing different resources didn't decrease the total cost from the original simulation. By altering one resource type at a time the air crews were the least expensive while the equipment and hand crew surpassed the original simulation's cost by roughly 600 thousand. The purpose of these simulations was to analyze how cost was impacted when the number of crew units were increased or decreased. From these results, the original simulation still provides the lowest cost solution. However, when crews are increased, increasing the air crew had the least impact on cost compared to the other crews. Rather than focus on just one dispatch center, the next step is to analyze what occurs when the same one wildfire model is simulated under each dispatch center.

6.1.2 One Wildfire Results From Each Dispatch Center

Rather than analyzing the one-fire model with only one dispatch center, the next step was to run the simulation with all of the centers in Montana. This will give an idea of how resource availability impacts the cost between all of the dispatch centers in Montana. Again, the LP simulated the one month wildfire scenario, but this time it was with each dispatch center. Figure 5 displays the LP's results for the individual total cost between all of the dispatch centers.

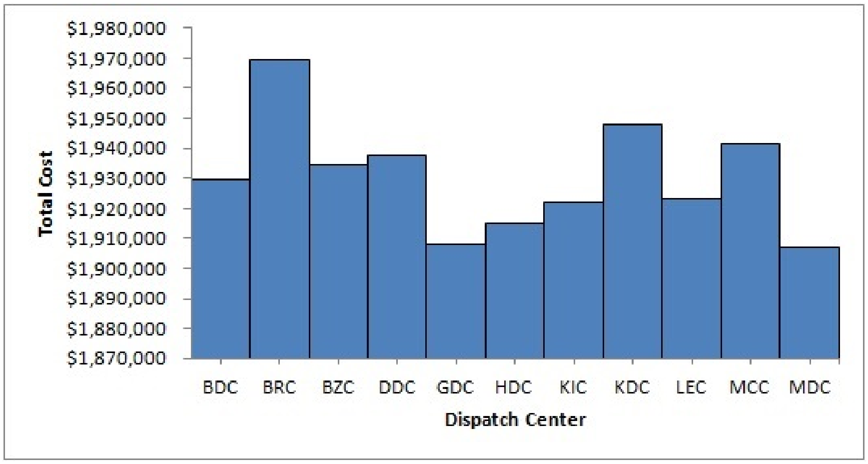

Figure 5: LP's Results for Total Cost of One Month Wildfire by Each Dispatch Center

The optimal cost for the one month wildfire scenario is fairly consistent between all of the dispatch centers except the MDC (Missoula Dispatch Center) and the GDC (Great Falls Dispatch Center). The LP's results within the location of the MDC and GDC accumulated a total cost of $1,906,867 and $1,908,267, respectively. This is lower than the rest of the optimal costs compared to the other dispatch centers. Having more dispatch resources available is the key to why the MDC unit has a lower cost than the rest of the dispatch centers. The model will choose the resource with the smallest cost that meets the requirements based on the stage of the fire. The MDC unit currently holds 112 equipment crew resources with a wide variety of available equipment. Since the dispatch unit has such availability, then the model has more low cost items to choose from, which will lower the optimal cost. It is important to note that in a high wildfire stage each unit has the option to call in federal aid support from outside sources. This will actually cost less since the resource item is owned by the government versus privately owned equipment. Without federal owned equipment the crew price would increase which would increase the optimal cost solution. The next step is to analyze what suppression resources were used the most during the simulations.

Table 9 displays the LP's results for the number of resource units deployed by each dispatch center. Under the same scenario each dispatch center resembled similar quantities of hand, air, and equipment crews that were allocated to suppress the wildfire.

		Resource Type		
Dispatch Unit	Total Cost	Hand	Air	Equipment
BDC	$ 1,929,763	164	103	514
BRC	$ 1,969,307	164	103	514
BZC	$1,934,387	164	103	514
DDC	$ 1,937,507	164	103	514
GDC	$1,908,267	164	103	514
HDC	$1,915,267	164	103	514
KIC	$1,922,107	164	103	514
KDC	$1,947,707	164	103	514
LEC	$1,923,187	164	103	514
MCC	$1,941,587	164	103	514
MDC	$1,906,867	164	103	514

Table 9: Number of Resource Units Deployed By Dispatch Center

The average number of crews that were used under each resources type were 164 for hand crews, 103 for air crews, and 514 for equipment crews. In the same scenario all of the dispatch units have similar deployment numbers. However, the total cost differs between all of the units. This is because each unit has different types of crews, and some have a higher expense than others. MDC deploys similar number of units as the other crews, but the reason why it has a lower cost is due to having feasible equipment available.

