Design of a Ski Lift Inspection & Maintenance System

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INSPEX - “Because ski lift inspections shouldn’t be a slippery slope”

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1.0 Context Analysis

1.1 Ski Resorts and Ski Lifts

Ski resorts are popular recreation destinations developed specifically for skiing, snowboarding, and other winter sports. Although the primary season for a ski resort is winter, ski resorts are now operating their lifts 12 months a year to expand operations for summer sports such as mountain biking. Ski areas are mountainous areas with pistes (ski runs), ski trails, and a ski lift system. The NSAA categorizes U.S. ski areas by region: Pacific Northwest, Pacific Southwest, Rocky Mountain, Midwest, Northeast, and Southeast. Pennsylvania, Maryland, Virginia and West Virginia are all part of the southeast region. The United States consists of a total of 521 ski resorts with 4 operating in Virginia [1]. During the 2015/16 ski season, the number of customers at ski resorts varied between 50,000 and 499,000 for downhill snowsports [2].

Ski resorts use ski lifts as their primary mode of uphill transportation. A ski lift is a motor-driven conveyor system used to safely and reliably transport skiers and sightseers up a slope to the top of a run. Ski lifts typically consist of a series of bars or seats attached to an overhead moving cable. A total of 2,705 ski lifts are operated across the US with 18 operating in Virginia [1]. These lifts vary in type, consisting of traditional double, triple and quad chair lifts, gondolas, surface lifts, rope tows, and aerial tramways [3]. The case study for operational analysis is Bryce Resort in Basye, Virginia. It has five surface lifts and two aerial lifts that service 8 runs. The area has 25 acres of skiable terrain and a vertical drop of 500 feet [23]. Bryce Resort was chosen as the case study because their double chair aerial lift is one of the oldest ski lifts in the country and it is one of the closest ski resorts to George Mason University.

Skylark Drone Research is investigating the use of unmanned aerial vehicles (UAVs) to inspect ski lift towers. The purpose of this analysis and system design is to examine the viability of using UAVs as a potential design alternative for an inspection system in comparison to other alternatives. Some ski resorts operate on US Forest lands where the use of drone systems is banned, but Bryce Resort does not fall under US Forest Service rules. There is a non-FAA regulated airfield nearby with low frequency local traffic that does not interfere with UAV operation over the lift area. However, inspection personnel would need to obtain a waiver or an FAA 14 CFR Part 107 license to operate a UAV for commercial use.

1.2 Operating Costs

The cost of operating a ski lift is based on multiple variables because ski areas and resorts are both capital and labor intensive. Operating expenses include direct labor, maintenance and repairs, property/other taxes, land use fees, and insurance. The average operating expenditure in the Southeast was $13.8 million for the 2015/2016 season [4]. The largest expense category is direct labor accounting for 24% in overall expenditures with an average of $7.9 million per ski area in the 2015-16 season [4]. Lift operations account for 4.1% of expenses and the average maintenance and repair cost was $735,000 in the 2015-16 season accounting for 2.3% of overall expenditures. It takes an average of $423,500 to inspect a ski lift per year [5]. Examples of operating costs include the cost of:

- Installation of ski lifts based on type, configuration, and installation method
- Running base lodges, which house a variety of services, and their maintenance
- Purchase, replacement, and labor costs of snow grooming tractors which move and recondition the snow each night
- Purchase and energy cost of snowmaking equipment
- Energy costs required to run equipment and lifts, and to heat the base facilities

- Labor costs for lift and grooming operators, rental shop technicians, instructors and patrollers, accounting, road maintenance personnel, marketers, snowmakers, IT, and administrative support. [6].

The cost of the most recent ski lift installed at Bryce Resort in 2012 was $1.5 million alone. Ski resorts are dependent on the mechanical soundness of their ski lift components and safety systems in order to operate their businesses. Any mechanical breakdown could cause closure of the slopes, strand passengers, and cost their business millions.

1.3 Components

The major components of a ski lift, defined in Table 1, are the haul rope, terminals, towers, carriers, and safety systems.

	Components	**Description**
Major Components	Haul Rope	The lift cable that moves the carrier up the hill while supporting its weight and passengers
	Terminals	Houses the motor, gearbox, auxiliary engine and drive and safety circuitry
	Towers	All other lift towers in line with the haul rope that are not drive/return terminals
	Carriers	The device on/in which customers ride (chairs, gondola cabins, tram cabins, T-bars)
	Safety Systems	Devices used to detect a cable coming off the sheave wheels or to trigger breaking during rollback.

Table 1: Major Ski Lift Components [7]

Ski lift towers are made of the components shown in Figure 2 that help support the haul rope and carrier. The tower head consists of the crossarm, sheave train, and support assembly. The haul rope, supported specifically by the support assembly, is covered by the brittle bars and cable catcher in the event of deropement. For bicable systems, there is both a haul rope and a stationary track rope to support the weight of the carrier. The track rope is supported on the tower by the saddle, which prevents excessive movement.

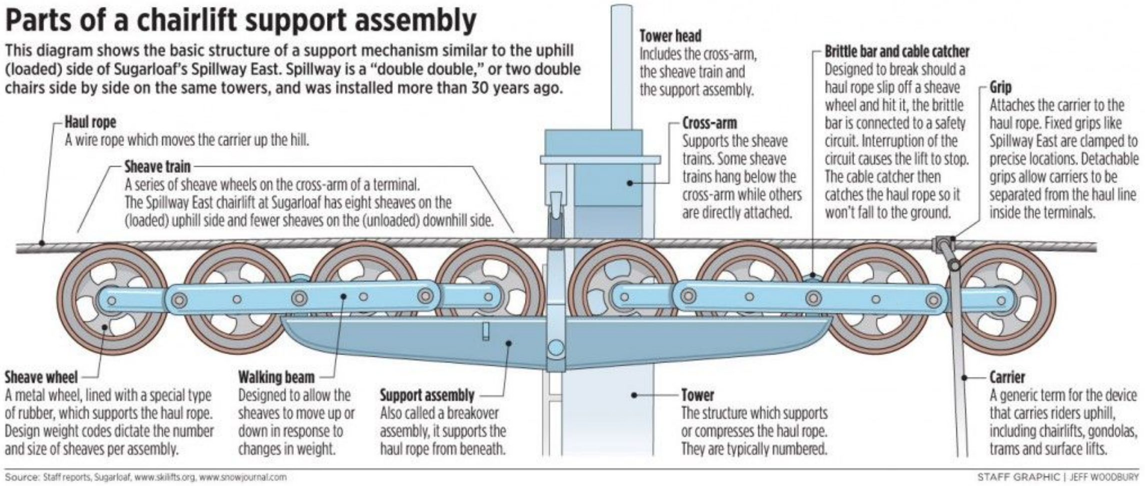


Figure 2: Components of the ski lift towers described in this section [8]

Table 3 below defines the subcomponents by component type. The power components generate and supply the energy for ski lifts to function. The mechanical components consist of the parts involved in the moving mechanism of the ski lift. The safety components ensure the ski lift is fail safe by activating when a failure in the system occurs. Another important component is the communications line (comm line) which carries data signals from each tower's safety and operating circuitry between the base and the summit and mountain dispatch. If the comm line breaks, a signal is sent to the terminal to indicate a fault, and problems related to the low voltage control system may occur.

Power Components		Mechanical Components		Safety Components	
Components	**Description**	**Components**	**Description**	**Components**	**Description**
Auxiliary	Backup power to the main motor	Bullwheel	Large wheel located at both ends of the lift used to change directions of the haul rope	Anti-Rollback Device	A type of brake that prevents ski lift from rolling backwards
Drive (Low Voltage Control System)	Controls speed and amount of voltage going to the main motor	Cross Arm	Arm at the top of the tower to which the sheave train is attached	Brittle Bar	A device connected to a safety circuit that breaks if a cable comes off the sheave wheel
Gearbox	Transfer power from the motors to the bullwheel	Service Brake	The main brake used to stop the lift during daily operations.	Cable Catcher	Catches the haul rope if it comes off preventing the rope from falling to the ground
Prime Mover	Primary motor	Sheave Train (Walking beam)	A series of sheave wheels on a crossarm that allows the wheels to move up and down depending on the weight of the carrier	Emergency Brake	Stops the ski lifts in case of emergencies
		Sheave Wheel	A wheel with rubber lining that supports the haul rope and provides grip/friction		

Table 3: Ski Lift Components [7]

1.4 Regulations

Ski lifts are regulated under the ANSI B77.1-2017 standards. Prior to being opened to the public, new or relocated aerial lifts must undergo and pass the following two test requirements:

1. qualified personnel shall thoroughly test and verify compliance with the plans and specifications of the designer/manufacturer.
2. designers or manufacturers shall propose and submit an acceptance test procedure [15].

Following the initial installation phase, as stated in the ANSI B77 standards, ski lift owners are subject to meet the following conditions for their ski lifts prior to being opened to the public: ”

a. tightness of all structural connections;

b. lubrication of all moving parts;
c. alignment and clearances of all open gearing;
d. installation and alignment of all drive system components;
e. position and freedom of movement of counterweights or other tension systems and carriages;
f. haul rope alignment at entrance to bull wheels;
g. operation of all electrical components, including circuit protection and grounding;
h. adjustment of brakes to design deceleration rates and baseline brake torque testing;
i. minimum clearances for carriers, track cable(s), and haul rope sags under the most adverse static loadings;
j. proper alignment of track cable saddles and haul rope sheave units;
k. proper track cable to saddle angles and unhindered inline motion of track cable in saddles as applicable;
l. actual testing of evacuation equipment and procedures at the most difficult location;
m. proper location of towers and terminals in accordance with the plans and specifications. Terminal and tower rope/cable working points shall be documented by an "as built" survey, and any variation from the design drawings shall be noted and approved by the engineer responsible for design;
n. slip testing of carriage haul rope clamps, if used, for required force (see 2.1.4.4.2.2(h))" [15].

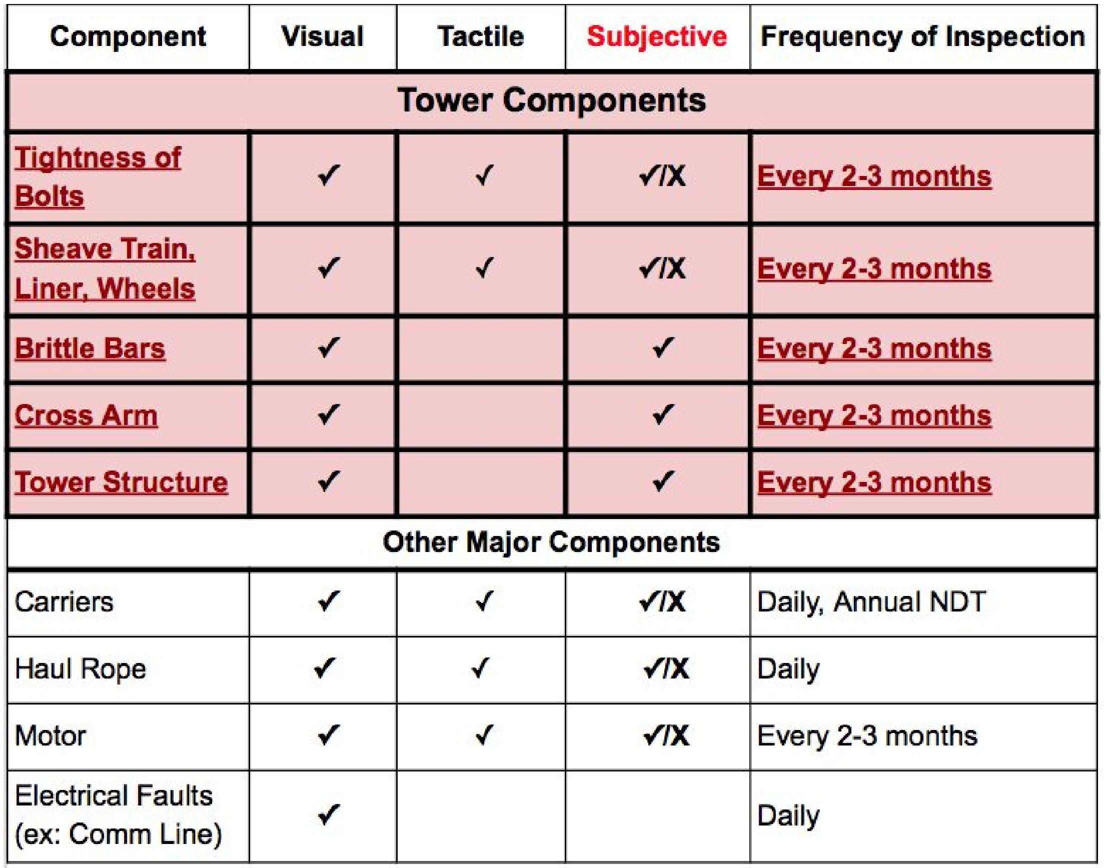
State inspection regulations reference ANSI B77 standards, and these conditions serve as the baseline for continuing ski lift inspections after the installation of the lift. ANSI B77 standards define that inspection schedules must be developed to ensure that "foundations and structural, mechanical, and electrical components, shall be inspected regularly and kept in a state of good repair" [15]. However, they seldom define what a state of good repair is. Inspection methods are also lightly defined in terms of tolerances.

1.5 Inspection Requirements, Frequency, and Methods

Ski resorts are required to follow state inspection requirements and those mandated by their insurance companies. This project is under the jurisdiction of Virginia state law, which requires a third-party inspection to be conducted once annually. In accordance with the law, Bryce Resort has a third-party state inspection once annually in accordance to ANSI B77 standards and is inspected twice annually by insurance. In addition to mandatory state and insurance inspections, Bryce resort also performs two in-house annual inspections, once prior to the summer season and once prior to the ski season. Additional inspections may be performed if there is cause for additional concern, such as a guest reporting noise. Other indications for failure are summarized in Table 4 in section 1.6.

In terms of inspection difficulty, 82% of the ski lift components listed below can be visually inspected without removing any shields. The communication line and the ski lift tower base require special inspection procedures. The comm line is held in a watertight enclosure that is checked every 3-5 years. However, electric faults in the comm line are indicated in the terminal's control system which is checked daily. The ski lift tower base is examined for cracks using X-ray imaging every 5-10 years at Bryce Resort and is more easily performed prior to snowy weather. Easier, non-visual checks include the physical inspection of components and connections such as tightness of bolts measured by torque, and inspection of abnormal sounds that may come from the tower's many moving parts. However, tower inspections themselves are difficult to perform due to the need to climb the tower often in snowy conditions.

The scope of the system's capabilities exclude components that can be inspected from fault indications or in the terminal, components that require the removal of covers, or tactile inspections. The red underlined components in the table below indicate which components are within scope for visual inspection. Gaps in system capabilities for the tactile inspection of these components can be performed during regular tower maintenance, such as greasing.



Component	Visual	Tactile	Subjective	Frequency of Inspection
Tower Components				
Tightness of Bolts	✓	✓	✓/X	Every 2-3 months
Sheave Train, Liner, Wheels	✓	✓	✓/X	Every 2-3 months
Brittle Bars	✓		✓	Every 2-3 months
Cross Arm	✓		✓	Every 2-3 months
Tower Structure	✓		✓	Every 2-3 months
Other Major Components				
Carriers	✓	✓	✓/X	Daily, Annual NDT
Haul Rope	✓	✓	✓/X	Daily
Motor	✓	✓	✓/X	Every 2-3 months
Electrical Faults (ex: Comm Line)	✓			Daily

Table 4: Visual versus Tactile Inspections

For comparison, the current inspection procedures for Bryce Resort and system capabilities are summarized in Table 5 below.

Components	Current Inspection Method	Required and Practiced Inspection Frequencies (inspecting party)	System Capabilities
Sheave Train	Climb up tower and check for misalignment or cracks visually; listen for noise	Annual (State), Biannual (Insurance), Offseason and Yearly (resort)	Substitute or increase visual inspections using enhanced imaging. -Substitute or increase audio inspections using enhanced imaging. -Use thermal imaging for detecting subsurface cracks not visible to the naked eye. -Record data to track wear over time and predict failures when degradation becomes worse.
Sheave Wheels/Liner	Climb up tower and check for misalignment, debris/ice, and liner wear visually; measure sheave liner groove depth	Annual (State), Biannual (Insurance), Offseason and Yearly (resort), Quarterly Lubrication Maintenance (resort)	
Brittle Bars	Climb up tower and check for debris/ice, corrosion; check for electrical fault in terminal	Annual (State), Biannual (Insurance), Offseason and Yearly (resort), daily operator's inspection (resort)	
Connections and Welds	Climb up tower and check for cracks visually; listen for noise; physically check tightness of bolts	Annual (State), Biannual (Insurance), Offseason and Yearly (resort)	
Cross Arm	Climb up tower and check for cracks, corrosion	Annual (State), Biannual (Insurance), Offseason and Yearly (resort)	
Ski Lift Tower Structure	Climb up tower and check for cracks or corrosion; check around base from the ground for corrosion and cracks visually	Off-season Inspection (resort)	

Table 5: Tower components, inspection procedure, frequency, and system capabilities

Due to the safety-critical structural support that ski lift towers provide and the frequency of component failures related to the tower, the tower is the most crucial part of ski lift inspections. The difficulty and risk associated with climbing the tower limit the frequency at which ski lift towers can be inspected. In general, there are five inspections performed annually for ski lift tower components, which have gaps of two to three months between them in which component failures can go unnoticed. The timeline for inspections can be found in Figure 6.

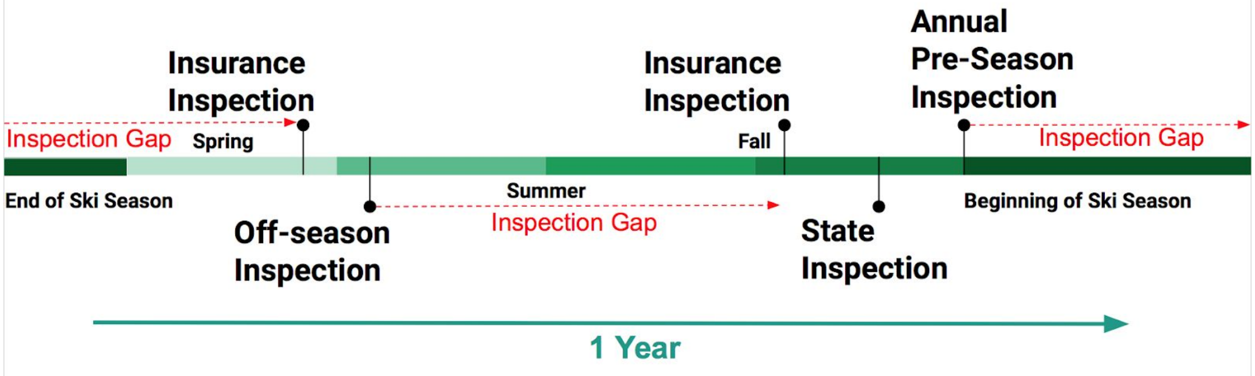


Figure 6: A yearly timeline for full-system inspections performed at Bryce Resort (tower inspections).

1.6 Failure Analysis

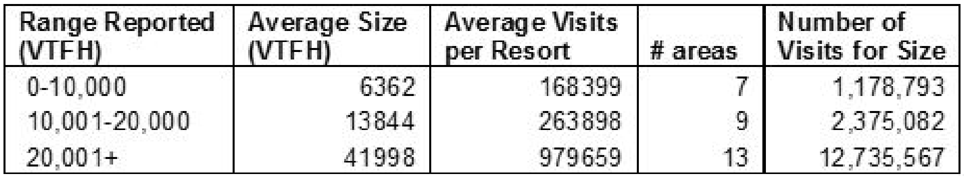
The purpose of inspections is to catch failures before they occur. Ski lifts have had 18 mechanical failures nationally resulting in accidents since 1972 [3]. There are four categories of failure type: deropement, rollback, detachment, and safety system failures. The types of incidents associated with ski lift tower components and their respective indications are described in Table 7.

Ski Lift Tower Component	**Failure**	**Incident**	**System Measurable Indications**
Sheave Train	Misalignment	Detachment Deropement	Misalignment, cracks, rattle
Sheave Wheels/Liner	Misalignment, Excess/Lack of Friction, Excess/Lack of Tension	Detachment Deropement	Misalignment, Debris/Ice, Wear of liner depth
Brittle Bars	Electrical Failure	Failure to Stop the Lift (during Deropement)	Corrosion, Debris/Ice
Connections and Welds	Collapse or Misalignment of Supporting Structures, Misalignment of Sheave Train	Deropement	Cracks, rattle, tightness/torque of bolts
Cross Arm	Collapse or Misalignment of Supporting Structures, Misalignment of Sheave Train	Deropement	Cracks, corrosion
Ski Lift Tower Foundation	Collapse or Misalignment of Supporting Structures, Misalignment of Sheave Train	Deropement	Cracks, Ground settling
Ski Lift Tower Structure	Collapse or Misalignment of Supporting Structures, Misalignment of Sheave Train	Deropement	Corrosion, cracks

Table 7: Failures and Indications

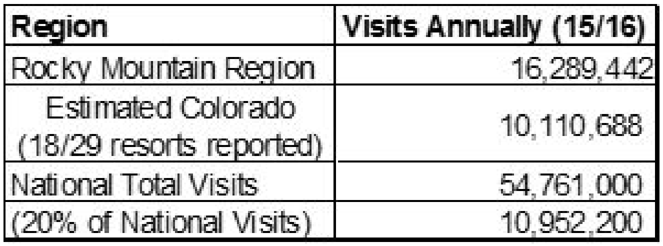
To analyze the level of how critical components are in terms of safety, each failure type was decomposed in the fault tree diagrams below with each bottom level component as a root cause. The fault trees in this section were based on failures reported to the Colorado Passenger Tramway Safety Board from 2000 to 2016 [25]. The probabilities for each root cause of failure were based on the Component Failure Report provided by the board. Probabilities were calculated based on the estimated number of annual visits for the entire state of Colorado. The number of visitors is reflective of the total system load or the number of passengers carried. The capacity of each lift is also reflective of the size of the lift, which determines the number of components.

The estimated number of annual visits to Colorado was computed both by scaling National data and by scaling the number of visits to the Rocky Mountain Region for comparison [22]. Table 8 below shows the three different categorizations of resort size for the Rocky Mountain Region as well as the average number of visitors reported per category from the 2015-2016 NSAA Economic Analysis Report Survey [1]. Based on the average number of visits reported per resort size category and the number of areas of that size, the total number of visits for the Rocky Mountain Region can be calculated. Of the reporting resorts, 18 out of the 29 resorts were from Colorado. The sum calculated for the Rocky Mountain Region survey from Table 9 was used to estimate the number of visits to Colorado resorts. The number of visitors was estimated by using a ratio of the reporting Colorado resorts to the total number of reporting resorts in the region. Compared to a common estimate that Colorado is responsible for 20% of all National visits, the sum of the surveyed resort sizes for the Rocky Mountain Region from 2015/16 is actually 18.5% of the overall national visits.



