Background

The Keystone Ski Resort in Keystone, Colorado provides its patrons with some of the best skiing in the Colorado area. In order to maintain a profitable business, Keystone Resorts must continue providing its patrons with the best ski runs, at a reasonable price, while minimizing operating costs. To do this we first identified what we consider the most popular routes for each type of skier. Second we identified where on these routes problems could occur that had the most effect on the popular routes. Finally, we used these problem areas to determine where best to place limited maintenance equipment. This analysis is usable for consideration in making maintenance decision to reduce costs.

Model

We modeled the network associated with the Keystone Ski Resort in Keystone, Colorado. Our analysis of the model focused on ski slope and ski lift usage by skiers with one of three different abilities: beginner, intermediate or advanced. From our network, we constructed a min-cost linear program (LP) shown as Primal in Figure 1. Our model's measure of effectiveness (MOE) is the maximum distance traveled in a specified amount of time. For each skier's ability we used the model to calculate the MOE. The arcs associated with the MOE gave us the most used ski runs and ski lifts for that skier ability. The model included attacks on the network. The attacks were interpreted as ski lifts becoming non-operational or ski runs becoming unusable from icing or balding due to overuse. A mixed-integer program (MIP) was used to calculate the attacks which can occur only on the initial optimal routes generated by the LP. The MIP equations are shown as Dual in Figure 1. We created resilience curves by varying the number of attacks allowed. Steep changes in the curve helped us determine which attacked arcs greatly affected our MOE. We then iterated over each set of attacks to determine the optimal positioning of an attack mitigation team in order to mitigate the effects of attack on the MOE.

Primal	Dual Variables	Dual
Max $\Sigma(d(I,j) * Y(I,j))$		Min $\Sigma(\pi(ji,j)*cap(I,j) + Tot\_Time*\theta(i))$
$\Sigma Y(I,j) - \Sigma Y(j,i) = 0$	$\rho(j)$	$\rho(j) - \rho(i) + \pi(I,j) + \Sigma\theta(i)*t(I,j) \geq d(I,j)$
$Y(I,j) \leq cap(I,j)$ for all (I,j)	$\pi(I,j)$	$\pi(I,j) \geq 0$
$\Sigma(Y(I,j) * t(I,j)) \leq Tot\_Time$	$\theta(i)$	$\theta(i) \geq 0$
$Y(I,j) \geq 0$		ρ is unrestricted

Figure 1. Primal and dual equations used in the model

Analysis

Table 1 provides the distances, our MOE, collected from the model. As stated above, the attacks in our model can only occur on the initial optimal route determined. The LP is allowed to use any route it wants in response to the attacks, but the attacks calculated by the MIP can only occur on the initial optimal route. This is why distances shown in Table 1 never go to 0, even when there are many attacks. We show in Table 3 that as the number of attacks increases the distance covered by the skier decreases monotonically across all three types of skier. This is in line with our expectation since we anticipated a decrease in distance covered as more attacks are levied upon the network.

Table 1. Distance Covered (miles) with Given Number of Attacks)

Slope/Skier Classification	Attacks					
	0	1	2	3	4	5
Green / 1	21.2	20.5	11.9	11.9	11.9	11.9
Blue / 2	42.9	41.9	39.5	33.8	32.1	32.1
Black / 3	63.0	61.9	59.8	45.2	44.1	44.1

We used the data from Table 3 to generate operator resilience curves for each skier type shown in Figure 2. These curves allowed us to determine the best locations to place our mitigation equipment. This was done by determining the largest change in resilience when attacks were increased. We identified all arcs attacked where the change occurred. We "mitigated" an attack on one of these arcs making it un-attackable. The model was rerun to determine new MOE's and a new resilience curve, it was then repeated for a different arc until all identified arcs were processed. The Beginners Operator Resilience Curves in Figure 1 show a drastic decrease in distance for unmitigated attacks when attacks increased from one to two attacks while no mitigation equipment was in use. After mitigating attacks we determined the best place to station mitigating equipment is a tie between edge (A1, Pickup1) and edge (A1, Pickup2). In this case we recommend placing the equipment at the A1 node to cover both edges. The Operator Resilience Curve for the Intermediate and Advanced skiers was done in the same fashion. In the intermediate case the unmitigated resilience curve decreased sharply when attacks increased from two to three attacks. In this case we suggest placing mitigation equipment at edge (B2, Pickup4) since the result is more resilient throughout all increased attacks tested. In the advanced case the unmitigated resilience curve decreased sharply when attacks increased from two to three attacks. Here we recommend placing mitigation equipment at edge (Pickup4, Drop3). This is the optimal choice and in fact the only logical choice due to its stochastic dominance over the other curves. We also recommend an emphasis on ski lift maintenance for the advanced ski routes since three of the attacked arcs are lifts. The identified attacked edge for the beginner and intermediate routes are ski runs, so mitigation equipment consists of snow making and grooming machines. In the advanced route the identified attacked edge is a ski lift so our mitigation consists of a ski lift maintenance crew.

Conclusion

Using our model we showed we can implement a preventive maintenance program that allows the facility to keep customer satisfaction high with a relatively small amount of mitigation equipment. By only pre-placing two sets of snow making machines and one ski lift maintenance crew we greatly decreased the effects of attacks on our calculated most popular route in the Keystone network.

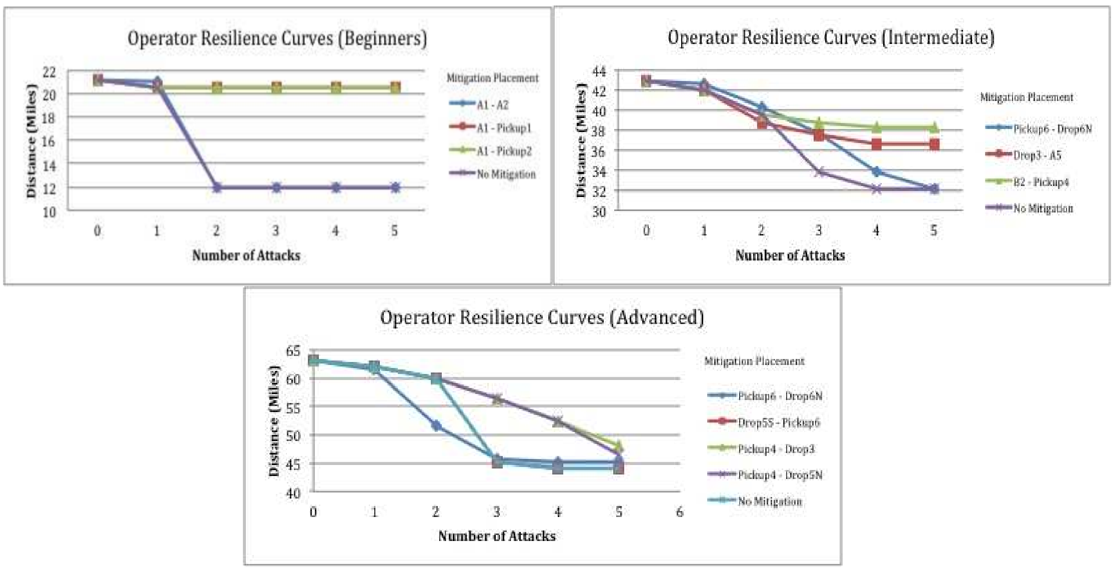

Figure 2. Operator Resilience Curves for each level of skier