6.2 The Actual Chrandal Fire Data

The 2012 Chrandal Fire located south of Darby, Montana actually allocated the dispatch resources differently. The management team for the actual fire decided to use more hand crews than any other suppression resource. In doing this the estimated cost of the actual wildfire was estimated to be $8.3 million[13].

	Dispatch Crews		
Total Cost	**Hand**	**Air**	**Equipment**
$ 8,300,000	231	62	106

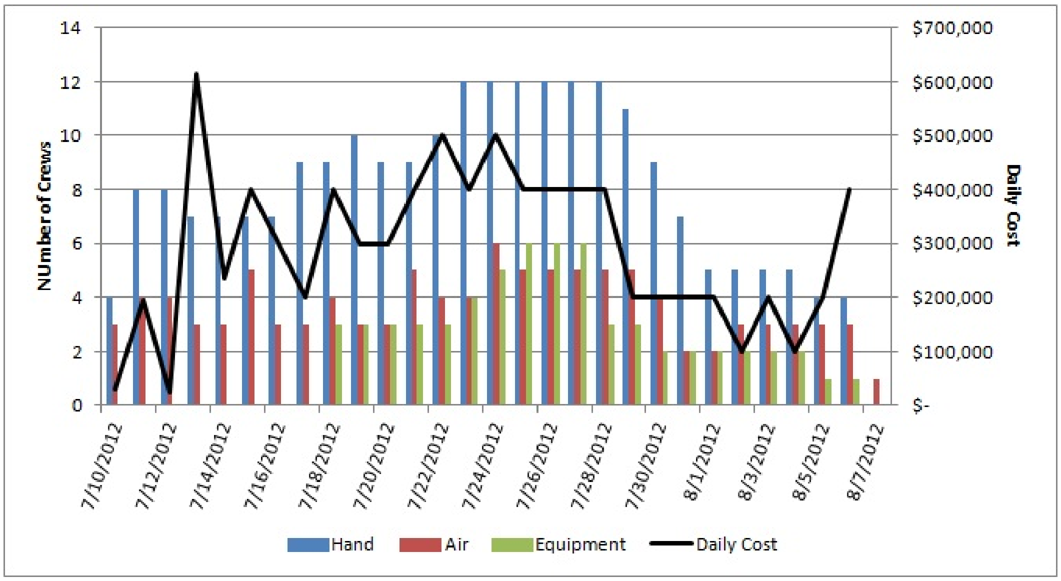

Figure 6: Number of Different Crews and Daily Cost of Actual Chrandal Fire

Figure 6 shows that the BRC dispatch center decided to increase all the crews during the highest stage of the fire. Most likely the dispatch center decided not to use as many air or equipment crews since the majority of the fire did not threaten any vital structures.

7 Multiple Wildfire Model

There were several extreme Montana wildfires in 2012. The majority of these fires took place during the critical fire months (June-August). With the information from these wildfires, the linear program was changed to resemble the 2012 wildfire season.

First, the LP finds optimal solutions for everyday of the wildfire season. Secondly, the optimal results of the dispatch units deployed per day were analyzed. Finally, the actual data for the wildfire season was analyzed with the LP's optimal solutions. The reasoning behind this was to simulate many fire stages at one time, and to determine the impact that wildfire durations and resource allocation have on the optimal suppression cost. Table 10 displays the major wildfires with time durations through the months of June-August [13].

Wildfire	**Dispatch Center**	**Duration**	**Actual Cost**
Corral	HDC	6/26-7/3	$550,000
Pony	DDC	6/26-7/9	$4,700,000
Ash Creek	MCC	6/27-7/11	$7,500,000
Chrandal Creek	BRC	7/10-8/7	$8,300,000
Sarpy Hill	BDC	8/3-8/10	$4,100,000
Rosebud	MCC	8/5-8/17	$9,000,000
Delphia	BDC	8/25-8/31	$2,200,000

Table 10: 2012 Wildfires with Respective Dispatch Centers and Duration

7.1 LP Results for Multiple Wildfire Scenarios

The severity between wildfires varied. Figure 7 displays the LP results of the daily and running cost of the multiple wildfire simulation. The results show that the cost spikes during the last month, which is in August. To get an idea of what is making the cost jump up so high during the end of the simulation, we need to determine what units are being deployed.