Range Reported (VTFH)	Average Size (VTFH)	Average Visits per Resort	# areas	Number of Visits for Size
0-10,000	6362	168399	7	1,178,793
10,001-20,000	13844	263898	9	2,375,082
20,001+	41998	979659	13	12,735,567

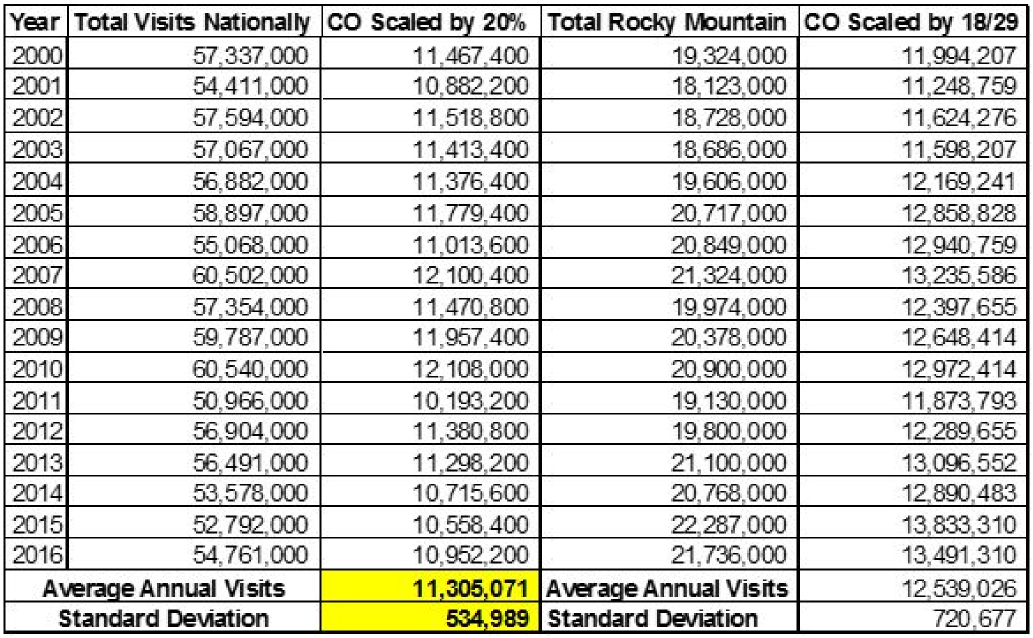
Table 8: Surveyed Average Visitors per Size for the Rocky Mountain Region[1]



Region	Visits Annually (15/16)
Rocky Mountain Region	16,289,442
Estimated Colorado (18/29 resorts reported)	10,110,688
National Total Visits	54,761,000
(20% of National Visits)	10,952,200

Table 9: Total Reported Visitors from Table 7 above Scaled to Estimate Colorado [1].

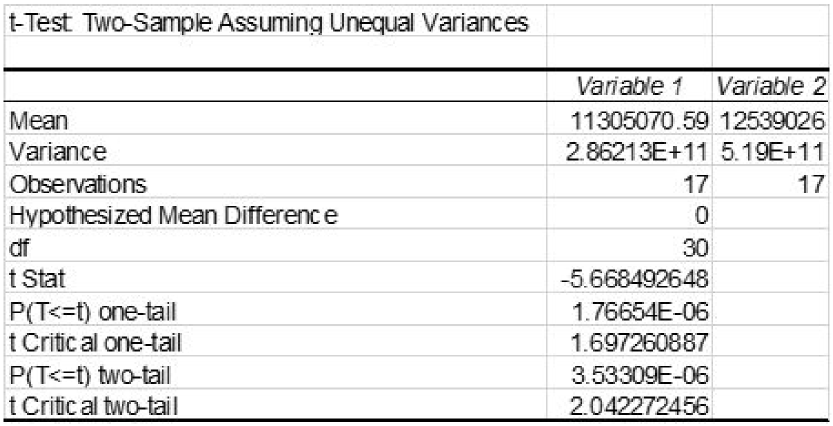
From the actual recorded national visits and visits for the Rocky Mountain Region, the averages were taken for both methods and compared. Due to annual variation, the average for the past 16 years of the 20% scaled estimate is actually 20.6% of the overall average of recorded national visits. By ratio, the scaled estimate is 22.8% of the overall average of recorded national visits. Table 10 below shows a year to year scale comparison.



Year	Total Visits Nationally	CO Scaled by 20%	Total Rocky Mountain	CO Scaled by 18/29
2000	57,337,000	11,467,400	19,324,000	11,994,207
2001	54,411,000	10,882,200	18,123,000	11,248,759
2002	57,594,000	11,518,800	18,728,000	11,624,276
2003	57,067,000	11,413,400	18,686,000	11,598,207
2004	56,882,000	11,376,400	19,606,000	12,169,241
2005	58,897,000	11,779,400	20,717,000	12,858,828
2006	55,068,000	11,013,600	20,849,000	12,940,759
2007	60,502,000	12,100,400	21,324,000	13,235,586
2008	57,354,000	11,470,800	19,974,000	12,397,655
2009	59,787,000	11,957,400	20,378,000	12,648,414
2010	60,540,000	12,108,000	20,900,000	12,972,414
2011	50,966,000	10,193,200	19,130,000	11,873,793
2012	56,904,000	11,380,800	19,800,000	12,289,655
2013	56,491,000	11,298,200	21,100,000	13,096,552
2014	53,578,000	10,715,600	20,768,000	12,890,483
2015	52,792,000	10,558,400	22,287,000	13,833,310
2016	54,761,000	10,952,200	21,736,000	13,491,310
Average Annual Visits		**11,305,071**	**Average Annual Visits**	12,539,026
Standard Deviation		**534,989**	**Standard Deviation**	720,677

Table 10: Total Visitors Recorded by the NSAA since 2000, scaled to Colorado [22].

A t-test was performed to compare the 20% scale and resort ratio scale to confirm that the difference between means is statistically significant (Table 11 below). Since the p-value is less than the confidence level of .05, these scales used to estimate the number of visitors are not equal. The 20% scale has a smaller variance and it provides the closest value to the surveyed visits for the Rocky Mountain region in Table 8. For the fault trees and simulation, the estimated number of visitors for the state of Colorado will be based on the 20% scale highlighted in Table 9 above.



t-Test: Two-Sample Assuming Unequal Variances		
	Variable 1	*Variable 2*
Mean	11305070.59	12539026
Variance	2.86213E+11	5.19E+11
Observations	17	17
Hypothesized Mean Difference	0	
df	30	
t Stat	-5.668492648	
P(T<=t) one-tail	1.76654E-06	
t Critical one-tail	1.697260887	
P(T<=t) two-tail	3.53309E-06	
t Critical two-tail	2.042272456	

Table 11: t-Test Comparison

Deropement failures are caused by excess or lack of friction between the haul rope and wheels, misalignment of sheave train, track rope system failures, bullwheel failures, and excess or lack of tension in the haul rope. Excess or lack of friction is caused by wear in the sheave liner, tensioning system, or too much/little lubrication. Misalignment of the sheave train is caused by wear in the bearings and axles, sheave wheels, connections and welds, and the sheave wheel liner. Excess or lack of tension can be caused by either tensioning or the collapse/misalignment of supporting structures. Collapse or misalignment of supporting structures can be caused by the cross arm, connections and welds, or the ski lift tower base, footing, or structure. Other supporting structures for the haul rope include a failure of the bullwheel. Bicable systems can also have deropement due to the track rope failing. A derailment of either rope can cause the other rope to also come off the tower.

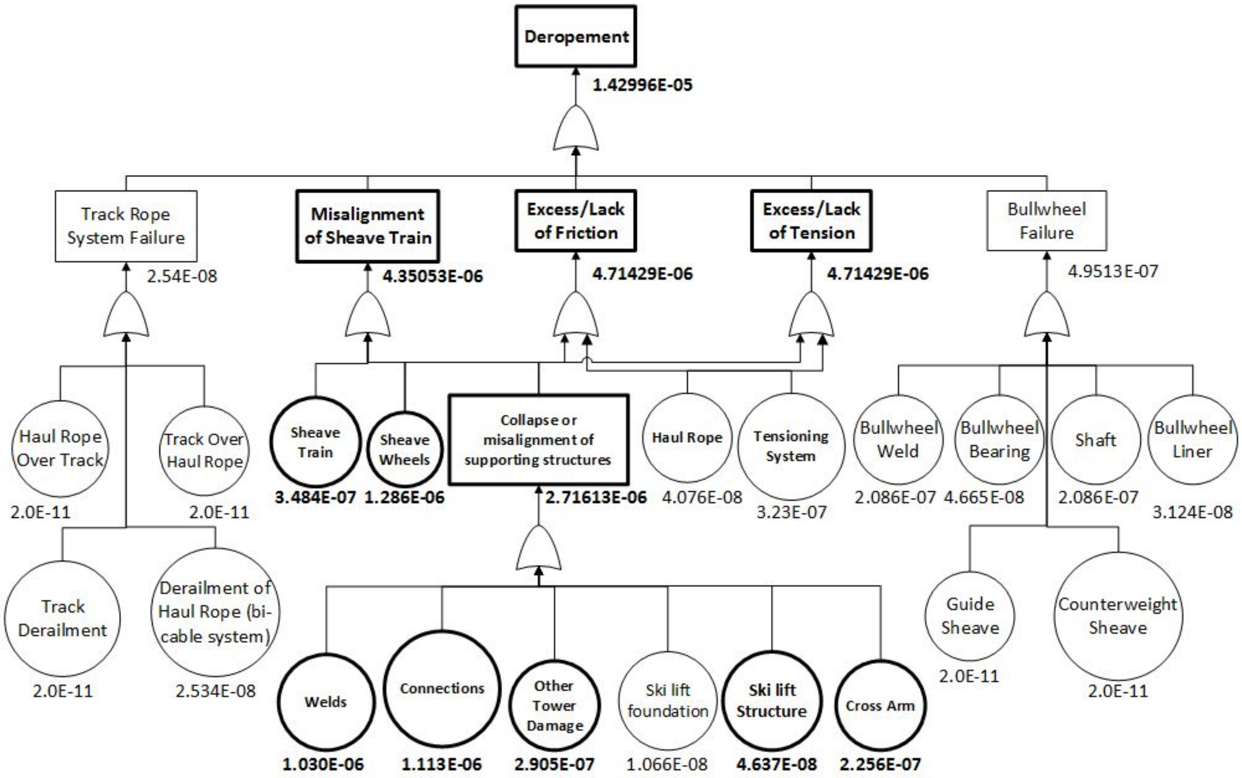


Figure 12: Deropement Fault Tree

Rollback failures are caused by loss of circuit connections, motor failures and brake failures as shown in Figure 13 below. Loss of circuit connections involve components such as the electrical circuit, brakes, and motor failure. Motor Failure involves components such as the gearbox, the prime mover drive, and auxiliary motor. Brake Failure involves components including the gearbox and the anti-rollback brake. Electrical failures can be caused by the low voltage control system or an incoming power failure.

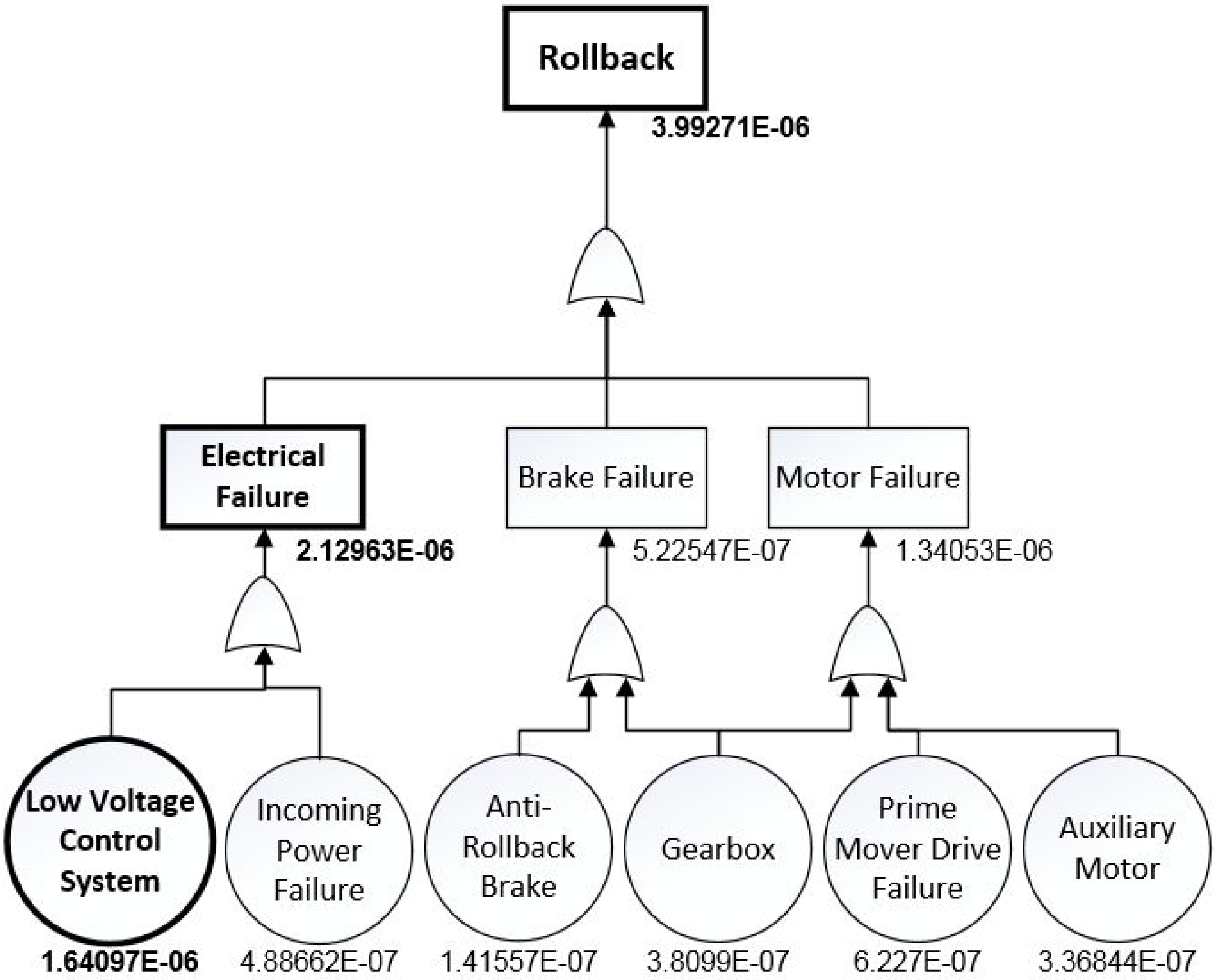


Figure 13: Rollback Fault Tree

Carrier detachment failures (Figure 14) can be caused by misalignment of the sheave train, track rope system failure, or carrier failure. Misalignment of the sheave train can be caused by sheave wheels, the sheave train assembly components such as the walking beam, or tower structural components. Carrier failure can be caused by grip failure, carriage/chair failure, the hanger assembly, or collisions. Collisions can be caused by a violation of clearances. Violation of ski lift tower clearances can be caused by wind, the haul rope, the tensioning system, or a secondary carrier failure. A separate carrier failure can cause two carriers to collide and detach.

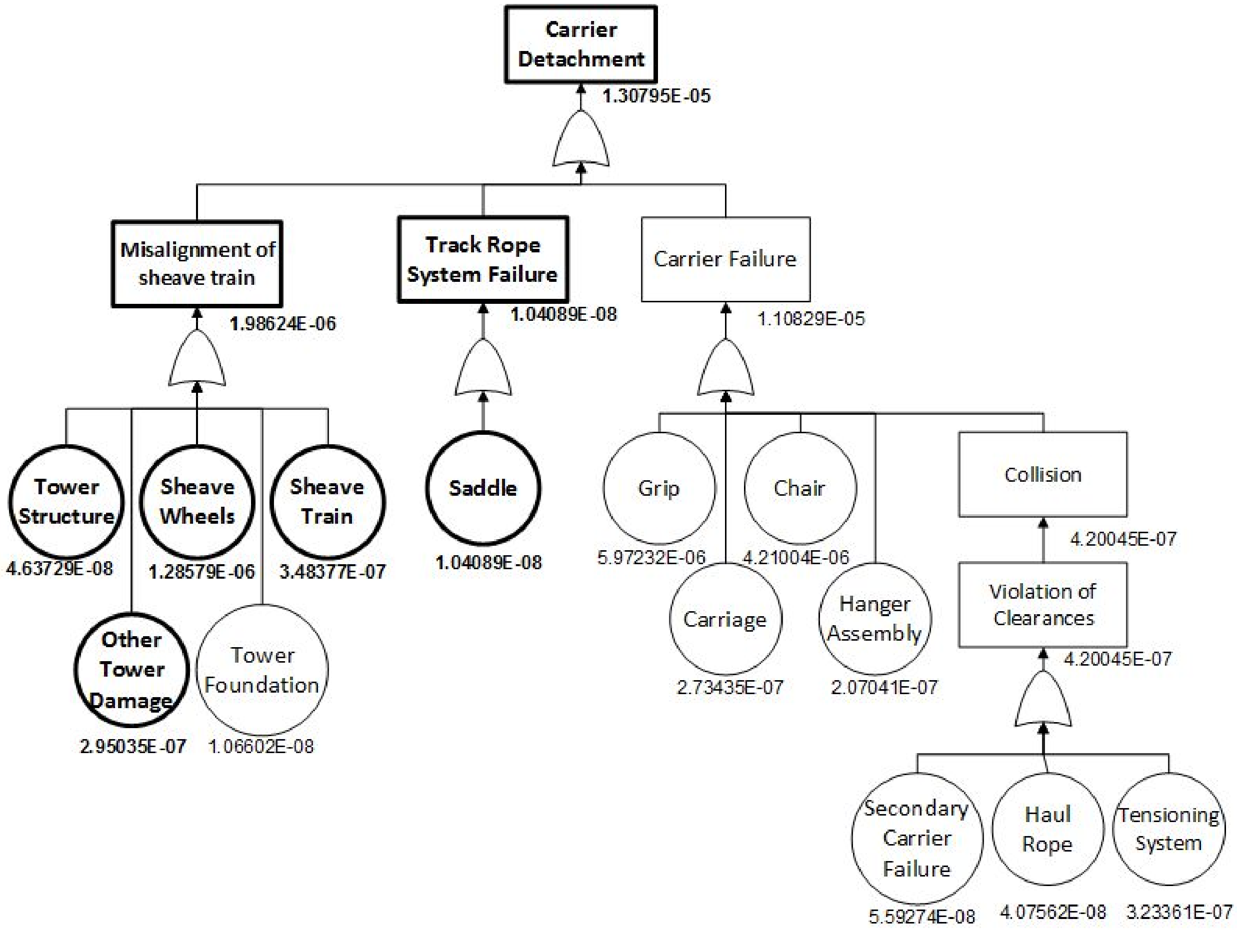


Figure 14: Detachment Fault Tree

Safety system failures result in the failure to stop a ski lift. Figure 15 further decomposes these failures. The failure to stop a ski lift is caused by emergency brake failure, service brake failure, rollback brake failure or electrical failures. Brake failures are a result of component failures such as the physical brake itself or a failure in the gearbox. The failure of manually triggered brakes such as the emergency or service brake can also be attributed to the user. Electrical failures can be attributed to the brittle bar or a failure in the low voltage control system that controls acceleration and deceleration of the lift.

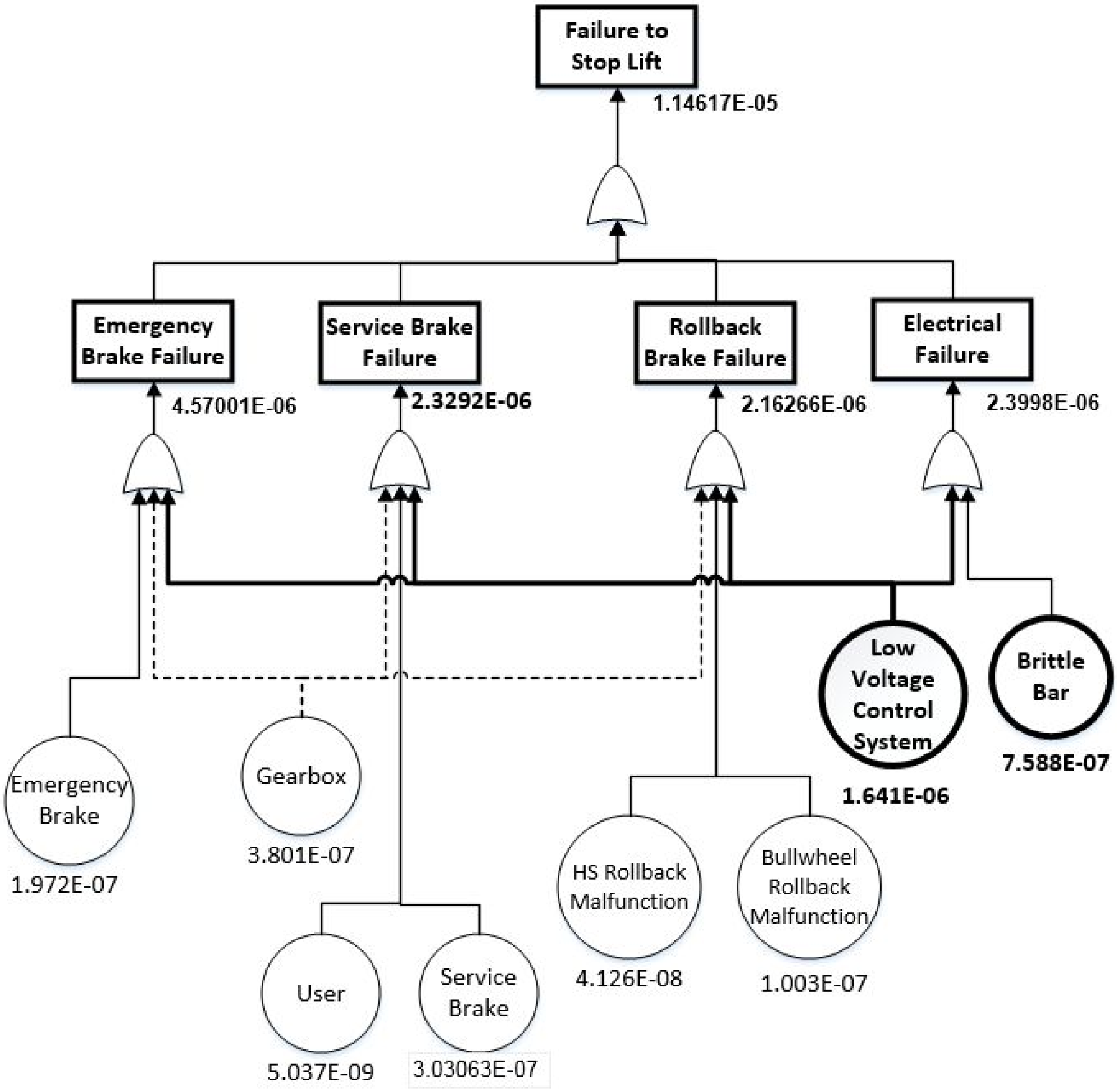
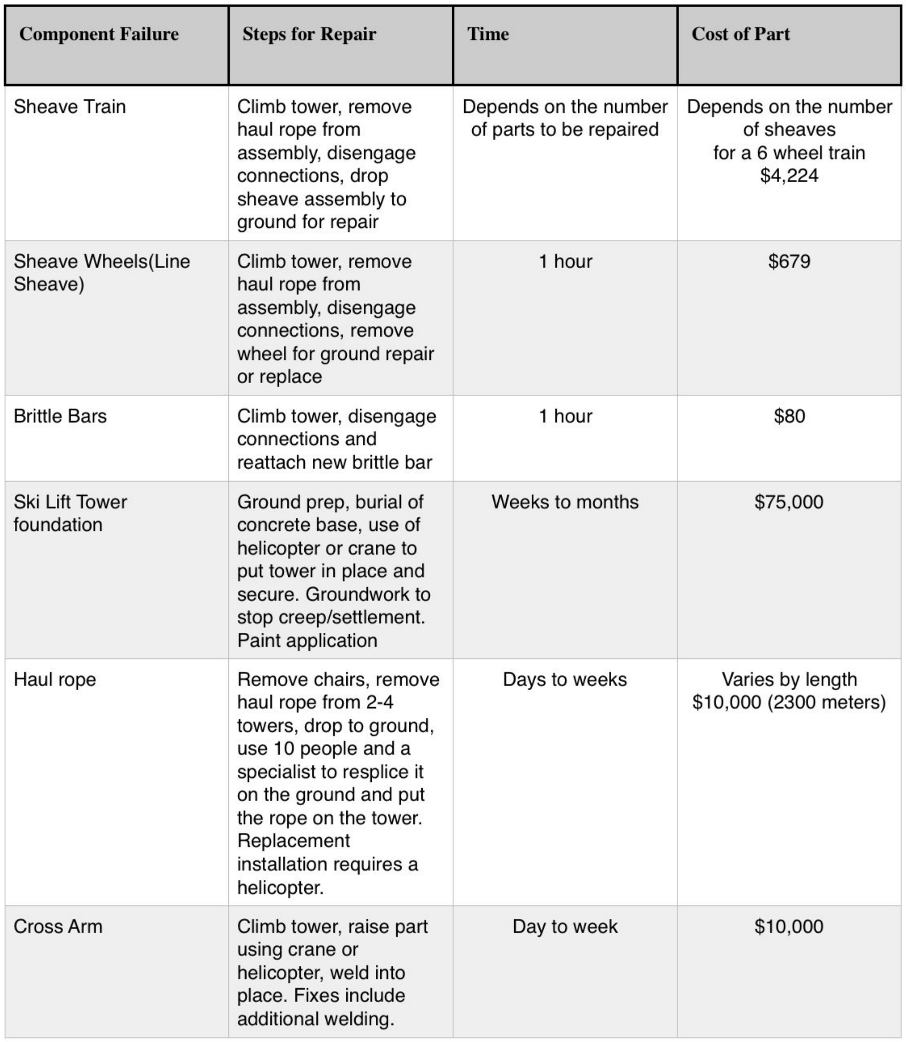


Figure 15: Failure to Stop Lift Fault Tree.

1.7 Economics of Ski Lift Maintenance

All component failures have a cost associated. Component failures prolong ski lift closures and increase costs due to the required re-inspection prior to reopening. On February 20, 2016, Vermont's Suicide Six Ski Area had an inspection following an accident at another resort serviced by the same manufacturer. During the inspection, cracks found in a crossarm resulted in a mandatory five day closure of the resort while all welding and a complete inspection could be performed [9]. In 2016, ski resorts in the Northeast averaged 2,323 daily visits with an average $89.89 of revenue per visit of [4]. Based on those figures, a 5 day closure costs $1,044,072 in revenue losses alone. Table 16 below summarizes repair procedures, time, and costs for ski lift tower components and components impacted by tower component failures.



Component Failure	Steps for Repair	Time	Cost of Part
Sheave Train	Climb tower, remove haul rope from assembly, disengage connections, drop sheave assembly to ground for repair	Depends on the number of parts to be repaired	Depends on the number of sheaves for a 6 wheel train $4,224
Sheave Wheels(Line Sheave)	Climb tower, remove haul rope from assembly, disengage connections, remove wheel for ground repair or replace	1 hour	$679
Brittle Bars	Climb tower, disengage connections and reattach new brittle bar	1 hour	$80
Ski Lift Tower foundation	Ground prep, burial of concrete base, use of helicopter or crane to put tower in place and secure. Groundwork to stop creep/settlement. Paint application	Weeks to months	$75,000
Haul rope	Remove chairs, remove haul rope from 2-4 towers, drop to ground, use 10 people and a specialist to resplice it on the ground and put the rope on the tower. Replacement installation requires a helicopter.	Days to weeks	Varies by length $10,000 (2300 meters)
Cross Arm	Climb tower, raise part using crane or helicopter, weld into place. Fixes include additional welding.	Day to week	$10,000

Table 16: Component repair procedure and cost [10].

The cost per component replacement and the annual number of component failures found from the Colorado Passenger Tramway Safety Board were used to calculate the total cost in Figure 17 below. Common failures require a greater number of part replacements which add up over the life of a lift. The cost of replacing certain components is comparable to buying a new lift. By comparison of failure frequency and individual repair cost, repairs to the foundation are the most costly over the life of a lift, followed by haul rope repairs, sheave train repairs, and repairs to the tower structure.

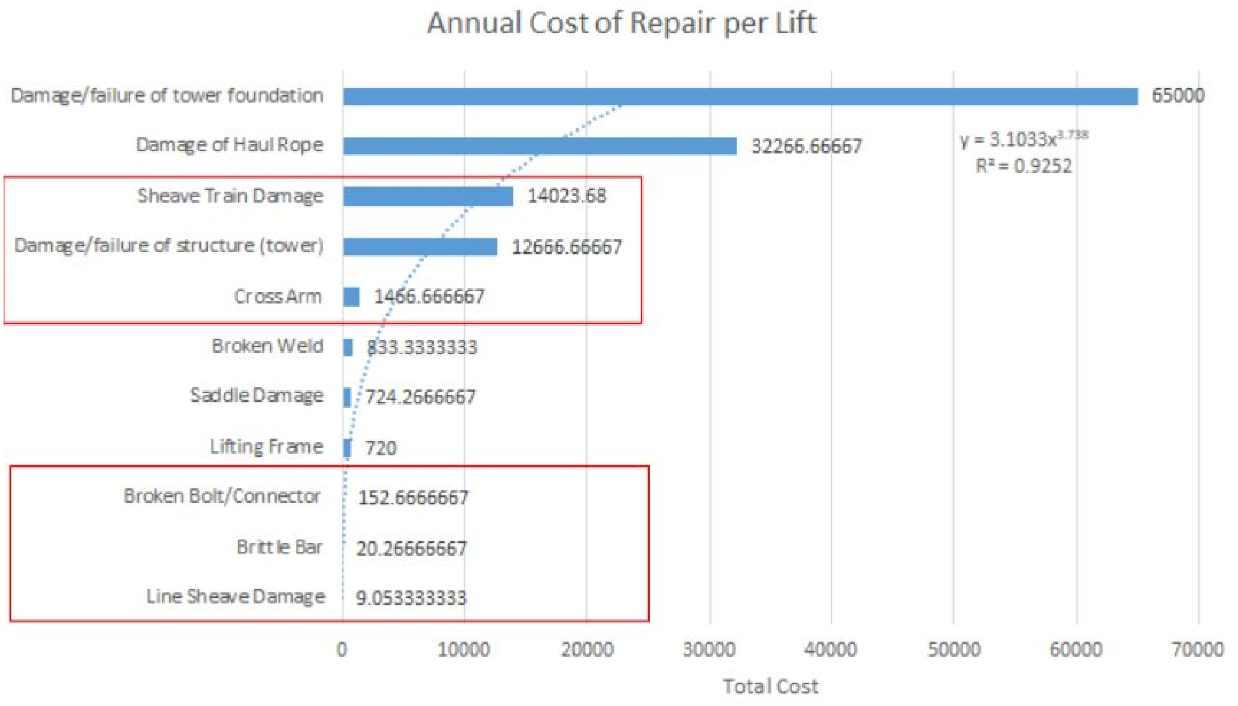


Figure 17: The Total Cost of Component Failures by Occurrence.

The replacement of parts over the life of a lift is a continuous process; Therefore, the age of a lift is not necessarily correlated to component failure. The age of the lift can be indicative of the number of components that have been replaced or need replacing, but trends for replacement are unique to every resort. Since 2000, the average lift age for a component failure in the state of Colorado was 18 years old. The average lower and upper quartiles from Figure 18 below indicate that 50% of component failures occur between 9 and 27 years of age. The mean line from Figure 18 is shown in Figure 19, which indicates a slight increase in the average age for a failure since 2000.

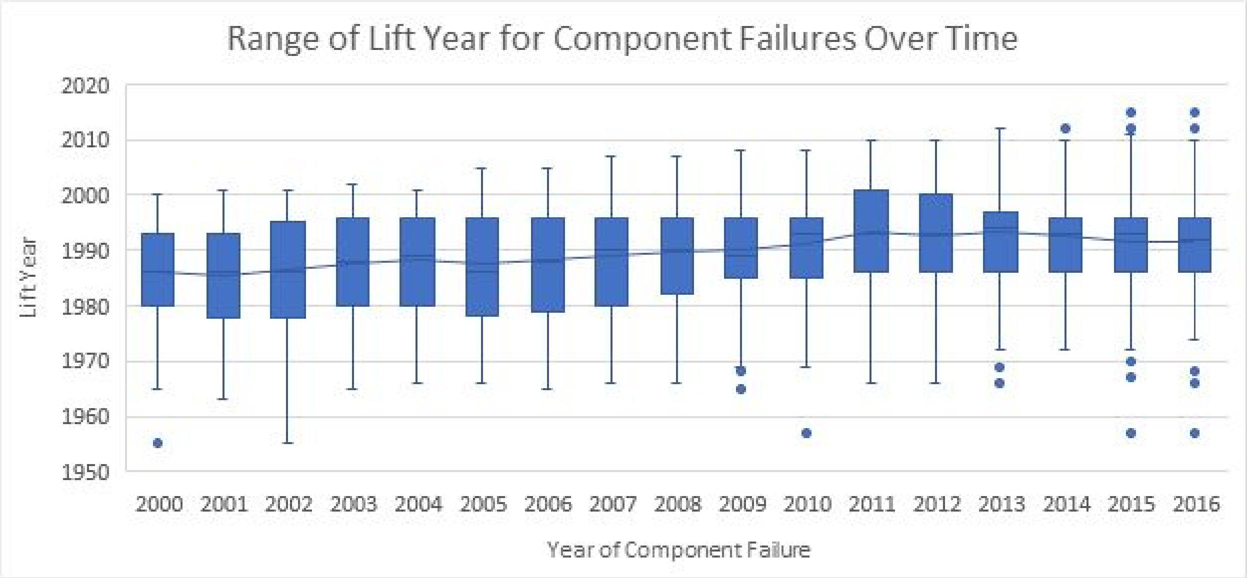


Figure 18: Component Failure by Lift Year Over Time

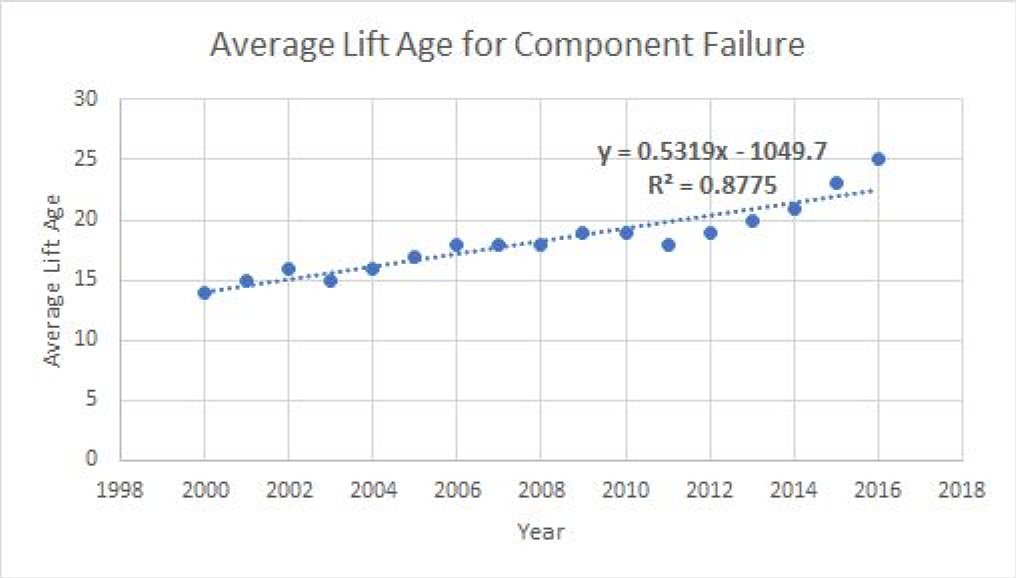


Figure 19: Average Lift Year for a Component Failure Over Time

1.8 Accident/Incident Statistics

1.8.1 Passenger Statistics

During the 2015/16 US ski season, there was a total of 52.8 million skier visits resulting in 19.8 billion passenger miles [3]. Since 1972, there have been a total of 19 accidents involving ski lift malfunctions resulting in passenger injuries and fatalities in the United States. Of the 19 incidents, 6 resulted in fatalities (with the last reported death occurring in 2016) [3]. The overall lift fatality rate is 0.418/yr equating to 0.211 fatalities per 100 million miles transported by ski lifts. Accidents not involving ski lift mechanical failures (i.e. passengers falling) are not included in this analysis.

The severity of accidents is measured by the number of fatalities and injuries by each cause. Deropements are the most common and the most fatal type of accident. A summary of accident severities can be found in Figure 21 below.

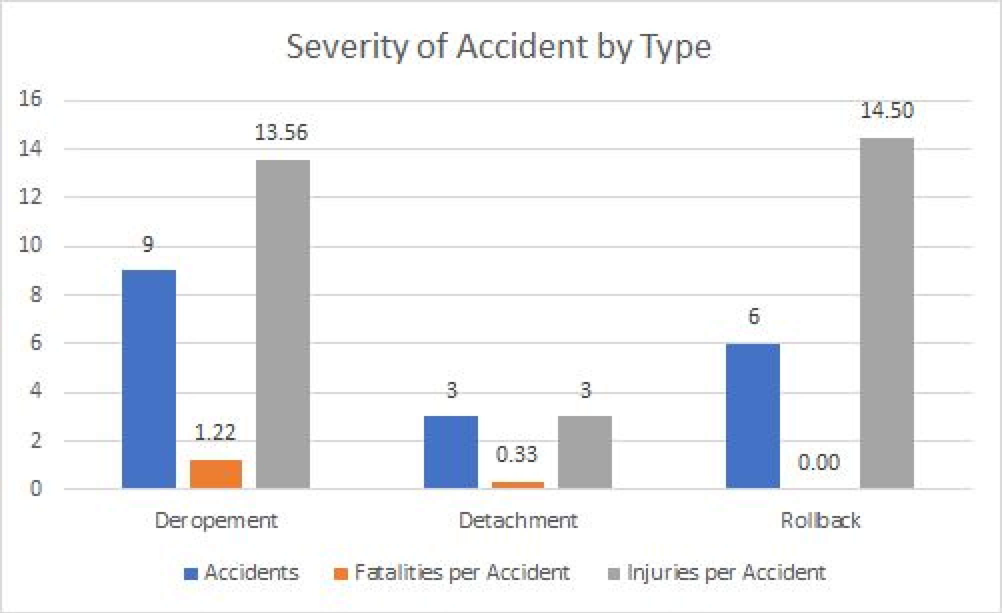


Figure 21: Severity of Accidents by Cause, based on average injuries and fatalities.

The number of accidents over the past 43 years has fluctuated but injuries and fatalities are significantly lower now compared to the 1970s and 1980s [3]. The number of accidents, fatalities, and injuries over time is shown in Figure 22. Before a fatal accident in late 2016, the last reported fatality occurred in 1993. During the 23 year period of no fatalities, there were 46 injuries across 6 accidents relating to ski lift malfunctions.

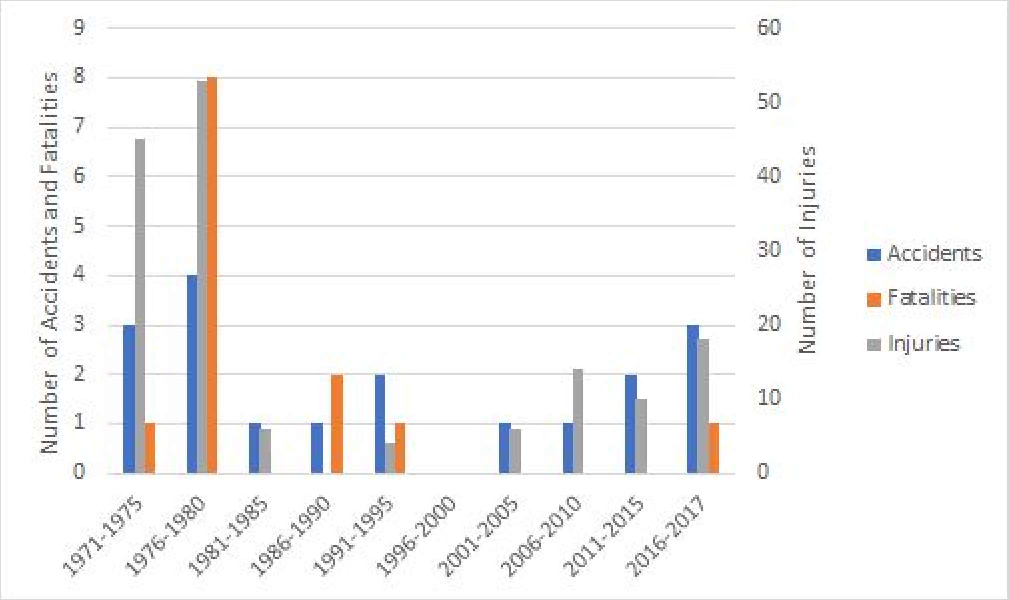
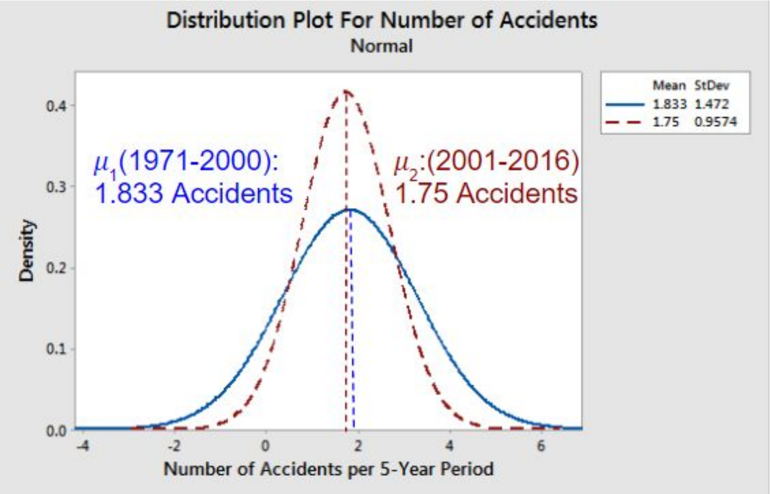
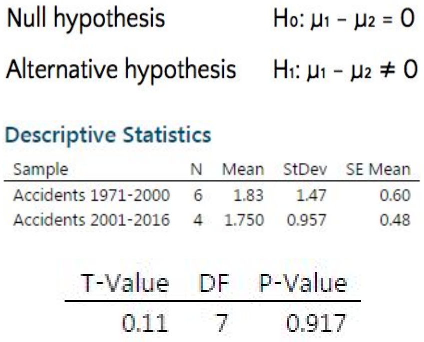


Figure 22: Frequency of Accidents, Fatalities, and Injuries by Year

Although the period 2001-2017 appears to have a lower average number of accidents and injuries than 1971-2000, the t-test shown in Figure 23 indicates that the difference in the means is not statistically significant. The number of fatalities has decreased, but the rate of accidents has not decreased. Considering accidents are random events and accident severity is not easily controlled, the overall safety for ski lift systems has not improved.





Null hypothesis H₀: μ₁ - μ₂ = 0

Alternative hypothesis H₁: μ₁ - μ₂ ≠ 0

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Accidents 1971-2000	6	1.83	1.47	0.60
Accidents 2001-2016	4	1.750	0.957	0.48

T-Value	DF	P-Value
0.11	7	0.917

Figure 23: A Comparison of Accident Distributions for 1971-2000 and 2001-2016.

1.8.2 Occupational Statistics

According to the National Safety Council (NSC), one of the top ten causes of serious workplace injuries is falls to a lower level (second leading in unintentional fatal events and the fifth leading event in days away from work). Maintenance personnel use ladders to reach ski lift tower tops. Of the varying falls to a lower level, 33% occur on ladders resulting in days away from work [11]. The Bureau of Labor Statistics (BLS) tracks data on the number of nonfatal occupational injuries and illnesses for skiing facilities in the US. Although the data does not specifically state how many incidents are directly related to maintenance and inspections of ski lift towers, it provides a general idea of the amount of risk that maintenance personnel experience. Figure 24 below shows the number of workplace incidents per year from 2006-2015. It should be noted that not all incidents are related to ski lift towers and not all falls are related to maintenance personnel. However, a t-test shows that installation, maintenance and repair personnel have a higher rate of injury than other ski resort employees for falls including ladder related incidents.