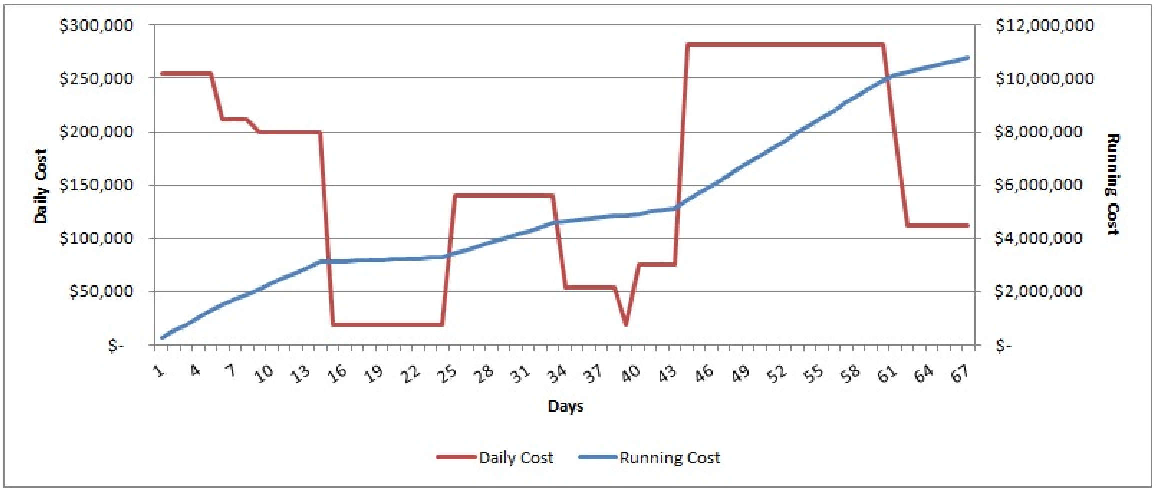

Figure 7: LP Results of Daily and Running Cost for Multi-fire Simulation

Figure 8 displays the number of units deployed from each resource along with the daily cost. From the figure, equipment is the largest factor that is driving up the daily cost. The daily cost appears to correlate to the number of units for equipment.

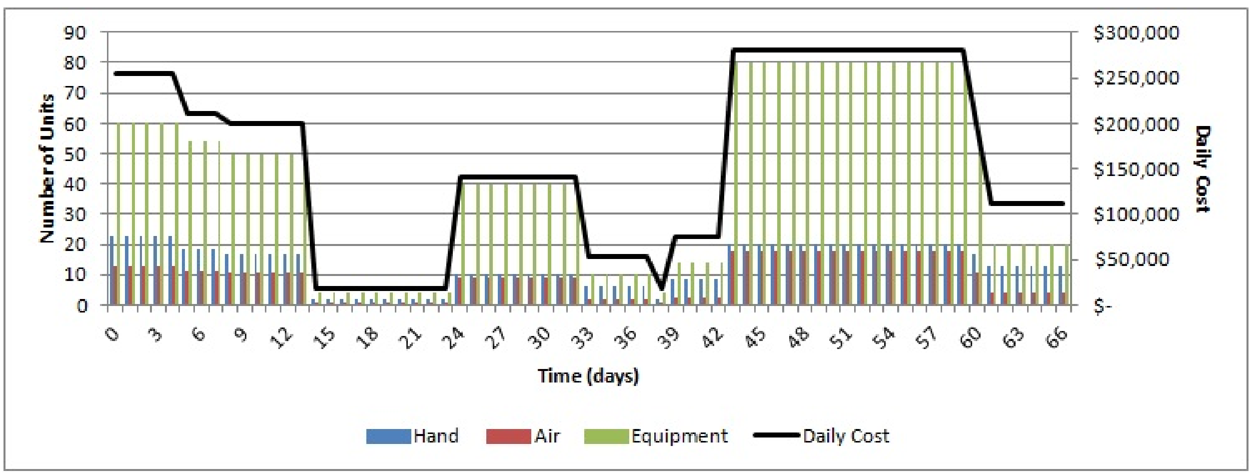

Figure 8: Number of Resources Used Daily for Multi-fire Simulation

Air units are the least used of all of the other resources. The cost and equipment units increase dramatically in the case of extreme wildfires where residencies or structures are in danger. Based on the constraints of the model, equipment crews are required the most out of the three types of crews. This may lead to why equipment increases drastically between the time periods where the majority of wildfires are in a high stage.