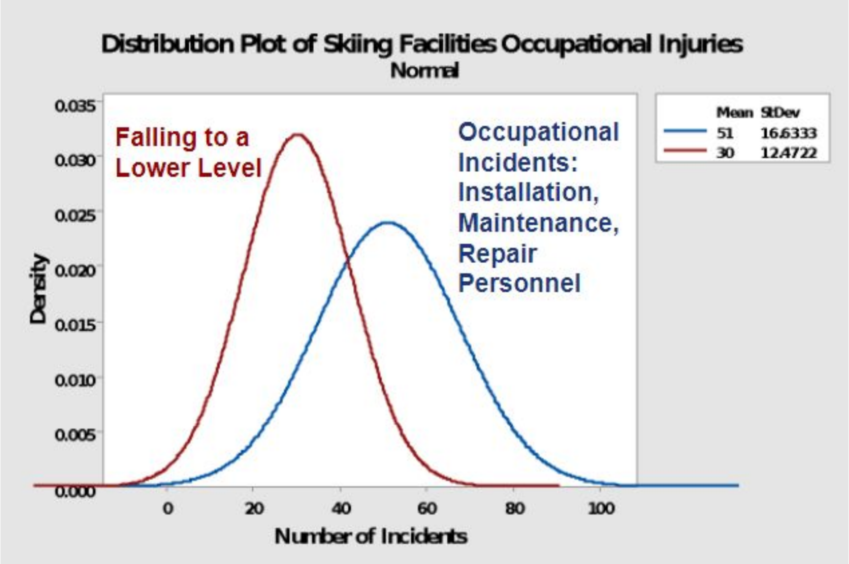


Figure 24: Number of non-fatal skiing facility occupational injuries in the US [23]

1.8.3 Reliability

As discussed in section 1.8.1, the severity of incidents involving mechanical ski lift failures has declined since the 1970's. According to the Colorado Tramway Safety Board, from 2001-2012, only 2% of the 227 non-fatal chairlift incidents in Colorado were caused by mechanical failure [12]. However, several mechanical failures have occurred in recent years, in part due to age of the ski lifts [13]. In early 2016, an accident took place in the Timberline Four Seasons Resort in West Virginia after a failure in the cross arm caused the haul rope to slip free sending 25 people to plummet 30 feet to the ground. The lift was installed in 1985 [14]. Within days after the West Virginia incident, Vermont's Suicide Six Ski Area closed down a 40-year old lift when cracks were discovered on the towers where the towers meet the crossarm [14].

Visitor statistics are gathered and calculated by the NSAA. To calculate statistics and rates, the NSAA made the following assumptions:

1. For each skier visit, the average rate is 7.5 rides per visit.
2. The average lift ride is 0.5 miles long in distance traveled.

To analyze the severity of accidents, several lists were compiled and cross-verified between the NSAA's reports and Illicit Snowboarding's compilation of newspaper articles. Between 1972 to 2016, there have been 19 recorded accidents involving mechanical failure which resulted in 13 fatalities and 220 injuries. The NSAA estimates 16.7 billion ski lift rides since 1972 (43 years) based on their conservative assumptions of data trends tracked since 1978. The probability of an accident, death, or injury occurring per ride is summarized in Table 26 below. Due to these specific accidents' causes, the probability of an accident occurring per ride is equivalent to the probability of a catastrophic mechanical failure per ride.

Event	Total number of events since 1972	Average number of events per ride	Average number of events per year
Accidents	19	1.1377×10^{-9}	0.4419
Deaths	13	7.7844×10^{-10}	0.3023
Injuries	220	1.3174×10^{-8}	5.1163

Table 26: Average Accident, Death, and Injury per ride and per year.

For comparison to other modes of transportation, the NSAA estimates an average of .5 miles traveled per ski lift ride, which equates to 8.35 billion miles transported since 1972. The comparison between ski lifts, elevators, and automobiles for the number of deaths per 100 million miles transported shows that a person is five times more likely to die in an elevator than a ski lift and eight times more likely to die in an automobile than a ski lift. However, a passenger is more likely to be injured on a ski lift than to die in an automobile per 100 million miles transported, as shown in Table 27.

Event	Passenger Miles Transported Annually (2015/2016 for US ski lifts)	Average Number of Events per mile transported	Number Events per 100 million miles transported
Accident - Ski Lifts	198,000,000	2.2316×10^{-9}	0.2232
Injury - Ski Lifts	198,000,000	2.5840×10^{-8}	2.5840
Ski Lifts - Death	198,000,000	1.5269×10^{-9}	0.1527
Elevators - Death	1,360,000,000	7.4×10^{-9}	0.74
Automobiles - Death	3,041,000,000,000	1.16×10^{-8}	1.16

Table 27: Occurrences per 100 million miles transported [3].

1.9 Economics of Increased Inspections

One solution for mitigating the risk associated with component failure is to increase the frequency of inspection, which increases the probability that a failure would be detected. Although the cost may increase for inspections, the potential savings for increased inspection frequency are exponential. The article “Aging Lifts: The cost & collateral damage of deferred maintenance” in the NSAA Journal (Spring 2017 Edition) mentions the consequences of deferred maintenance. According to David Todd Geaslin, many executives are aware of the positive correlation between continuing to operate equipment that needs repair and the cost to fix it [16]. His theory of the “Inverse Square Rule of Deferred Maintenance” says that “if a part is known to be failing and the repair is deferred and allowed to remain in service until the next level of failure, the resultant expense will be the square of the cost of the failed part” [16].

For example, consider keeping an $84 worn-out sheave liner in service. The cost goes up from $84 to the square of $84 and becomes $7056 due to the following sequence of events: unlined metal sheaves damage the cable while ruining the value of the sheave train. Damage to the cable causes it to wear prematurely requiring an additional inspection for the haul rope. Steps are taken to inspect the haul rope in order to prevent or repair a cable splice. All these steps incur labor cost. However, if the sheave liner problem causes a serious injury, the cost can square again to an upward of $50 million and any potential incident could ruin the resort's reputation [16]. One increment of increased inspection will save an amount equivalent to the square root of current replacement costs. Increased inspections also save the immeasurable cost of losing a human life.

2.0 Stakeholder Analysis

Primary stakeholders are: Ski Resorts, Maintenance and Inspection Personnel, and Visitors. Ski resorts profit driven and own ski lifts so they take the brunt of the costs for maintenance and repair. They are also accountable for safety and reliability of the ski lifts. However, maintenance and inspection personnel are directly responsible for the safety of the lift. A new system would cost the resorts money and it would impact the maintenance budget of the personnel. Visitors are the main source of revenue for ski resorts and experience the most risk when using ski lift systems. The price of visitor tickets is also dependent on resort expenditures, which has a direct impact on their revenue and capability to price competitively. Other stakeholders include parts manufacturers, insurance companies and the NSAA who works with regulators, such as the ANSI and USFS. Overall, tensions between stakeholders are due to cost and risk and nothing would prevent a full implementation of a new inspection system as everyone benefits from improved safety and decreased costs.

Ski Resorts

Ski resorts are the primary stakeholders for this project. Ski resorts need to ensure that the ski lifts meet ANSI safety standards as well as individual state requirements for operation and insurance requirements. Bryce Ski Resort in Virginia is the case study for this project. Their operational procedure and lift specifications will be the basis of the simulation design. Their objective is to maintain safety, minimize cost, and maximize profitability of their operations. A tension exists between ski resorts and inspection personnel due to the potential for increased costs and the risk for maintenance personnel performing their duties.

Maintenance and Inspection Personnel

Maintenance personnel are also primary stakeholders and are responsible for the inspection, maintenance and repair procedures of ski lifts. They are the end-users of this project who will ultimately use the system. This group of stakeholders also includes the third party inspectors, such as state inspectors and insurance inspectors, that experience similar risks and have the same objectives. Their objective is to minimize risk and provide safety to personnel and visitors regardless of the cost, which causes a tension with ski resort owners looking to profit.

Bryce Resort personnel currently inspect ski lift towers once before the start of every ski season and once prior to the summer season. As part of their objective for minimizing risk, there has been an expressed desire by Bryce Resort employees to increase ski lift tower inspections as often as once daily.

Visitors

The objective of ski resort visitors is to use amenities at an affordable rate and safe transportation up slopes. Visitors are prone to the risks involved in using ski resort amenities, facilities, and attractions. A tension exists between visitors and ski resorts over liability for safety and increasing prices.

Parts Manufacturers

Parts manufacturers are responsible for supplying reliable systems as well as replacement parts for the duration of the ski lift system's life. They are also responsible for supplying maintenance and inspection recommendations for every individual ski lift installation, as is required by ANSI B77 Standards. Their objective is to sell ski resorts a reliable system and provide new parts. Tensions exist to maintain a reasonable cost while making a profit as well as following all required regulations.

Regulators

American National Standards Institute (ANSI) is an organization that provides standards and enforces compliance for various systems in the United States. ANSI's objective is to ensure that ski resorts conform to their standards in order to maintain safety for visitors. A tension exists between regulators and ski resorts due to the complexity and cost of maintenance.

The Federal Aviation Administration (FAA) regulates and permits the use of unmanned aerial vehicles (UAV), also known as drones. Under 14 CFR Part 107, the FAA requires drone pilots to be certified for commercial operations where "commercial" means any kind of flight operation that can be tied to economic benefits [17]. Therefore, ski resort drone operators are required to obtain a waiver and/or a Part 107 drone certification. Official FAA records show Bryce Resort owns Sky Bryce--a daylight operations only, VFR only, privately owned airport. Their objective is to enforce aviation safety. A tension exists for resorts that wish to use drones on their property.

The US Forest Service regulates and provides permits for ski resorts that operate on US Forest Lands. Ski resorts on US Forest Lands must comply with their additional requirements for inspection. The US Forest Service currently bars the use of drones on US Forest Lands regardless of the existing FAA allowances. Their objective is to regulate ski lift operations with respect to safety of people and land protections. A tension exists for resorts that wish to use drones on their property.

NSAA

The National Ski Areas Association is a trade association that represents the ski industry in the United States. It ensures industry growth and provides necessary promotion by hosting conferences, trade shows and bi monthly publications. The

NSAA also provides training, manuals, and ensures that the industry complies with regulations [18]. Their objective is to provide information about the industry to promote economic growth. A tension exists between the NSAA, regulators, and visitors to provide accurate information on the safety of ski lifts.

Insurance Companies

Insurance Companies provide protections for ski resorts if an incident were to occur. Insurance can involve the ski resort, employees and workers compensation, as well as the ski lift itself. Their objective is to ensure compliance with ANSI B77 standards by requiring their own independent inspections. Another objective is to charge for insurance with respect to the amount of risk. A tension exists between ski resorts and insurance companies to keep costs low while providing the same coverage.

Other

The other stakeholders in the system include the local businesses, local governments, parts manufacturers/suppliers and insurance companies. A new inspection system would be beneficial to these stakeholders. Increased visitors benefit local businesses and governments due to increased sales and taxes. The main benefits of the system are financial, maintaining reduced costs, and maximizing returns on investments (ROI).

Stakeholder	Objectives	Tensions	Notes
Ski Resorts	- profit from ticket sales - optimize ski lift performance -ensure ski lift safety to visitors	- with maintenance personnel: risk, increased cost - with regulators: cost of regulation compliance, increased cost of maintenance	Primary Stakeholder
Maintenance & Inspection Personnel	Earn income Work in safe environment	- with ski resort: hazardous working environment, job involves risk	Primary Stakeholder
Visitors	Use ski resort amenities for leisure	- with ski resorts: safety concerns about ski lift usage	Primary Stakeholder
Parts Manufacturers	profit from ski lift owners	-with ski resorts: to keep costs low over the life of lifts -with regulators: follow all regulations	Primary Stakeholder
Regulators	provide standards and regulations to ensure safety	- with ski resorts: rigid and complex regulations could increase costs for ski resorts	- ANSI - FAA - USFS
NSAA	represent and ensure continued growth in skiing industry	-with visitors and regulators: Providing accurate information on the safety of ski lifts while protecting industry interests.	
Insurance Companies	profit from premiums in exchange for benefits to ski resorts	-with ski resorts: to keep costs low and provide adequate coverage	
Local Government	collect taxes from local ski resorts and businesses	with ski resorts	
Local Businesses	profit from economy created by the influx of customers in the area visiting ski resorts	with local government	local economy grows as ski resorts expand into the summer months

Table 28: Stakeholders Objectives and Tension Table

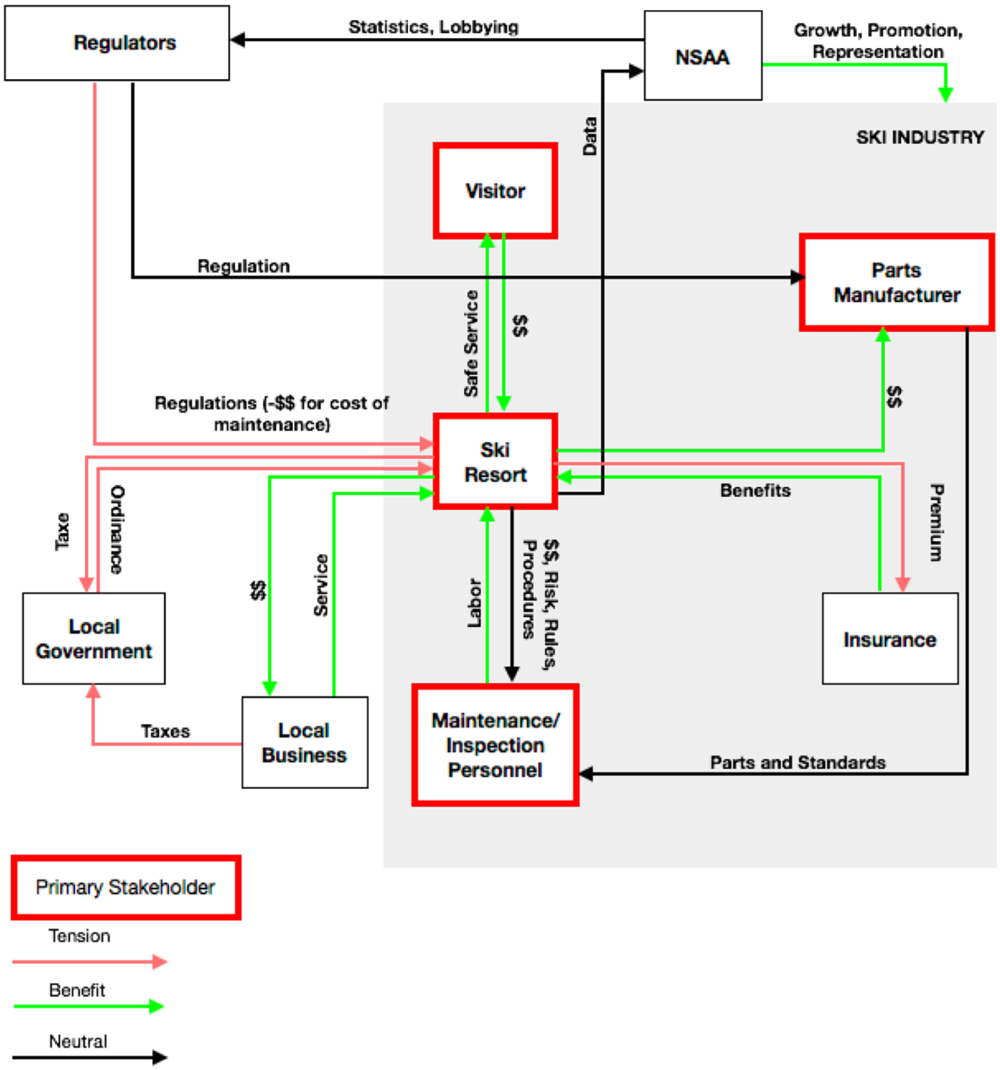


Figure 29: Stakeholder Tensions and Interactions Diagram

3.0 Gap Analysis and Problem Statement

3.1 Gap Analysis

Ski lift towers play a vital role in ski resort operations. It takes an average of $423,500 to inspect a ski lift tower. Global temperatures have been rising at a rate of 0.35℉ per decade for the last 4 decades. Due to climate change, Virginia has seen a 6 day reduction in the average ski season length (105 days in 2014-15 to 99 days in 2015-16), a 4.9% decrease. The shortening of ski season length has negatively impacted ski resort operations resulting in a 30% decrease in visits and 6.3% decrease in revenue between the 2014-15 to 2015-16 ski seasons. In response to shorter ski seasons, ski resorts in the southeast region have added an average of 130 days for summer operations (Figure 30) by utilizing their ski lifts for summer activities such as mountain biking and zip lining. The percentage of total revenue for summer operations has increased by 2.8% in the last 10 years. However, the number of inspections have remained the same. The current number of manual ski lift tower inspections is 5 inspections per year.

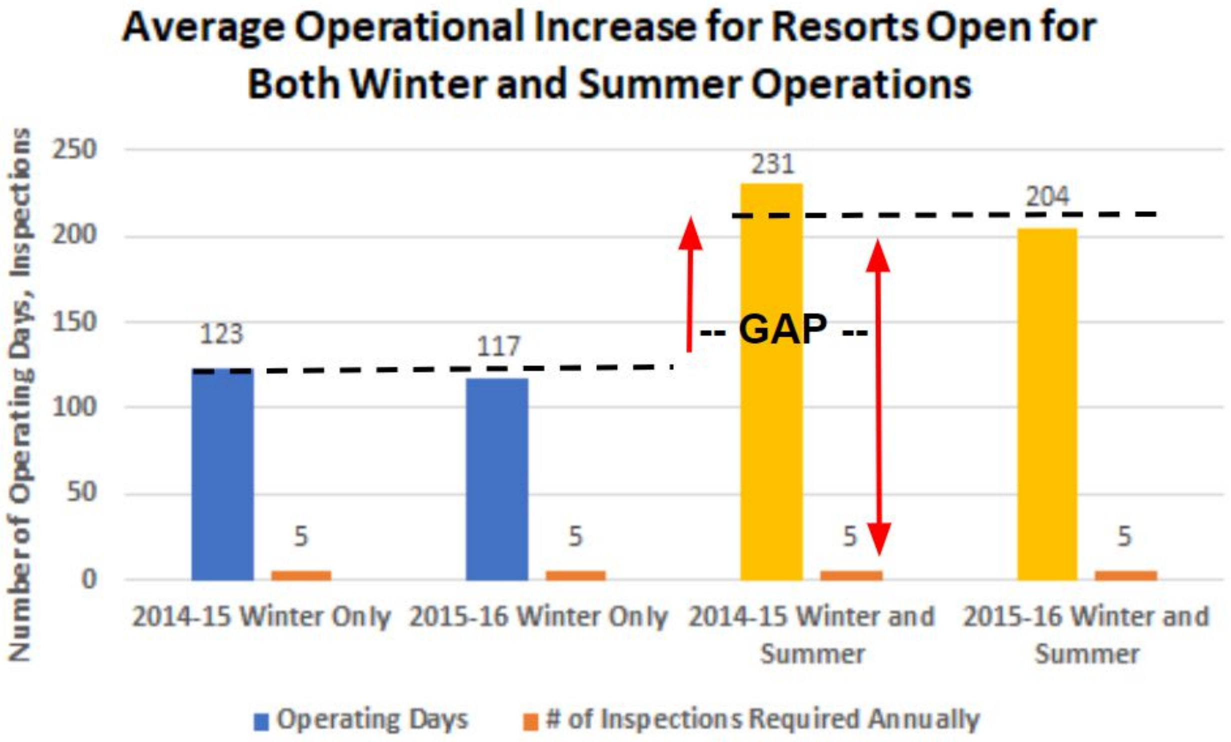


Figure 30: Gap between the increase in ski resort operating days to include summer operations and the number of inspections required annually [1].

3.2 Problem Statement

Climate change has shortened the ski season for ski resorts across the United States, leading them to expand their operations into the summer for sports such as mountain biking. Despite nearly doubling their lift operating days nationally from 117 to 204 days on average and subjecting lifts to a wider range of temperatures, the number of inspections has remained constant due to the danger of climbing lift towers and limited maintenance budgets (National Ski Areas Association). The inspection schedule at Bryce Resort in Virginia, the case study for this analysis, leaves gaps of two to three months between its five annual inspections in which failures can go unnoticed and cause an accident. However, more frequent inspections would increase the risk for inspectors. The current inspection method is also primarily visual and vulnerable to inaccurate subjective human judgement, as there are no numerical thresholds for component failures nor tools for consistent data collection or archiving.

4.0 Need Statement

The growing demand on ski lifts has created a need for more frequent inspections to decrease the probability that component failures will remain undetected. However, an increase in inspection frequency would increase the risk for inspectors. Therefore, there is a need for a safer, more cost-effective alternative method to inspect ski lift towers to reduce workplace incidents by 20%. An alternative method of inspection can also provide consistency of measurements, manage inspection data for easier access, and develop numerical thresholds for preventative maintenance.

5.0 Concept of Operations

General Concept of Operation for the Current Method

The current maintenance strategy is a combination of running components to failure with minimally scheduled preventive maintenance [19]. Preventive maintenance is usually set by time, usage, or hours of operation with the intention of identifying parts that are degrading. The degradation of ski lift components is impacted by the hours of operation and ski season length, load factor and the number of visitors, weather (temperature and precipitation), and frequency of parts replacement or inspection. Due to the interoperability of ski lift components, a worn part or misalignment can cause wear or failure in other parts. Outside of regularly performed maintenance (i.e. greasing and tightening of bolts), inspections serve as a precursor for the maintenance of ski lift tower components as they identify needing repairs.

Current inspections are primarily visual and stored on paper logs. Paper logs do not provide any method of data tracking and analysis. There are few numeric thresholds for component failures and inspections heavily rely on personal experience which can be subjective. Personnel must climb the lift towers and record information after the completion of the inspection which is both dangerous and inaccurate. During the time between the inspection and when the information is recorded on paper, inspectors can forget important details or measurements. The concept of operations for the overall process of inspection is summarized in Figure 31.

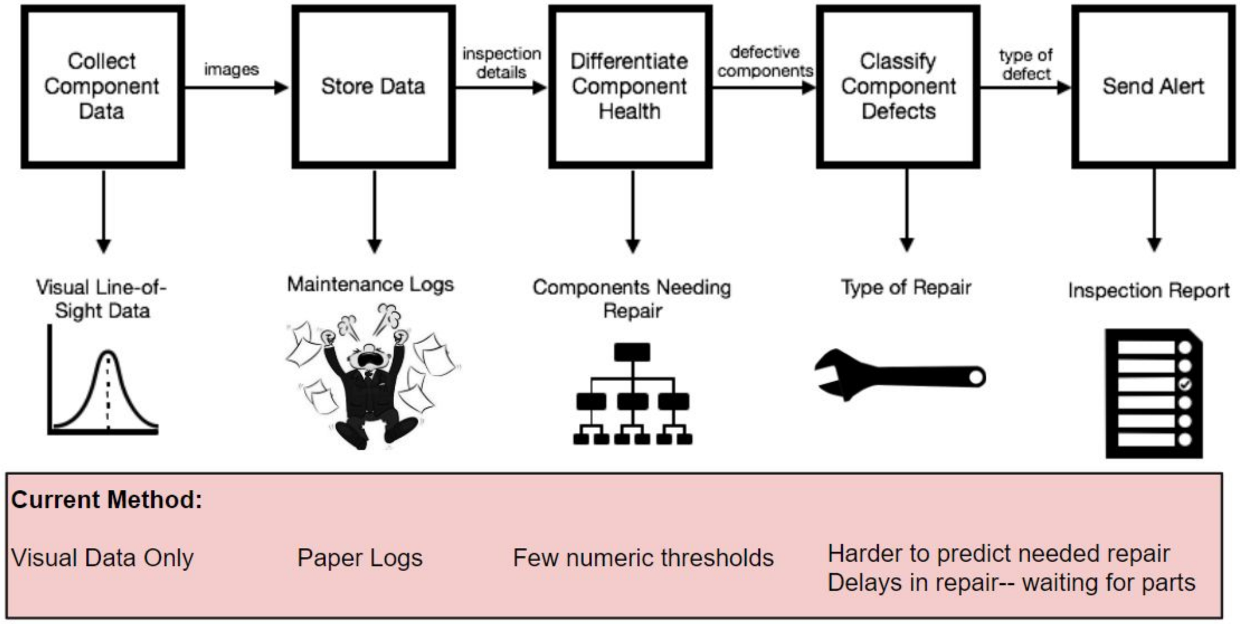


Figure 31: CONOPS for the Current Inspection Process

Proposed Concept of Operations

To obtain a safe system and minimize the probability of failure, gaps in operation can be filled with a new system to increase frequency of inspections, begin preventative maintenance, and identify when the lift should be inspected through predictive analytics.

A ski lift inspection system would apply visual and thermal technology integrated with an automated image processing software to identify defects and indications for failure. The inspection system can be equipped with lights to improve visibility for image processing. The system would replace the human eye with thermal and HD cameras for visual data collection, replace paper with a cloud-based data management system, and replace subjective component health differentiation with image processing. Images and videos can be stored on the cloud for data analysis and archiving. Through consistent data collection and analysis, resorts can review their failure progression in an organized report. More frequent inspections and predictive data analysis can also provide resorts advanced warning on repairs which can lower repair costs.

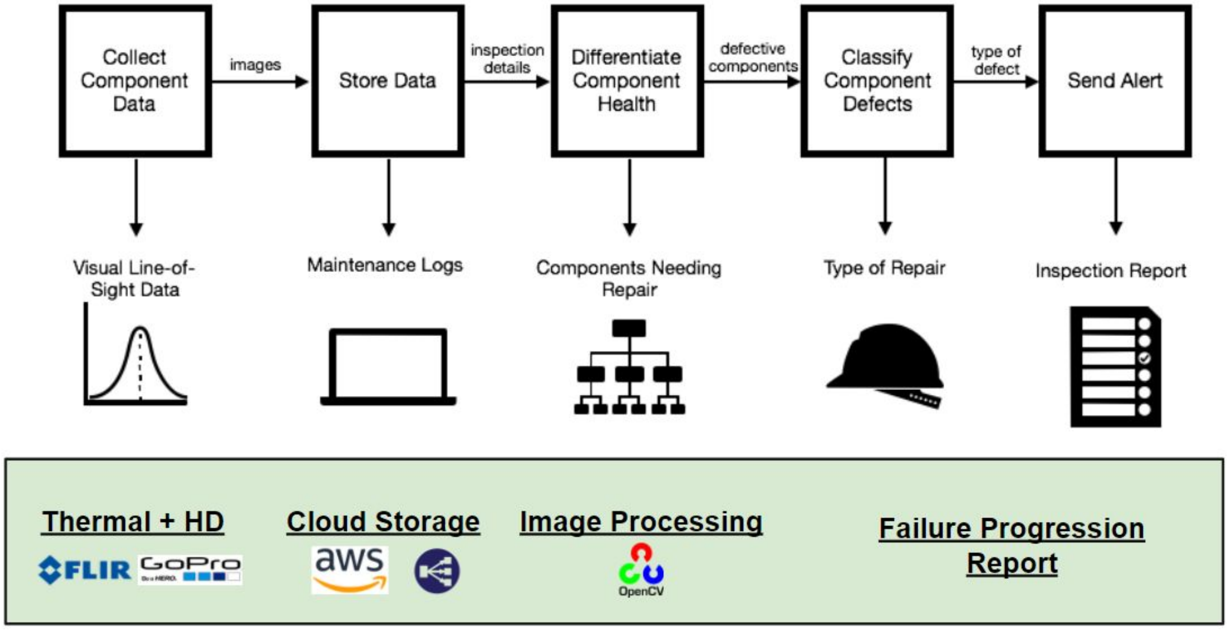
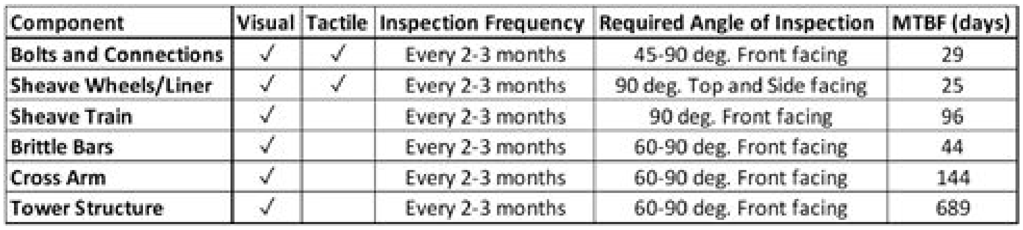


Figure 32: Proposed Concept of Operations

A list of inspected components was developed from Bryce Resort's Inspection Schedule and ANSI B77 Standards. A list of inspected tower components can be found in Table 33 with their Mean Time Between Failure (MTBF) which was analyzed from data from the Colorado Passenger Tramway Safety Board. Based on the lowest MTBF, the frequency of inspections should be increased to weekly.



Component	Visual	Tactile	Inspection Frequency	Required Angle of Inspection	MTBF (days)
Bolts and Connections	✓	✓	Every 2-3 months	45-90 deg. Front facing	29
Sheave Wheels/Liner	✓	✓	Every 2-3 months	90 deg. Top and Side facing	25
Sheave Train	✓		Every 2-3 months	90 deg. Front facing	96
Brittle Bars	✓		Every 2-3 months	60-90 deg. Front facing	44
Cross Arm	✓		Every 2-3 months	60-90 deg. Front facing	144
Tower Structure	✓		Every 2-3 months	60-90 deg. Front facing	689

Table 33: Inspected Components, Inspection Type, Frequency, and Requirements

Image Processing for the Aerial and Tower Platforms

Images from HD and Thermal Cameras can be processed using OpenCV. OpenCV is an open source library for asynchronous and real-time computer vision algorithms. Indications for failure that can be identified through image processing include wheels out of alignment, wheels wobbling, structural cracks, debris or ice that can cause component failure, and corrosion in the tower structure or brittle bars. Optical flow algorithms can track motion between video frames for dynamic analysis as shown in Figure 34 below. Other image processing algorithms include corner and circle detection or color analysis. Heat signatures from the thermal cameras can indicate hot bearings or areas with excessive friction, which can also be analyzed through color analysis.

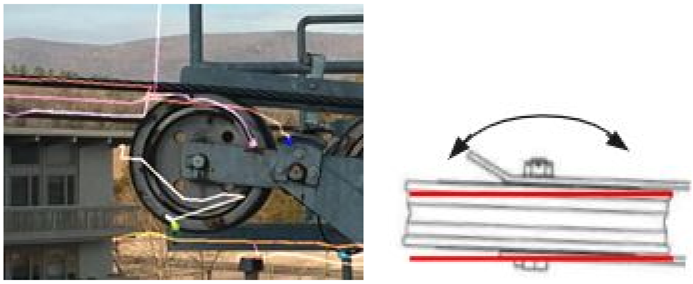


Figure 34: Image Processing Application for Motion Tracking (Side view and top view)

6.0 Design Alternatives

Current Method

The current process for ski lift inspections is a manual inspection process by which personnel use a ladder to climb up to the top of each tower. Under section *3.1.3.1 - Towers* of the ANSI B77 standards, ground personnel must be provided a means for ground access to tower tops. Every resort is required to have a minimum 1:1 ratio of portable ladders to towers. Portable ladders are allowed to extend up to no more than 20 feet (6.10 meters). Therefore, towers greater than 20 feet in height are required to have permanent ladders. Personnel must be provided work platforms along each tower crossarm for access to all line sheave and saddle assemblies. Personnel must also be provided permanent anchor points on all tower tops for the attachment of fall protection devices [15].

This method involves manual labor which incurs cost, is time consuming, and puts personnel at risk of falling. Manual tower inspections take an average inspection time of 31 minutes per tower and cost $423,000 per year. In 2015, there were 20 incidents involving maintenance, inspection, and repair personnel, for more information refer to Figure 18 in Section 1.8.2 [23]. The frequency of tower inspections is extremely low due to the level of risk associated with climbing the tower. This method has a significant gap in time between tower inspections leading to unnoticed degradation and component failures. For example, Bryce Resort recently had a ski lift stop and strand riders on a busy Saturday when the weight of a mud dauber nest caused a brittle bar to break.

Inspection data is stored on paper logs. Information is recorded after time has passed, which causes personnel to forget details. There are few numeric thresholds that allow resorts to track failure progression and paper logs can be lost and forgotten.

Aerial Platform

An unmanned aerial vehicle (UAV)-based system would allow for indirect inspection of components and monitoring at a higher frequency than manual inspections without increasing risk for personnel. The drone will be equipped with thermal and high definition cameras, and it will fly along the lift line to inspect tower by tower. The cameras would allow for higher-ranging angle views of components and replace purely visual inspections with less subjective numerical measurements. Thermal cameras allow for the damage inspection of the ski lift components by observing the component's surface temperature. The high definition cameras will be used to capture images and record videos for detecting damages using visual inspection. All data and recordings collected will be stored in removable memory card and transferred on the cloud. Analysis of data including image processing and damage evaluation will be performed on the ground by the evaluating inspector after the conclusion of the inspection.

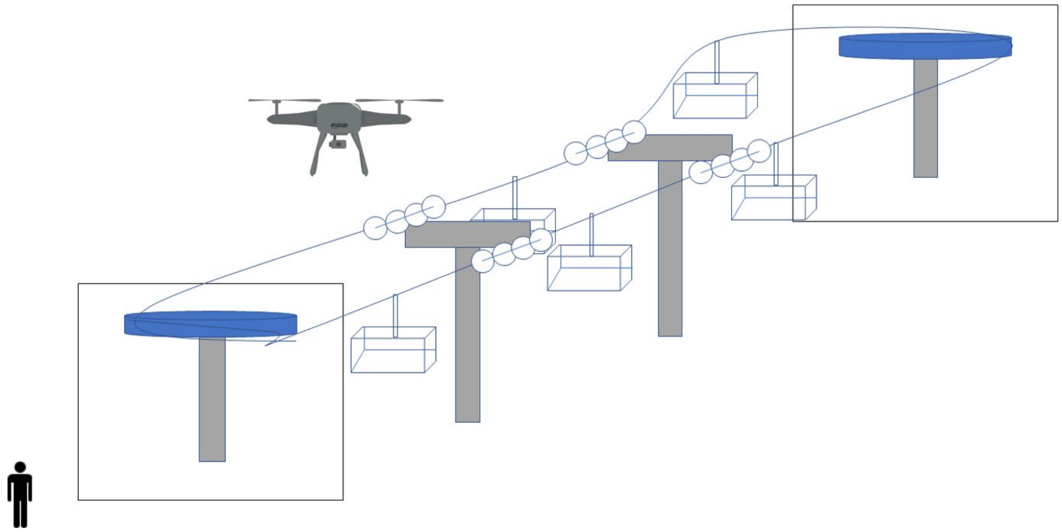
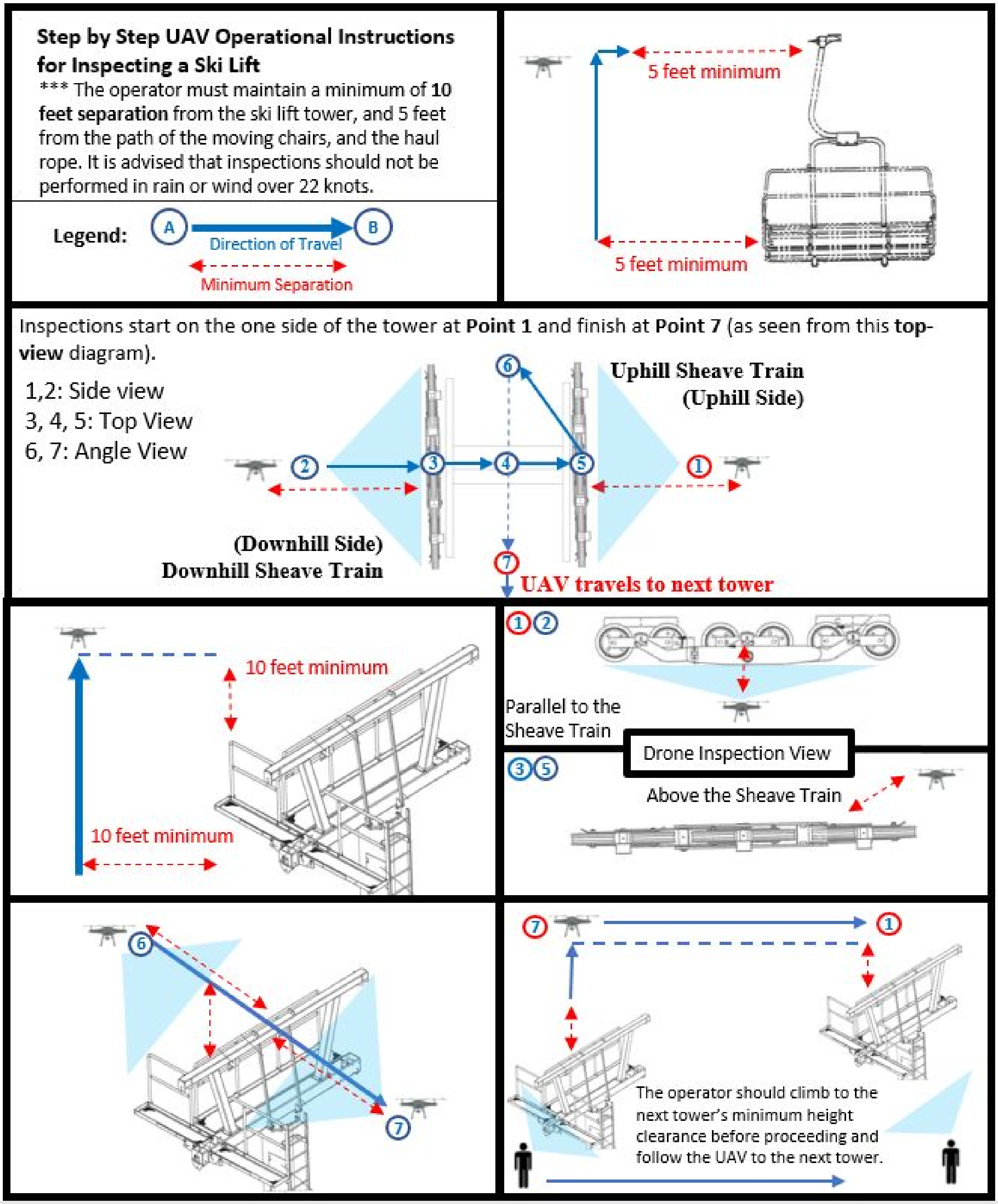


Figure 35: UAV - based inspection

The Aerial Platform requires precise operation by personnel for the safety of skiers and other personnel that may be in the area. An aerial platform procedure was developed based on the required list of components, safety, efficiency, and ease of operation. A pictorial summary of the tower inspection procedure can be found in Figure 36 below.



Step by Step UAV Operational Instructions for Inspecting a Ski Lift

*** The operator must maintain a minimum of **10 feet separation** from the ski lift tower, and 5 feet from the path of the moving chairs, and the haul rope. It is advised that inspections should not be performed in rain or wind over 22 knots.

Inspections start on the one side of the tower at **Point 1** and finish at **Point 7** (as seen from this **top-view** diagram).

1,2: Side view
3, 4, 5: Top View
6, 7: Angle View

The operator should climb to the next tower's minimum height clearance before proceeding and follow the UAV to the next tower.

Figure 36: A Summary of Upper-Tower Inspection Procedures

Aerial Platform Pre Checklist Procedure:

1. Before beginning inspection, identify whether or not the current wind and temperature conditions are operable. The maximum operable wind speed for the DJI Matrice 100 is 22 knots (25 mph). The lowest recommended temperature is 20 degrees Fahrenheit (-6 Celcius).
2. Prior to inspection, take note of the speed of the operating lift. The speed may have an effect on any mechanical analysis as well as the time required for a stationary inspection to capture at least three wheel rotations. Normal winter operations are 400 ft/min, which equates to 3.18 sheave wheel rotations per second. Normal summer operations are 200 ft/min, which equates to 1.59 sheave wheel rotations per second. Operating speeds should be consistent to the season when performing inspections.
3. If the wind is within operable speeds, setup and calibrate the UAV System and ensure the battery is full before operating. It is recommended that the operator have at least three fully charged spare batteries on hand. The operator should follow the 30% rule, meaning the aerial device should return to the operator for battery replacement after 70% of the battery has been drained.
4. The operator must be aware of ski lift tower clearances. The operator must maintain a minimum of 10 feet separation from the tower, which is 5 feet from the moving path of the chair due to the collision avoidance system. A visual observer is required to guarantee separation between the aerial device and the tower to prevent collision and damage. Prior to an aerial inspection, it is recommended that resorts remove tree branches that would limit a UAV’s tower clearances.
5. Prior to inspection, the area must be cleared of people or cordoned off. All personnel must be aware of the inspector’s operation. If the ski resort is within 5 miles of an airport, the operator must contact the necessary entities prior to flight. It is recommended that all resorts check the B4UFly app for any regional restrictions.

6. Personnel may choose to wear reflective gear or an identifiable pilot's vest so resort guests and other personnel can easily identify the drone operator.

Inspection Procedure during Normal Lift Operations:

7. **Inspection Point 1:** Starting from a point on the ground that is a minimum of 10 feet away from the tower, climb to be level and centered with the front of the sheave train on the uphill side of the tower and move no closer than 5 feet from the sheave train. Record video for a minimum of 20 seconds, maintaining as stationary of a position as possible.
8. Climb up to be 10 feet above the tower and cross the tower height to be 10 feet from the downhill side of the tower at **Inspection Point 2**. Align the UAV with the center of the downhill sheave train and move no closer than 5 feet from the sheave train. Record video for a minimum of 20 seconds, maintaining as stationary of a position as possible.
9. Climb to be 10 feet above the tower height and center the UAV above the top of the downhill sheave train at **Inspection Point 3.** Inspect the uphill sheave train by hovering over the center of the sheave train and recording video for 20 seconds.
10. Maintain a height of 10 feet above the tower and begin to cross the tower frame to be centered on the tower at **Inspection Point 4.** Inspect the top of the tower structure by maintaining a stationary position over the center and recording video for 20 seconds.
11. Continue along the tower frame to **Inspection Point 5,** maintaining the 10 foot height above the tower. Align with the center of the top of the uphill sheave train and record video for 20 seconds as stationary as possible.
12. Cross the tower frame to be centered 10 feet away from the front of the downhill side at **Inspection Point 6.** Angle the camera slightly downward to inspect the tower structure. Record video for 30 seconds at a stationary position.

13. Cross to the uphill side of the tower and rotate the aerial device so that the camera faces the uphill tower structure at **Inspection Point 7**.
14. Climb to the height of the next tower, maintaining a 10 foot buffer from the side and top of the tower. Fly the lift line to continue to the next tower. The next tower inspection should start on the uphill sheave train at **Inspection Point 1** and repeat the procedure for the next tower.
15. The UAV operator must travel with the UAV to the next tower to keep the it within his/her line of sight. Repeat these inspection procedures for each tower, keeping battery life in mind. The operator should not start a new tower inspection before replacing the battery if it is below 30%.

Tower-based Platform

This design alternative is a tower-based system where the cameras and sensors are mounted in a fixed position at the top of every tower above each sheave train (two sets of cameras per tower). Visual data and images can be collected from these cameras continuously for analysis. Due to additional equipment, the cost of this system is significantly more expensive than the aerial platform. For data analysis, this alternative would provide the highest amount of data, but quality of data would be limited by the camera angle views because all measurements would be taken from a fixed point. Cameras can be housed in a protective case to prevent camera damage with heating devices to maintain an optimal environmental temperature.