7.2 Actual Wildfire Season Data

From June to August, the fires in Table 10 cost Montana approximately 39.75 million [13]. Figure 9 shows the actual units deployed each day within this time range. Compared with the simulation resource units displayed in Figure 10, equipment resources are still used for the majority of fires.

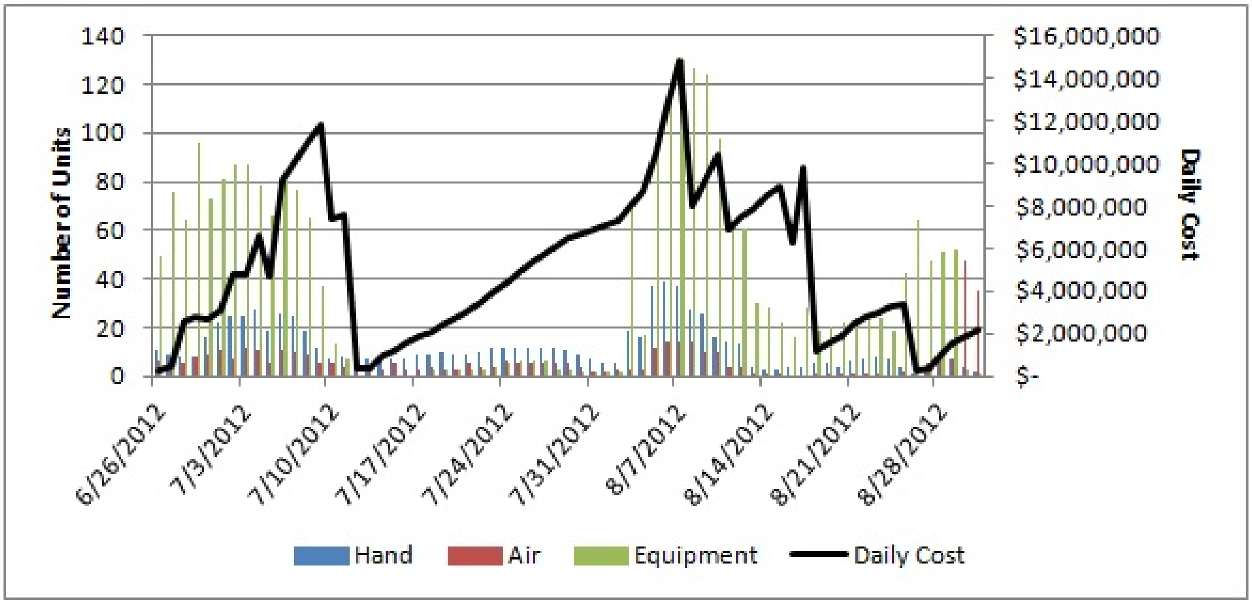

Figure 9: Number of Resources Used for Actual Fire Season

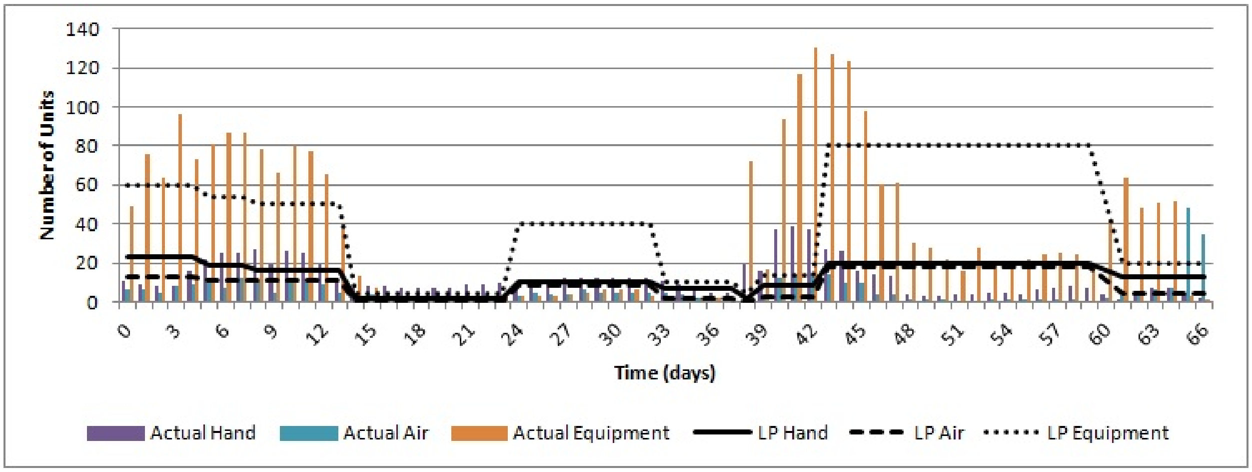

Figure 10: Number of Actual Resources Compared with LP Results

One interesting result is that the daily cost steadily increases between July 1st to August 1st. This differs from the LP results. Although the daily cost is increasing during this time span, the resources are not. This is likely due to more efficient resources being used to suppress the fire, rather than low priority units.

8 Conclusion

Since wildfire costs are increasing both in Montana and nationally, the importance of making successful decisions for wildfire suppression is becoming more and more vital. The allocation of suppression resources is the number one factor that leads to larger wildfire costs. The goal of this thesis was to create a model that optimizes wildfire cost by allocating the required wildfire support that match stages of a fire. Using 2012 wildfire data, several simulations were designed to replicate the stages of an actual fire, and to determine the best way to suppress it. By using linear programming, constraints were determined based on assumptions and suppression tactics. From the model's results, several conclusions can be made.

1. A dispatch center with more suppression resources available, will have a lower suppression cost because the dispatch center has more availability in selecting

the low cost units.

2. In the single wildfire simulation, increasing specific resources didn't lower cost. However, how the model selects the type of resource determines what the suppression cost will be. By doing this, the algorithm finds a feasible solution.

3. Out of the suppression resources, equipment has the highest number of crews in wildfire suppression.

Overall the model's behavior in allocating crews is similar to how actual wildfire management deploys units to attack a fire. However, the model does not account for scenarios in which decision management must suppress a fire in specific cases. These cases can be: can't attack fire with air crew because of terrain, not having hand crew availability in time, or crew units are divided between dispatch centers. In conclusion, the linear program provides an optimal solution for wildfire decision management, and under given constraints will efficiently determine the lowest cost while meeting suppression requirements.