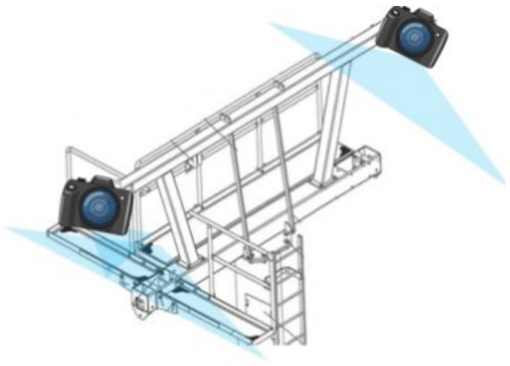
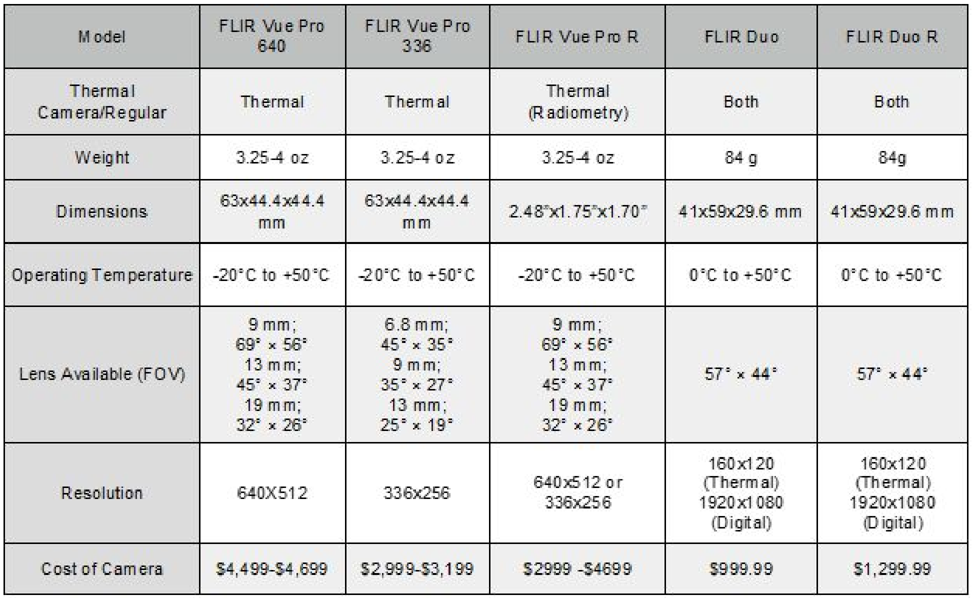


Figure 37: CONOPS for Tower based Platform

Cameras for the Design Alternatives

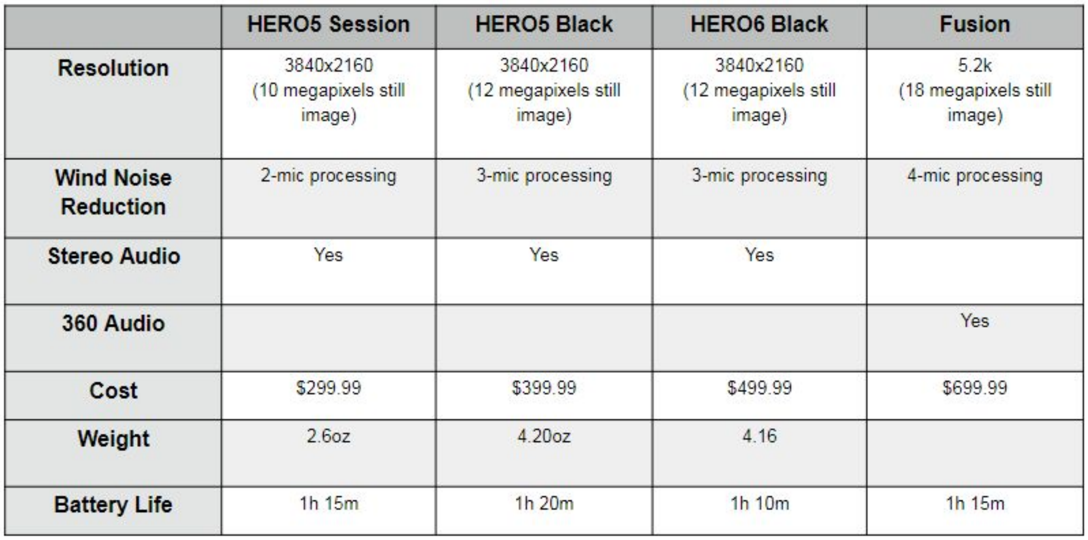
By comparison to the current method which is dependant on the human eye, cameras can track component degradation at a higher precision and provide less bias in data. Thermal cameras also have capabilities to see subsurface cracks that humans cannot see as well as provide numbers for comparison over time. However, thermal cameras would require emissivity correction. Due to varying costs, capabilities, and needs, the different camera models are compared in Table 38. The FLIR Vue Pro R has radiometry capabilities which provides temperature information in every pixel. The FLIR Duo and Duo R have both a thermal camera and an HD Camera included in the cost, but they both have limited operating temperatures. Depending on the different platforms for the camera, the best camera alternative will vary.



Model	FLIR Vue Pro 640	FLIR Vue Pro 336	FLIR Vue Pro R	FLIR Duo	FLIR Duo R
Thermal Camera/Regular	Thermal	Thermal	Thermal (Radiometry)	Both	Both
Weight	3.25-4 oz	3.25-4 oz	3.25-4 oz	84 g	84g
Dimensions	63x44.4x44.4 mm	63x44.4x44.4 mm	2.48"x1.75"x1.70"	41x59x29.6 mm	41x59x29.6 mm
Operating Temperature	-20°C to +50°C	-20°C to +50°C	-20°C to +50°C	0°C to +50°C	0°C to +50°C
Lens Available (FOV)	9 mm; 69° × 56° 13 mm; 45° × 37° 19 mm; 32° × 26°	6.8 mm; 45° × 35° 9 mm; 35° × 27° 13 mm; 25° × 19°	9 mm; 69° × 56° 13 mm; 45° × 37° 19 mm; 32° × 26°	57° × 44°	57° × 44°
Resolution	640X512	336x256	640x512 or 336x256	160x120 (Thermal) 1920x1080 (Digital)	160x120 (Thermal) 1920x1080 (Digital)
Cost of Camera	$4,499-$4,699	$2,999-$3,199	$2999 -$4699	$999.99	$1,299.99

Table 38: Thermal Camera Alternatives

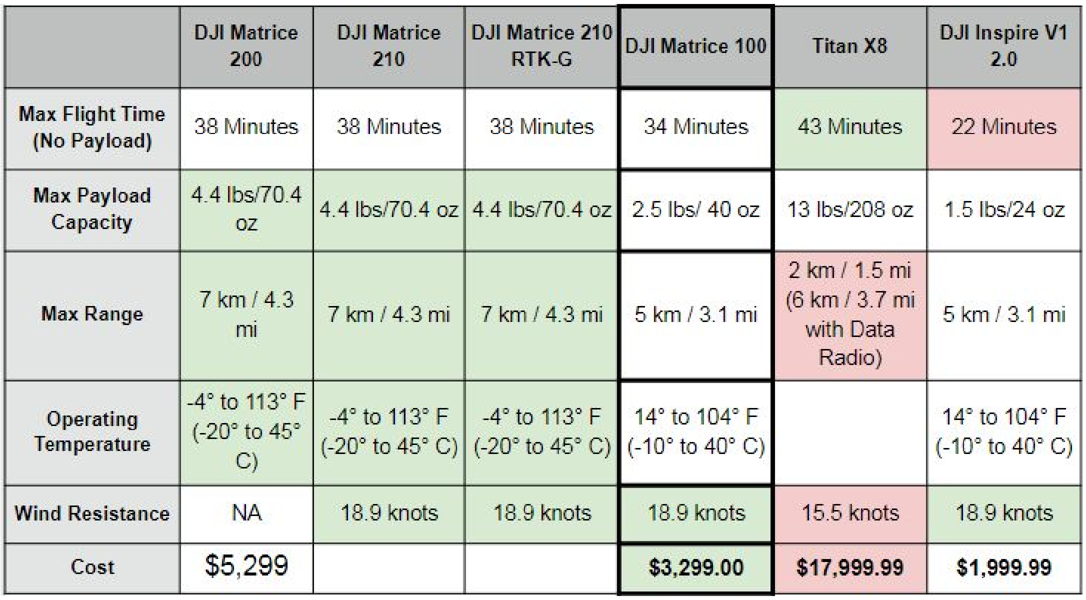
Certain cameras such as the FLIR Vue Pro 640/336 and the FLIR Vue Pro R only have thermal capabilities and would require an additional HD camera. Using two cameras would require a dual gimbal system, which is compatible with all UAV alternatives in Table 40 below. A dual camera system would also increase the system's operating range, as the dual HD and thermal cameras have the lowest operating temperature and altitude.



	HERO5 Session	HERO5 Black	HERO6 Black	Fusion
Resolution	3840x2160 (10 megapixels still image)	3840x2160 (12 megapixels still image)	3840x2160 (12 megapixels still image)	5.2k (18 megapixels still image)
Wind Noise Reduction	2-mic processing	3-mic processing	3-mic processing	4-mic processing
Stereo Audio	Yes	Yes	Yes	
360 Audio				Yes
Cost	$299.99	$399.99	$499.99	$699.99
Weight	2.6oz	4.20oz	4.16	
Battery Life	1h 15m	1h 20m	1h 10m	1h 15m

Table 39: HD Camera Alternatives

For smaller resorts, the DJI Matrice 100 is recommended. However, larger resorts with greater availability needs should use the DJI Matrice 200 with weatherproofing. The additional cost does not provide improved flight time, but it has a wider range of operating temperature.



	DJI Matrice 200	DJI Matrice 210	DJI Matrice 210 RTK-G	DJI Matrice 100	Titan X8	DJI Inspire V1 2.0
Max Flight Time (No Payload)	38 Minutes	38 Minutes	38 Minutes	34 Minutes	43 Minutes	22 Minutes
Max Payload Capacity	4.4 lbs/70.4 oz	4.4 lbs/70.4 oz	4.4 lbs/70.4 oz	2.5 lbs/ 40 oz	13 lbs/208 oz	1.5 lbs/24 oz
Max Range	7 km / 4.3 mi	7 km / 4.3 mi	7 km / 4.3 mi	5 km / 3.1 mi	2 km / 1.5 mi (6 km / 3.7 mi with Data Radio)	5 km / 3.1 mi
Operating Temperature	-4° to 113° F (-20° to 45° C)	-4° to 113° F (-20° to 45° C)	-4° to 113° F (-20° to 45° C)	14° to 104° F (-10° to 40° C)		14° to 104° F (-10° to 40° C)
Wind Resistance	NA	18.9 knots	18.9 knots	18.9 knots	15.5 knots	18.9 knots
Cost	$5,299			**$3,299.00**	**$17,999.99**	**$1,999.99**

Table 40: UAV Alternatives

7.0 Requirements

7.1 Inspection System Requirements

7.1.1 Mission Requirements

MR 1. The system shall detect the following external Ski Lift Tower and component defects:

- Corrosion in tower components
- Cracks in metal structural components such as the cross arm or the top of the tower structure
- Misalignment and/or wobble in sheave wheels
- Noise: clatter and/or screeching from sheave wheels
- Loose connections (i.e. nuts/bolts)

MR 2. The system shall inspect the ski lift in daylight hours without interrupting resort operations limiting the inspection system to inspect the lift or a portion of the lift in under two hours during resort operating days (i.e. between 7am and 9am prior to opening).

MR 3. The system shall be able to inspect ski lift components listed in MR.1. a minimum of every 2 weeks while maintaining inspection time constraints per MR.2.

MR 4. The system shall be operable by inspection and maintenance personnel with no previous technological experience other than the provided training.

7.1.2 Functional Requirements

F1. The system shall measure the alignment of the sheave wheels by identifying two points of visual reference above each wheel and send an alert if the wheels are more than 5% out of alignment.

F2. The system shall inspect the wobble of the sheave wheels by identifying two points of visual reference from above for each wheel when the ski lift is in motion to compare the angle and position for each wheel over time. The system shall indicate an alert for each individual wheel if the angles deviate more than 5% for each wheel when in motion.

F3. The system shall capture color and thermal images of metal components for corrosion, cracks, and material loss and process those images to report discolorations greater than 5% from a baseline measurement under static system lighting.

F4. The system shall inspect the ski lift for loose nuts and bolts by recording video of the system in motion from above (preferably weighted) and measuring deviations or vibration in video. The system shall indicate an alert for deviations greater than 5% from a baseline measurement.

7.1.3 Design Requirements

DR 1. The system shall illuminate system components using LED lights to establish a baseline environment for consistency of measurements.

DR 2. The system shall store recorded measurements and images for the user to review remotely through a device compatible with a standard computer (either via wireless transmission or a removable memory device).

DR 3. The system shall be operable at altitudes up to 12,000 feet above sea level, temperatures between 15 degrees and 105 degrees Fahrenheit, and winds up to 22 knots.

7.2 Simulation Requirements

7.2.1 I/O Requirements

SR 1. The simulation shall accept input values of the number of towers, the height difference and the distance between towers, and the number of sheave wheels per tower.

SR 2. The simulation shall output measures for time to inspect the ski lift, measures for accuracy, and measures for availability.

7.2.2 Time I/O Requirements

SR 3. The simulation shall output an average tower inspection time for the aerial platform equal to the average time to inspect a tower following the developed procedure five times with an error tolerance of ± 10%.

SR 4. The simulation shall assume an aerial inspection procedure respective to the UAV's collision avoidance system for all tower clearances.

SR 5. The simulation shall assume a speed distribution for the aerial platform including climb/descend speed, inspection speed, and horizontal travel speeds equal to repeated field tested values (five times) with an error tolerance of ± 10%.

SR 6. The simulation shall assume a headwind for the aerial platform based on historical wind data for all horizontal travel and assume no wind for vertical travel such that the airspeed is greater than the wind speed.

SR 7. The simulation shall output an average tower inspection time for the current method equal to the average time to inspect a tower based on the current inspection procedure with an error tolerance of ± 15%.

7.2.3 Cost I/O Requirements

SR 8. The simulation shall calculate the total labor cost for each design alternative based on the inspection time output by the simulation, including labor wages, workers compensation and insurance costs per hour.

SR 9. The simulation shall account for the cost of the UAV device in addition to the thermal and HD cameras to calculate the cost of an aerial platform. The simulation shall take into account the average time required to inspect the ski lift given a local historical wind distribution to determine the number of batteries required for the aerial platform.

SR 10. The simulation shall account for the cost of the thermal and HD cameras (inclusive of mounting materials and installation labor) for each sheave train to calculate the cost of the tower platform.

7.2.4 Accuracy I/O Requirements

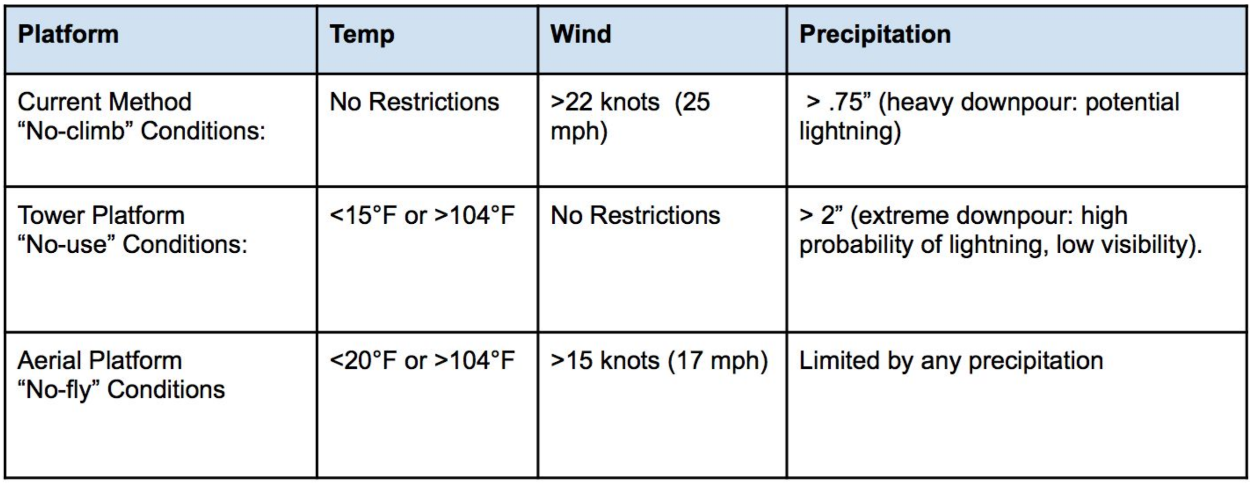
SR 11. The simulations shall output accuracy for the aerial platform based on the visibility of components from the distance of the aerial vehicle from the tower.

SR 12. The simulation shall output accuracy of the tower platform based on the height of the camera above the tower with a minimum fixed angle view of the farthest component of 60 degrees.

SR 13. The simulation shall output accuracy of the current inspection method based on the time elapsed between a tower inspection and recording the information using Ebbinghaus's forgetting curve.

7.2.4 Availability I/O Requirements

SR 14. The simulation shall output availability of each design alternative based on temperature, wind, and precipitation restrictions. (defined in the table 39 below)



Platform	Temp	Wind	Precipitation
Current Method "No-climb" Conditions:	No Restrictions	>22 knots (25 mph)	> .75" (heavy downpour: potential lightning)
Tower Platform "No-use" Conditions:	<15°F or >104°F	No Restrictions	> 2" (extreme downpour: high probability of lightning, low visibility).
Aerial Platform "No-fly" Conditions	<20°F or >104°F	>15 knots (17 mph)	Limited by any precipitation

Table 41: Availability based on Wunderground Local Weather Data (2014-2017)

8.0 Simulation Design

A stochastic simulation was developed to compare the inspection time, safety, accuracy, and availability of the three design alternatives, which are output by the simulation. Simulation inputs include the number of towers, the number of sheave wheels per tower, the height and location of each tower, as well as a random distribution for wind.

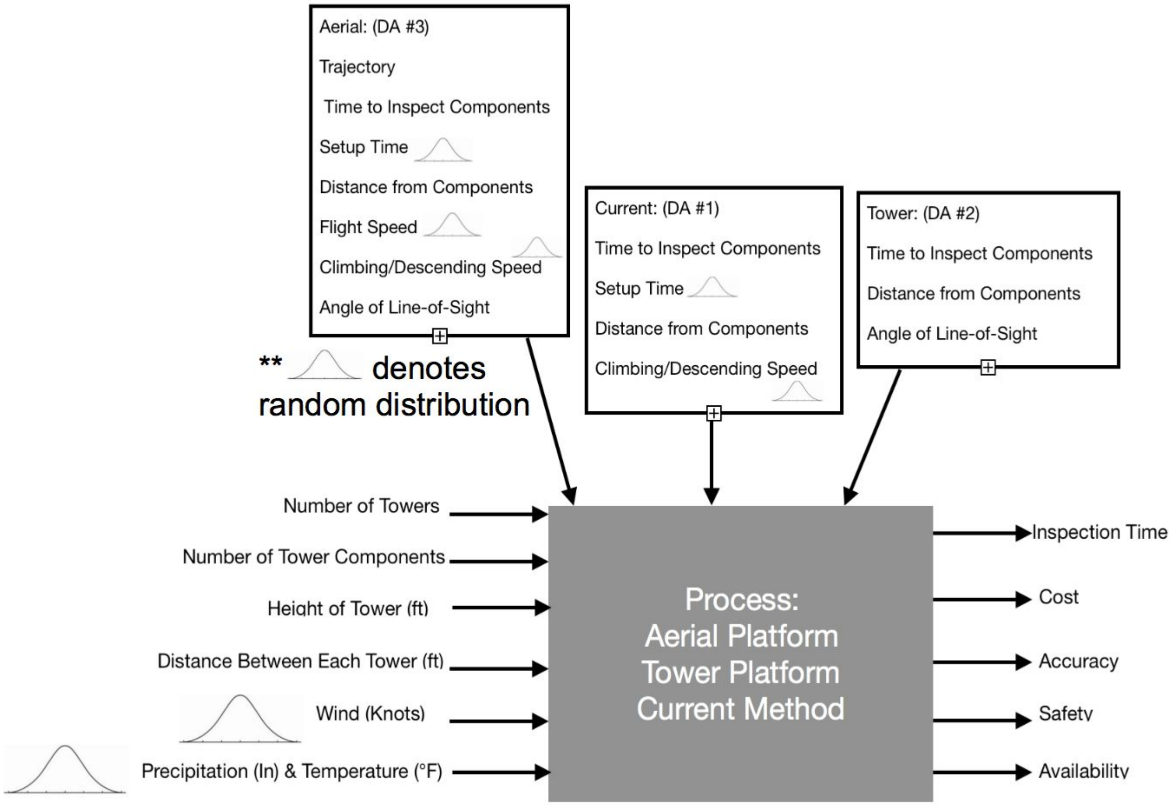


Figure 42: Simulation Design

8.1 Verification and Validation through Empirical Data Collection

For verification and validation of the simulation, extensive empirical data collection was performed. Random variables for the simulation were collected through experimentation and research. Travel speed for the mobile aerial platform includes horizontal travel speed, inspection speed, and vertical speed. Vertical speed is based on half of the maximum climb and descend speed for the DJI Matrice 100 Manufacturer Specifications. Horizontal and Inspection speeds were collected through an experiment. A UAV was flown between two markers for both a

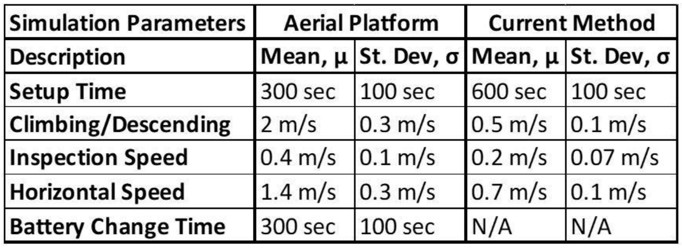
100 foot fence line and 13.5 feet to represent flying between towers and flying along the top of the tower five times. The number of trials was limited by the number of batteries brought by the pilot. The setup time for the aerial platform was based on the initial setup for two separate testing days at Bryce Resort. The time also includes walking from the office to the first tower.

The random distributions for the current method were based on research and subject matter expert experience. Horizontal travel speed was based on half the average human walking speed. Inspection speed was based on one third of the average human walking speed. Vertical speed was based on the difference between the horizontal and inspection speed and subject matter expert input. Setup time for the current method was based on the inspection procedure and subject matter expert input.

Figure 43: Experimental Setup for Aerial Inspection Speed Collection

8.2 Time

Inspection time is a cost-critical system characteristic, as it is related to labor costs. For the current method, the time required for a human to inspect the tower includes the time to setup, climb the tower, inspect all components, climb down, and travel to the next tower. The tower platform is considered continuous with a system delay of 1 minute. For the aerial platform, the simulation assumes that the procedure in Figure 36 is executed for inspections, including a maximum battery usage of 70% before replacement. Battery life was modeled based on stochastic wind conditions which can cause longer inspection times. Empirical data for random variables was collected for horizontal speed, climbing and descending speed, inspection speed, setup time, and battery change time.



Simulation Parameters	**Aerial Platform**		**Current Method**	
Description	**Mean, μ**	**St. Dev, σ**	**Mean, μ**	**St. Dev, σ**
Setup Time	300 sec	100 sec	600 sec	100 sec
Climbing/Descending	2 m/s	0.3 m/s	0.5 m/s	0.1 m/s
Inspection Speed	0.4 m/s	0.1 m/s	0.2 m/s	0.07 m/s
Horizontal Speed	1.4 m/s	0.3 m/s	0.7 m/s	0.1 m/s
Battery Change Time	300 sec	100 sec	N/A	N/A

Figure 44: Summary of Time Parameters from Empirical Data Collection

8.3 Cost

Cost was analyzed based on data from the NSAA's Economic Report including labor hours related to the simulated inspection time, insurance costs, and worker's compensation to calculate both the acquisition and annual operating cost for each design alternative.