8.1 Strengths

One of the biggest strengths of the model was the linear program's adaptability to simulate different scenarios. By utilizing the LP, we can run a scenario and alter the constraints. From this we can efficiently analyze if increasing/decreasing crews have an impact on the optimal cost for any dispatch center. If the constraints are based on fire suppression requirements that pertain to the stage of a fire, then the results of the LP will closely match actual suppression allocations. For a general optimization model, this LP can even be modified to match decision requirements in optimizing wildfire cost.

8.2 Limitations

The linear program selects the lowest cost resources to minimize wildfire cost. This is a method to optimize cost while meeting the constraints for wildfire suppression. However, the model does not take into account intangible factors that go into wildfire decision making. The model lacks the probability of other unforeseen problems such as weather, terrain, and fire fuels. Other expenses are not factored into the model. Expenses such as camp services, management operations, and additional crews should be added to the cost. This is why the daily cost differed from the actual fire cost. There are times that the linear program does not give integer solutions. When this occurs the number of allocated crews are rounded to give an estimate as an integer. This leads to an inaccuracy for the total cost.

8.3 Future Research

To increase the model's accuracy, the next step would be to integrate probability and integer solutions into the model. Many times the probability of weather, fire movement, and other wildfire criteria play a role in wildfire decisions. Then to make the linear program solve for integer solutions, binary constraints and mixed-integers would need to be programmed into the constraints. An expansion of suppression costs would be implemented into the model. From this the model could account for additional wildfire costs. Right now the model only consists of estimated costs. If more cost data could be provided from the DNRC, then the model would determine a more accurate wildfire cost. So if secured data (e.g. up to date air crew status or specific unit cost) is available, the next step would be to access and implement it into the model. With these modifications, the linear program can come closer to reaching an optimal solution that minimizes cost and efficiently allocates the correct number of resources to suppress a wildfire.

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A Notation Index

- LP-Linear Program
- x_i = Resource unit i
- c_i = Cost coefficient for unit i
- b_i = Resources available for x_i
- b_H = Constraints value for required number of hand crew units
- b_A = Constraint value for required number of air crew units
- b_E = Constraint value for required number of equipment crew units
- p_i = Percentage coefficient that requires unit i to be used in wildfire stage

B Appendix-Linear Program Layout

The following are the standard layouts for the linear program fire stages. The x_i resources can be found in Table 5.

B.1 Low Fire Stage

Minimize $c_1x_1 + c_2x_2 + \cdots + c_ix_i$
Subject to the constraints

$$\begin{aligned} x_i &\leq b_i \\ x_1 + x_2 + ... + x_5 &\geq b_H \\ x_6 + x_7 + ... + x_{11} &\geq b_A \\ x_{12} + x_{13} + ... + x_{17} &\geq b_E \end{aligned}$$

Constraints Based from Table 6

$$\begin{aligned} -0.6x_1 + 0.4x_2 + -0.6x_3 + 0.4x_4 + 0.4x_5 &\leq 0 \\ -0.5x_1 + ... + -0.5x_5 + 0.95x_6 + ... + 0.95x_{11} + -0.05x_{12} + ... + -0.05x_{17} &\leq 0 \\ 0.4x_1 + ... + 0.4x_5 + -0.6x_6 + ... + -0.6x_{17} &\leq 0 \\ -0.5x_{12} + -0.5x_{13} + -0.5x_{14} + -0.5x_{15} + -0.5x_{16} + 0.5x_{17} &\leq 0 \end{aligned}$$

B.2 Medium Fire Stage

Minimize $c_1x_1 + c_2x_2 + \cdots + c_ix_i$
Subject to the constraints

$$\begin{aligned} x_i &\leq b_i \\ x_1 + x_2 + ... + x_5 &\geq b_H \\ x_6 + x_7 + ... + x_{11} &\geq b_A \\ x_{12} + x_{13} + ... + x_{17} &\geq b_E \end{aligned}$$

Constraints Based from Table 6

$$\begin{aligned} -0.6x_1 + 0.4x_2 + -0.6x_3 + 0.4x_4 + 0.4x_5 &\leq 0 \\ 0.1x_1 + ... + 0.1x_5 + -0.9x_6 + ... + -0.9x_{11} + 0.1x_{12} + ... + 0.1x_{17} &\leq 0 \\ -0.65x_1 + ... + -0.65x_5 + 0.35x_6 + ... + 0.35x_{17} &\leq 0 \\ -0.5x_{12} + -0.5x_{13} + -0.5x_{14} + -0.5x_{15} + 0.5x_{16} + 0.5x_{17} &\leq 0 \\ -0.4x_{12} + -0.4x_{13} + -0.4x_{14} + -0.6x_{15} + 0.6x_{16} + 0.6x_{17} &\leq 0 \end{aligned}$$

B.3 High Fire Stage

Minimize $c_1x_1 + c_2x_2 + \cdots + c_ix_i$
Subject to the constraints

$$\begin{aligned} x_i &\leq b_i \\ x_1 + x_2 + ... + x_5 &\geq b_H \\ x_6 + x_7 + ... + x_{11} &\geq b_A \\ x_{12} + x_{13} + ... + x_{17} &\geq b_E \end{aligned}$$

Constraints Based from Table 6

$$\begin{aligned} -0.6x_1 + 0.4x_2 + -0.6x_3 + 0.4x_4 + 0.4x_5 &\leq 0 \\ 0.15x_1 + ... + 0.15x_5 + -0.85x_6 + ... + -0.85x_{11} + 0.15x_{12} + ... + 0.15x_{17} &\leq 0 \\ 0.3x_1 + ... + 0.3x_5 + -0.7x_6 + ... + -0.7x_{17} &\leq 0 \\ -0.5x_{12} + -0.5x_{13} + -0.5x_{14} + -0.5x_{15} + 0.5x_{16} + 0.5x_{17} &\leq 0 \\ 0.6x_{12} + -0.4x_{13} + -0.4x_{14} + -0.6x_{15} + 0.6x_{16} + 0.6x_{17} &\leq 0 \end{aligned}$$