8.4 Accuracy

Accuracy was simulated through experimentation using the Camera Calibration Tool developed by Bouguet in MATLAB to measure distortion through the pixel error for a camera between the expected corner position for a checkerboard and the location where the grid corner was detected across 10 images [7].

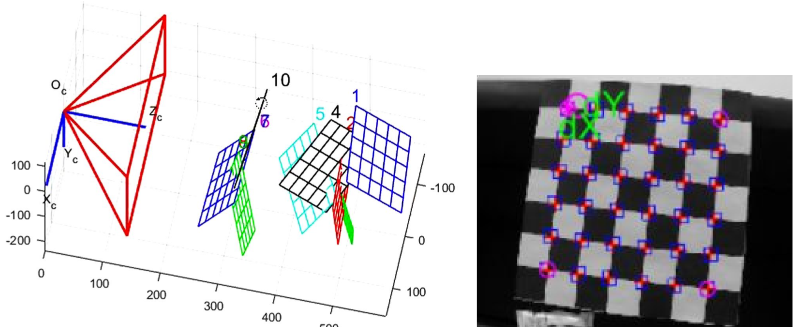


Figure 45: Experimental Setup for a MATLAB Distortion Model

Camera distortion effects both image processing algorithms and shape interpretation of the human eye. For example, an inspector would not be able to recognize a wheel misalignment if the pixels themselves do not appear aligned due to distortion. The pixel error measures the difference between the expected corner location and where the corner was located due to distortion, as shown in Figure 46 below.

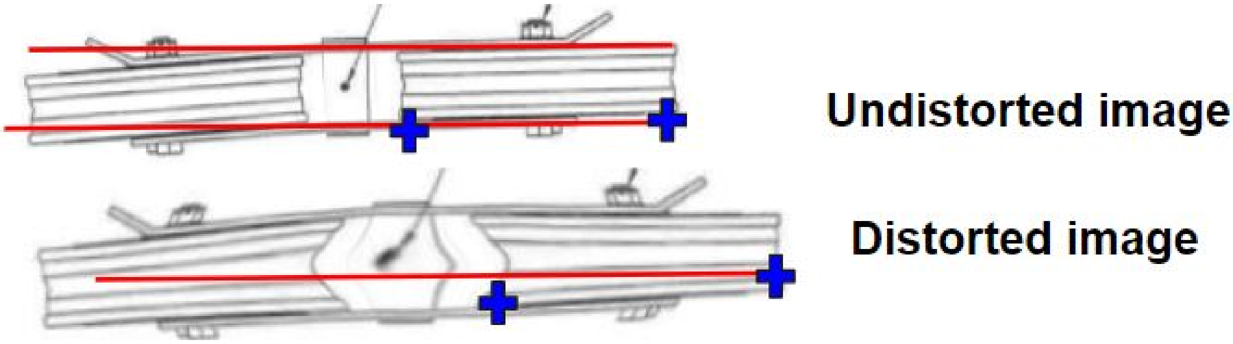


Figure 46: Wheel Alignment Example for Pixel Error

The Pixel Error analysis provides each design alternative's accuracy based on camera distortion respective to the camera's extrinsic parameters: distance and angle from components. The mobile aerial platform is restricted to 10 feet at a 90-degree angle from components due to the collision avoidance system. The accuracy of the tower platform was averaged between the camera angles from the 47-inch height above the tower center (90 degrees) and the 60-degree angle from the farthest component.

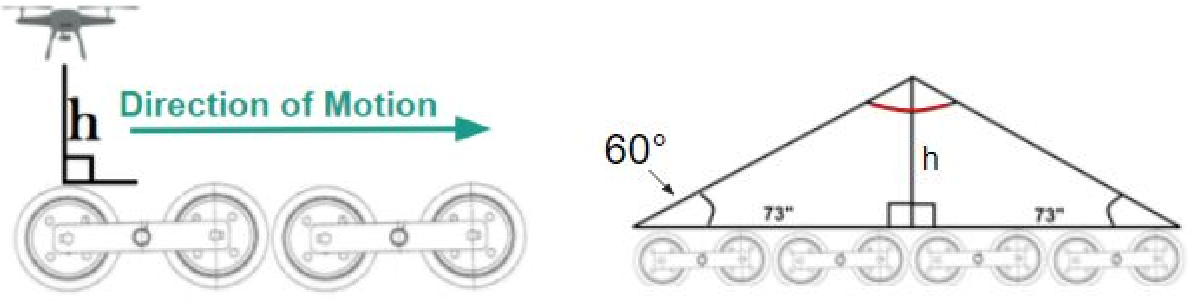


Figure 47: Accuracy extrinsic parameters for the aerial and tower platforms.

The camera angle has a greater effect on image distortion than distance. For example, the 60-degree angle for the tower platform distorts the image of sheave wheels from above. Figure 48 below shows how the camera angle can impact the appearance of shapes. Camera calibration can adjust distortion for image processing analysis to identify a misalignment. However, extreme distortion cannot be corrected.

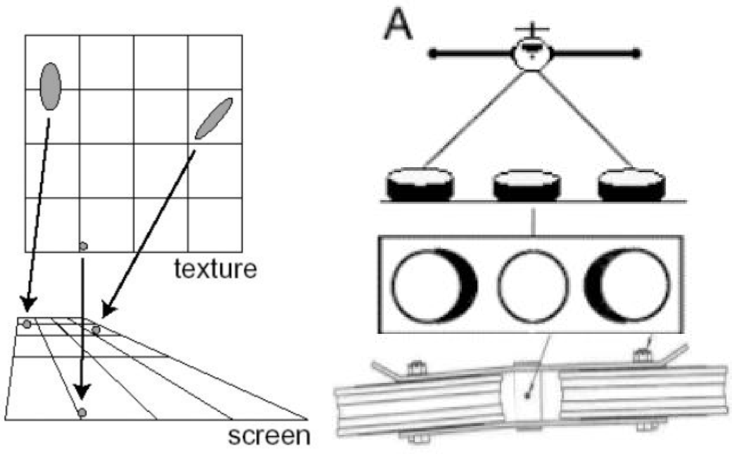
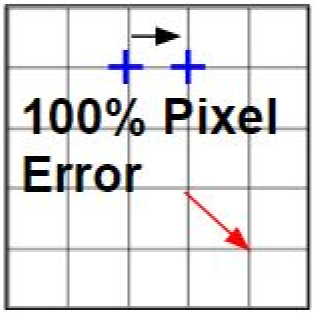


Figure 48: Tower Platform Shape Distortion

Since the size of each grid box and pixel will vary based on the camera distance from the grid, accuracy is scaled by the diagonal pixel error in comparison to the diagonal length of each box in pixels. Using diagonal pixel error also simplifies the error for a 1 to 1 comparison because the error may not be symmetrical across the x and y axes. For example, one grid box is 28.5 mm by 28.5

mm, but at 10 feet each box is 15 pixels by 15 pixels. If a corner is found the next corner over, it is considered to have 100% error or 0% accuracy.



$$\%Error = \frac{Diagonal\ Pixel\ Error}{Diagonal\ \#\ of\ pixels\ per\ box} * 100$$

$$\%Accuracy = 100 - \%Error$$

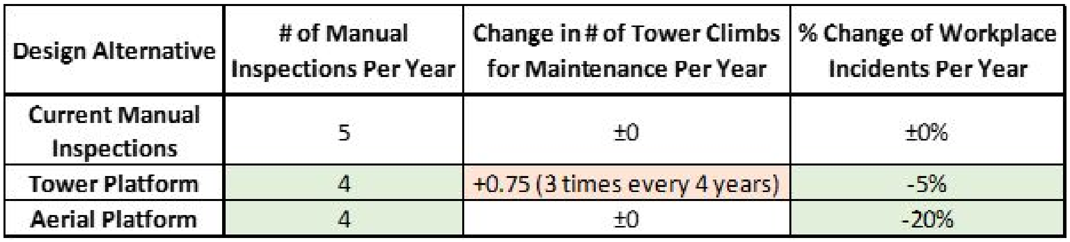
Figure 49: Accuracy Equation

For comparison to manual inspections that do not use cameras, accuracy was calculated based on Ebbinghaus’ Forgetting Curve, which calculates the percentage of human memory retention over time. Accuracy for manual inspections is based on the time between a manual inspection and when the information is recorded on paper at the bottom of the tower. In the equation below, ‘b’ is the percent retention over time ‘t.’ The equation was determined by Ebbinghaus’ experiments and repeated many times [8].

$$b = (184)/(1.25\log(t)+1.84)$$

8.5 Safety

System safety is measured by the number of workplace incidents for maintenance and inspection personnel. For comparison, the number of workplace incidents is assumed to have a linear relationship with the number of inspections and the same standard deviation. Manual inspections cause an average of 51 workplace incidents per year with a standard deviation of 16 workplace incidents per year [1]. Aerial-based inspections would reduce the current rate of workplace incidents by 20%, which is the equivalent of reducing 5 manual inspections to 4. The tower platform would reduce 5 manual inspections to 4, but the system would require personnel to climb the tower to perform system maintenance. The tower platform would reduce the current rate of workplace incidents by 5%.



Design Alternative	# of Manual Inspections Per Year	Change in # of Tower Climbs for Maintenance Per Year	% Change of Workplace Incidents Per Year
Current Manual Inspections	5	±0	±0%
Tower Platform	4	+0.75 (3 times every 4 years)	-5%
Aerial Platform	4	±0	-20%

Figure 50: Safety Change Analysis

For comparison, only the mean number of workplace incidents was analyzed between the different design alternatives because there is not enough information to comment on the changes in variance or consistency of occurrences.

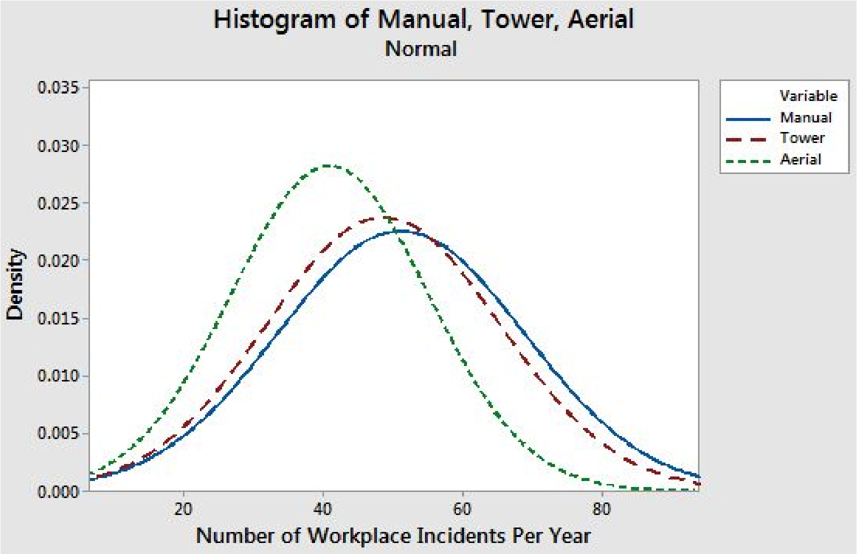
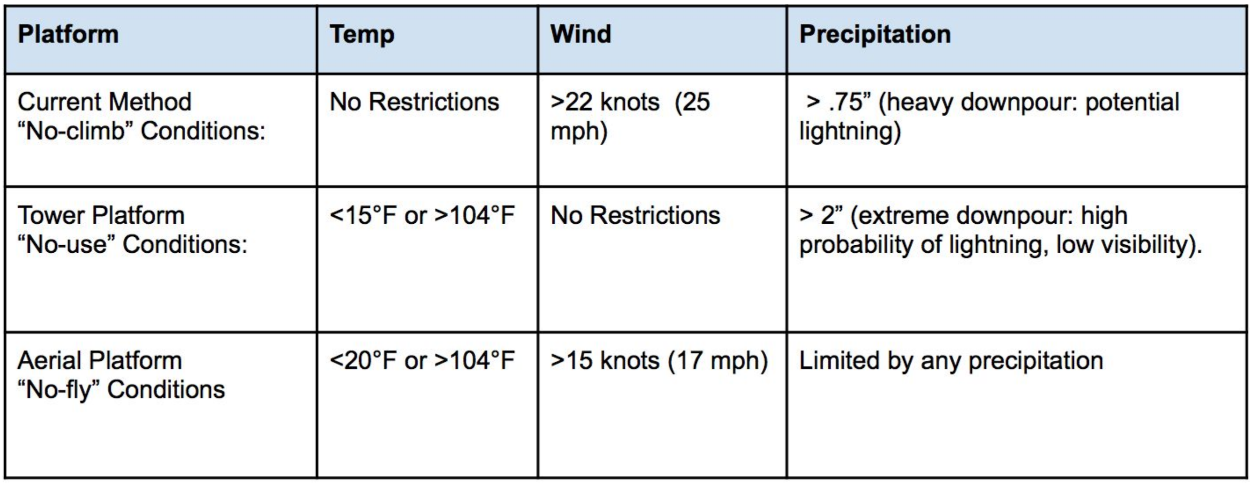


Figure 51: Safety Distributions

8.6 Availability

The availability requirement for inspections was defined based on the lowest Mean Time Between Failure (MTBF) for tower components. The lowest Mean Time Between Failure (MTBF) for a tower component is 25 days between Sheave Wheel failures [3]. The recommended inspection frequency is one third of the MTBF, which is every 8 days or weekly inspections. Due to the on-demand nature of maintenance concerns, personnel may perform an inspection on any day. Availability is defined as the percentage of days per year in which a design alternative can inspect lift towers based on weather conditions. Historical weather data was analyzed for Bayse Virginia, where Bryce Resort is located [9]. Availability restrictions were defined by Bryce Resort's inspection procedure and manufacturer specifications for a UAV as well as HD and thermal cameras.



Platform	**Temp**	**Wind**	**Precipitation**
Current Method "No-climb" Conditions:	No Restrictions	>22 knots (25 mph)	> .75" (heavy downpour: potential lightning)
Tower Platform "No-use" Conditions:	<15°F or >104°F	No Restrictions	> 2" (extreme downpour: high probability of lightning, low visibility).
Aerial Platform "No-fly" Conditions	<20°F or >104°F	>15 knots (17 mph)	Limited by any precipitation

Table 52: Availability Restrictions

9.0 Design of Experiment

To compare the different design alternatives, time, safety, accuracy, and availability were analyzed across the same number of towers and lift characteristics including the number of sheave wheels per tower as well as the height, slope, and distance between each tower from the Bryce Resort Lift Specifications. The cost of each alternative was compared based on the number of people required to perform an inspection: 4 people for manual inspections, 1 person for the tower platform, and 2 people for the mobile aerial platform. It was hypothesized that either the mobile aerial platform or tower platform would decrease cost by 20%, which would be the equivalent to reducing manual inspections from 5 to 4 inspections per year.

Design Alternative	Inputs			Parameters					Outputs				
	Lift Traits	# of People Required	Weather	Horizontal Speed (m/s)	Vertical Speed (m/s)	Inspection Speed (m/s)	Setup Time (sec)	Angle of Line-of-Sight (deg)	System Characteristics:				
(#1) Current Method	9 Towers Height (m) Slope (m) # of Sheaves Location (m)	4	Precipitation: -.001*WEIB(.0171, .375) Temperature: 5+104*BETA(3.86,4.39) Wind: -0.001+11*BETA(1.54,5.08)	N(0.67, 0.1)	N(0.5,0.1)	N(0.2,0.07)	N(600,100)	90	Inspection Time (min)	Cost	Safety	Accuracy	Availability
(#2) Tower Platform	9 Towers Height (m) Slope (m) # of Sheaves Location (m)	1	Precipitation: -.001*WEIB(.0171, .375) Temperature: 5+104*BETA(3.86,4.39) Wind: -0.001+11*BETA(1.54,5.08)	N/A	N/A	N/A	60	60	Inspection Time (min)	Cost	Safety	Accuracy	Availability
(#3) Aerial Platform	9 Towers Height (m) Slope (m) # of Sheaves Location (m)	2	Precipitation: -.001*WEIB(.0171, .375) Temperature: 5+104*BETA(3.86,4.39) Wind: -0.001+11*BETA(1.54,5.08)	7*Beta(2,4.94)	N(2, 0.3)	N(0.399, 0.1)	N(300, 100)	90	Inspection Time (min)	Cost	Safety	Accuracy	Availability

Figure 53: Design of Experiment

10.0 Results

Results were obtained from 1,453 replications of the simulation. A summary of simulation outputs and system characteristics for comparison can be found in the table below.

Design Alternative	Time per Tower (min)	Safety (workplace incidents per year)	Accuracy (%)	Availability (% Days/Year)
Manual Inspection	31.67 ± 2.89	51 ± 16	40% Memory Retention	98% ± 1%
Tower Platform	1	48 ± 16	90.4% Visual Accuracy	97% ± 1%
Aerial Platform	8.33 ± 0.78	40 ± 16	85.9% Visual Accuracy	65% ± 10%

Figure 54: Simulation Results

10.1 Results: Time

The mobile aerial platform reduces inspection time by an average of 23 minutes per tower per inspection compared to manual inspections. The tower platform reduces inspection time by 31 minutes per tower per inspection. Due to stochastic wind conditions and operating speeds, the mobile aerial platform has a standard deviation of 0.78 minutes per tower compared to 2.89 minutes per tower for manual inspections.

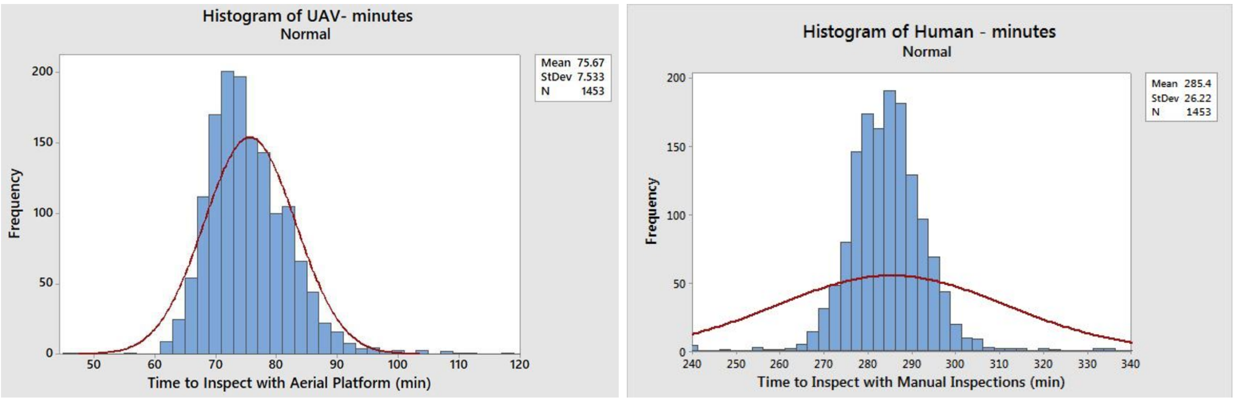


Figure 55: Time Results for Aerial Platform (left) and Manual Inspections (right)

10.2 Results: Availability

Although the mobile aerial platform has the lowest daily availability to perform inspections of the three design alternatives, the mobile aerial platform fulfills the requirement that weekly inspections can be performed. The average number of unavailable days per week is 0.79, which means resorts have 6 out of 7 days per week to perform an inspection.

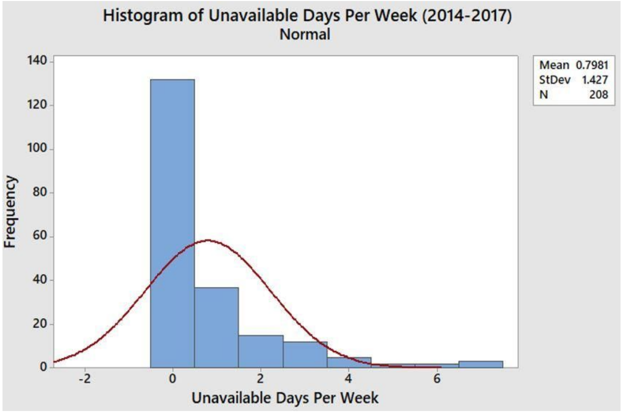


Figure 56: Historical Weekly Availability Distribution for the Aerial Platform

Historically, there have been three weeks out of four years (between 2014 and 2017) in which the mobile aerial platform was not available for seven consecutive days.

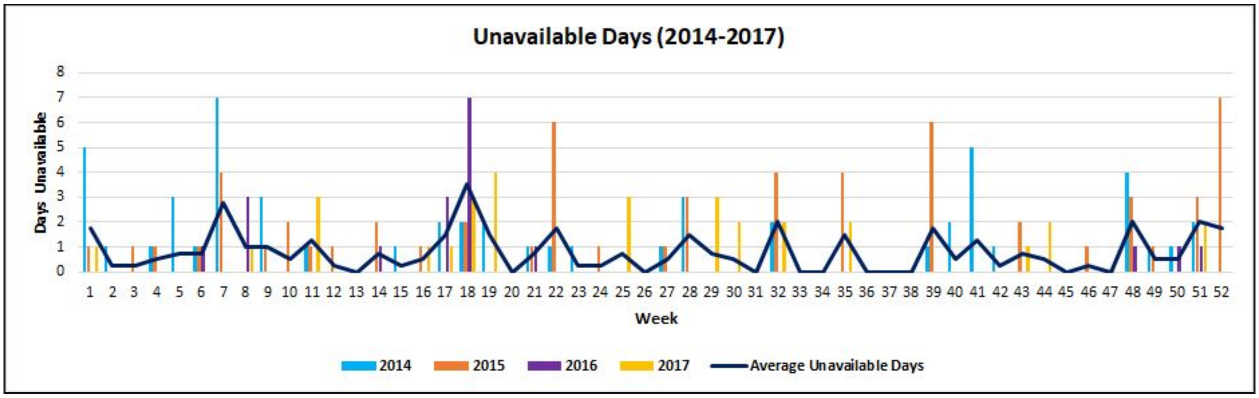


Figure 57: Historical Days Unavailable per Week for the Aerial Platform

The most restricted month for the Aerial Platform is the month of May due to heavy precipitation during the Spring season. Although May is considered the resort off-season, pre-season maintenance occurs throughout the month prior to the summer mountain biking season. The tower platform is 1% less available daily than manual inspections.

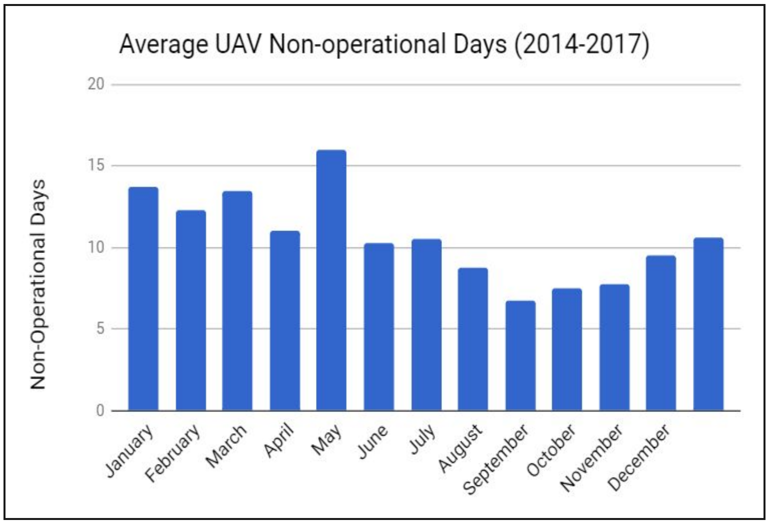


Figure 58: Average Monthly Availability for the Aerial Platform

10.3 Results: Safety

The availability constraints for the mobile aerial platform and tower platform were defined to have lower risk to the inspection system than manual inspections that place inspection personnel at risk of falling. The mobile aerial platform improves safety by 20% and the tower platform improves safety by 5% due to occasional camera maintenance. Safety is constrained by resorts only having control over two out of the five annual inspections. Safety could be improved further if insurance companies or state agencies were to implement a new inspection system.

10.4 Results: Accuracy

Due to poor data recording procedures and the extended period of time between manual inspections and recording the information on a paper log, the mobile aerial platform improves accuracy by 50% and the tower platform improves accuracy by 45% compared to current manual inspections. The tower platform has greater pixel error compared to the mobile aerial platform due to the angle of view from the farthest component. The average pixel error from the 60-degree angle was 4.074 pixels X and 11.957 pixels Y. The average pixel error at a 90-degree angle from 47 inches away was 0.077 pixels X and 0.093 pixels Y. Since components are viewed at a range between the two tower camera angles, the average pixel error from both camera angles was used for comparison: 6.376 pixels diagonally.

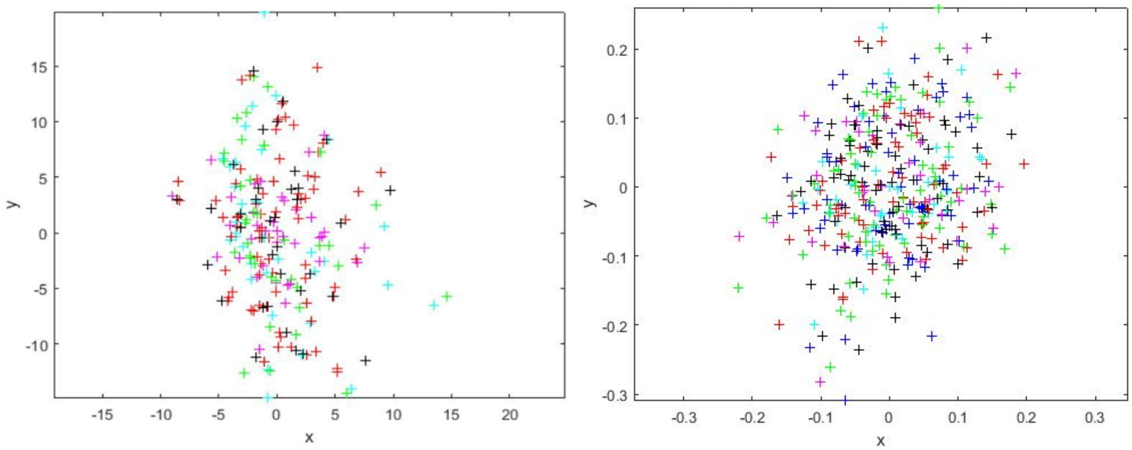


Figure 59: Tower Angled View (Left), Centered View (Right) Pixel Error Distribution

The mobile aerial platform at a 90-degree angle from 10 feet away had an average pixel error of 1.262 pixels X and 1.605 pixels Y, or 2.042 pixels diagonally.

The error distributions for the mobile aerial platform can be found in Figure 60 below.

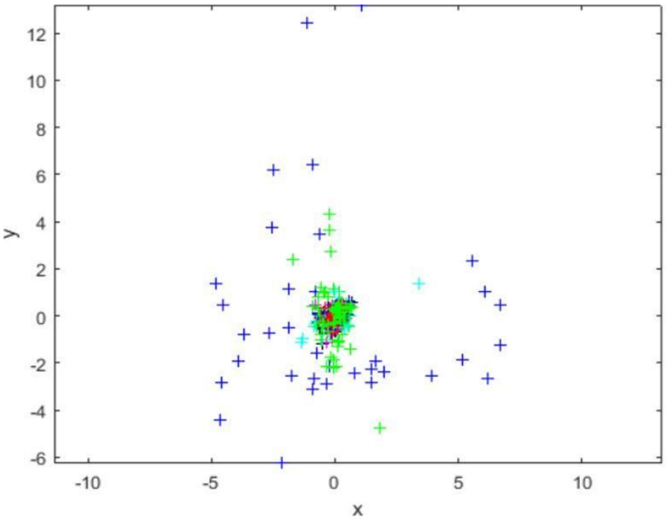


Figure 60: Aerial Platform View Pixel Error Distribution

For comparison, the thermal camera pixel accuracy for the mobile aerial platform at a 90-degree angle from 10 feet away was 0.182 pixels X and 0.171 pixels Y, or 0.239 pixels diagonally. From 10 feet away, the thermal camera has 97.8% spot accuracy.

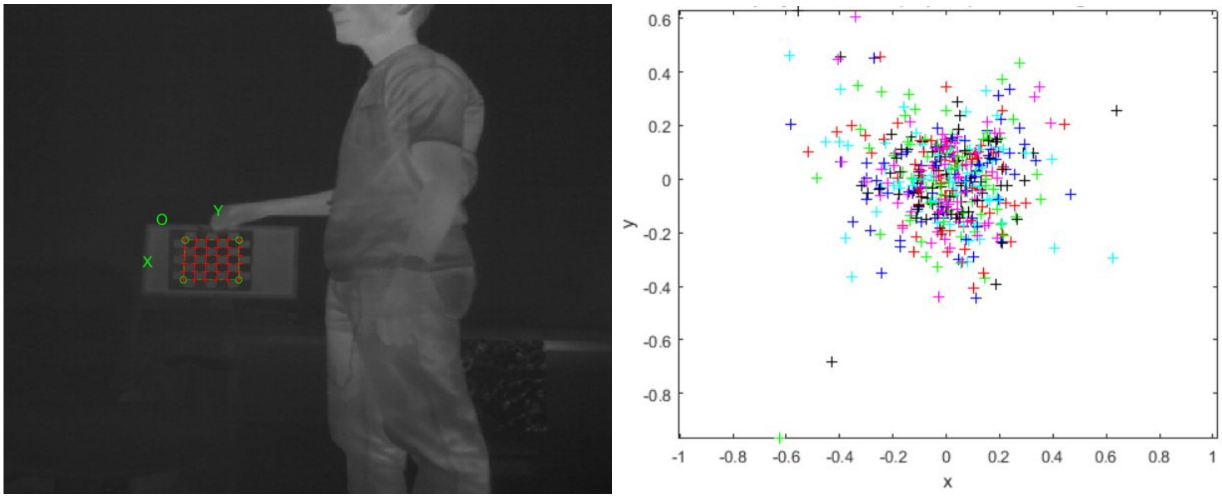
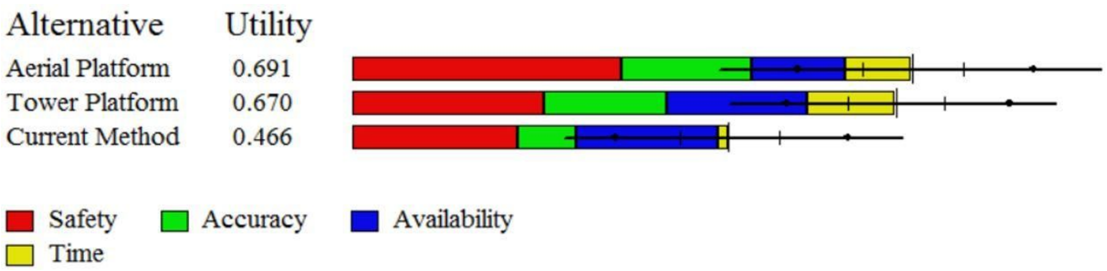


Figure 61: Aerial Platform Thermal Camera Experimental Setup and Pixel Error Distribution

11.0 Analysis

11.1 Utility Analysis

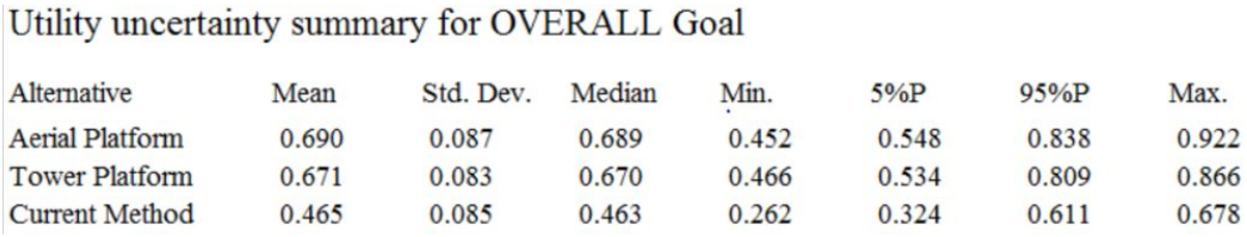
It was determined that the aerial platform has the highest utility, followed by the tower platform then the current method. The overall ranking can be found in Figure 62 below.



Alternative	Utility
Aerial Platform	0.691
Tower Platform	0.670
Current Method	0.466

Figure 62: Utility ranking for the inspection systems

The mean and standard deviation for utility uncertainty was calculated based on 5,000 replications of random number generation for each simulation output's distribution. The range of utility is shown by the lines in Figure 62 above for the mean as well as one, two, and three sigma. The summary of uncertainty including 5% and 95% probability density values can be found in the figure below.



Utility uncertainty summary for OVERALL Goal

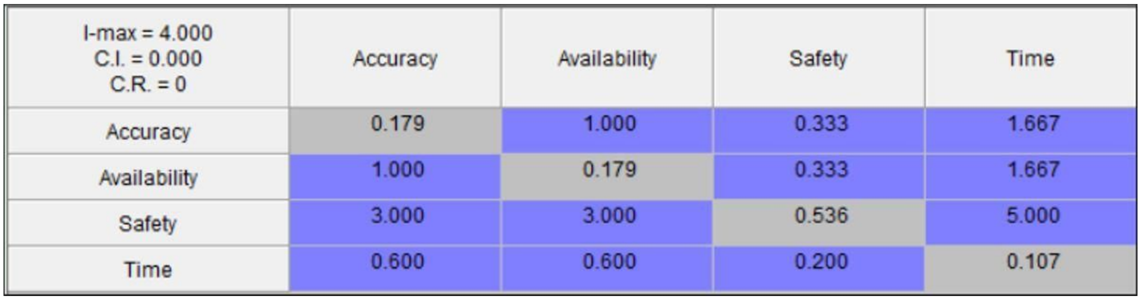
Alternative	Mean	Std. Dev.	Median	Min.	5%P	95%P	Max.
Aerial Platform	0.690	0.087	0.689	0.452	0.548	0.838	0.922
Tower Platform	0.671	0.083	0.670	0.466	0.534	0.809	0.866
Current Method	0.465	0.085	0.463	0.262	0.324	0.611	0.678

Figure 63: Utility Uncertainty Summary

11.2 Analytic Hierarchy Process

The weights for accuracy, availability, and time were calculated using the Analytic Hierarchy Process (AHP) method. The weights were based subjectively on the viewpoint of two groups of stakeholders with two subject experts per group were asked to provide a pairwise comparison: ski resort management and ski lift maintenance personnel.

Safety was weighted the highest due to risk associated for inspection personnel when they climb up the tower. Availability and Accuracy was weighed the second highest due to the risk associated with gaps between inspections in which failures could go unnoticed for availability and accuracy due to the risk of failing to detect structural defects or declaring a faulty component in error. Misreadings may also require additional inspections and incur a greater cost. Time was weighed the lowest because the process of inspection and the thoroughness of the inspection is more important than the time it takes to complete.



I-max = 4.000 C.I. = 0.000 C.R. = 0	Accuracy	Availability	Safety	Time
Accuracy	0.179	1.000	0.333	1.667
Availability	1.000	0.179	0.333	1.667
Safety	3.000	3.000	0.536	5.000
Time	0.600	0.600	0.200	0.107

Figure 64: Calculated weights for each system goal.

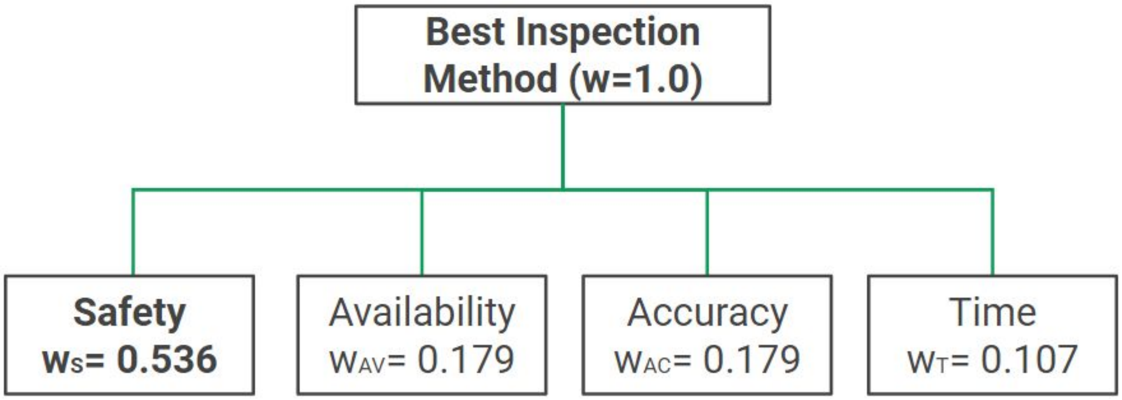


Figure 65: Affinity Diagram for each weighted goal.

11.3 Sensitivity Analysis

If cost is not included in the decision making process, the aerial platform has the highest utility at the weights determined using the AHP method. The vertical lines shown in Figure 66 below indicate the weights determined from the stakeholder's perspective and the relative utility for each design alternative. The Aerial Platform is preferred when the weight of safety is greater than 0.48, weight of availability is less than 0.21, weight of time is less than 0.15, and the weight of accuracy does not change the outcome. The second most preferred is the tower platform. The current method is only better if availability is greater than 0.97.

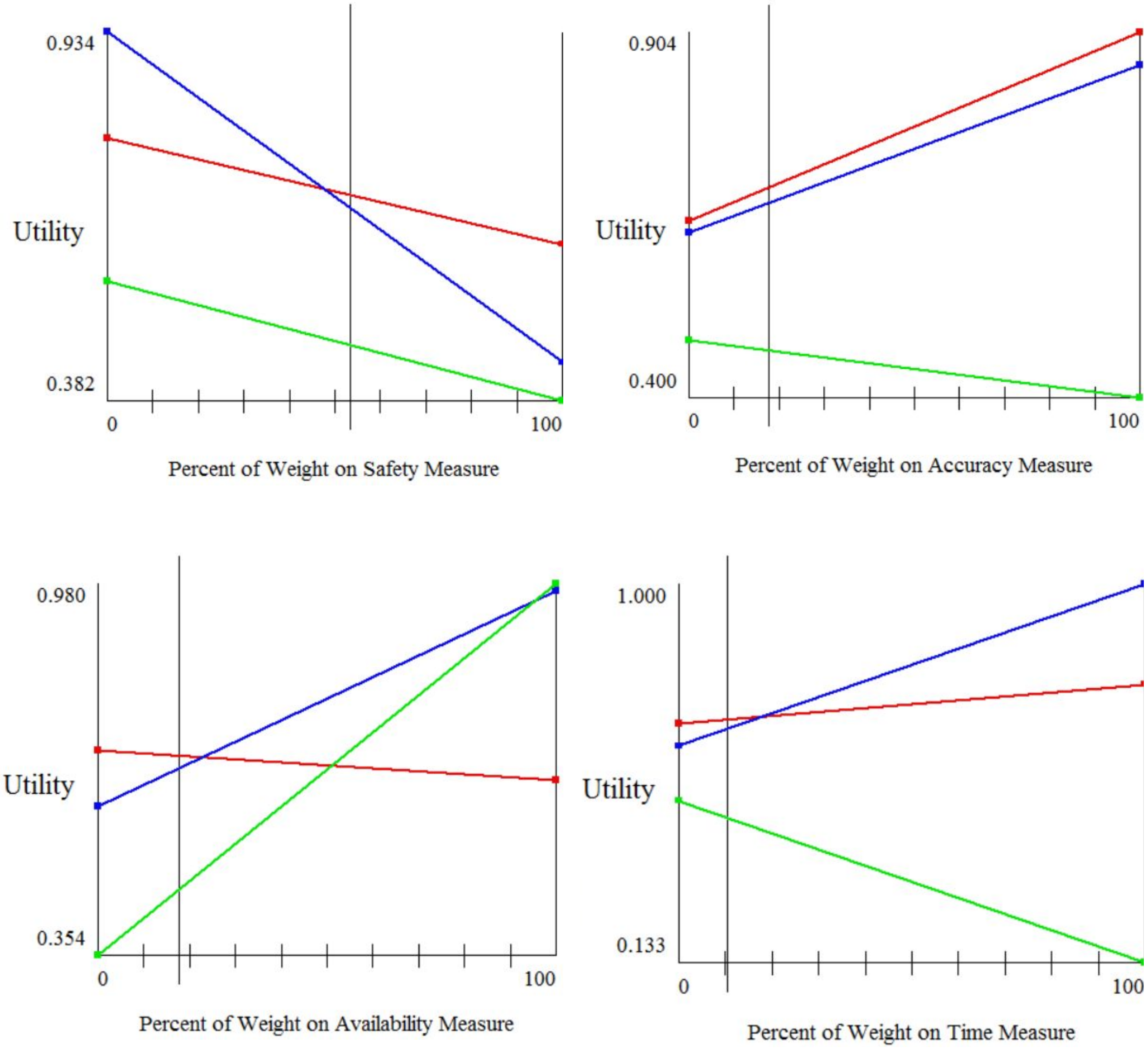


Figure 66: Sensitivity Analysis for Weights

11.4 Cost Versus Utility Analysis

Compared to current manual inspections that cost $423,500 per year on average in the United States, both the mobile aerial platform and tower platform would improve utility (by 48.3%, 43.8% respectively) at a lower cost. The mobile aerial platform would cost $31,862 over the first year of implementation, which includes both acquisition and operating costs. The annual operating cost for the mobile aerial platform is $22,864. The tower platform acquisition cost is $105,316 and has a lower annual operating cost of $16,716. The variance shown in the graph below represents one sigma for utility. If a resort desires continuous monitoring with the Aerial Platform, they would lose 0.0002 in utility for every additional $1,000 spent.

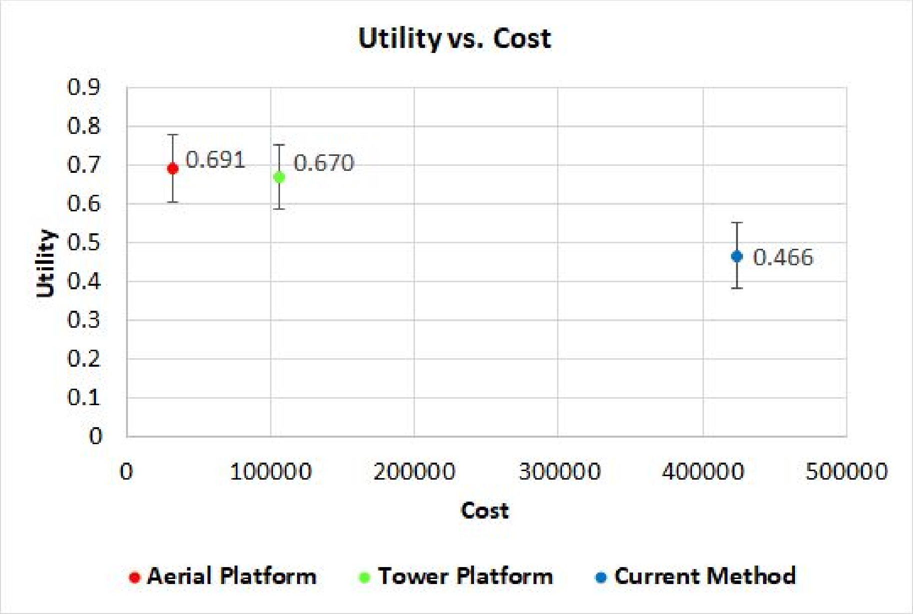


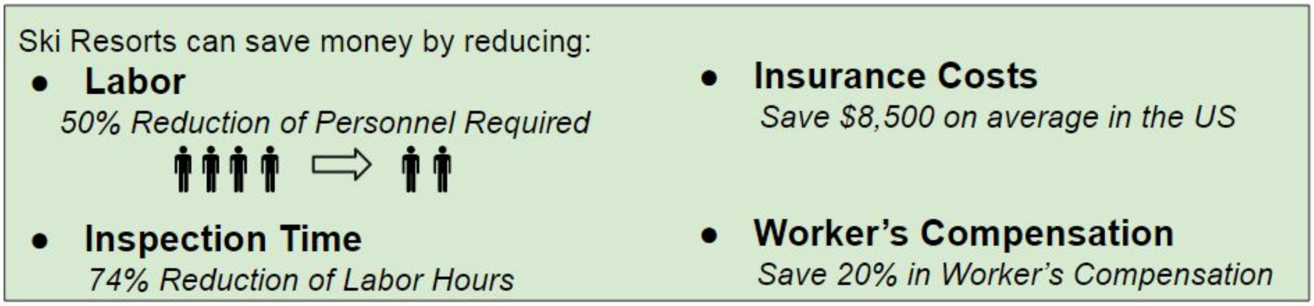
Figure 67: Utility vs. Cost Comparison.

12.0 Business Plan

12.1 Motivation and Business Thesis

Ski lifts transport 51.8 million ski resort visitors on average annually for downhill snowsports that are the main source of revenue for over 500 ski resorts nationwide. Due to climate change shortening the winter season, 80% of ski resorts are now open during the summer. Despite nearly doubling their lift operating days nationally from 117 to 204 days on average and subjecting lifts to a wider range of temperatures, the number of inspections has not changed due to the danger of climbing lift towers (National Ski Areas Association). Tower inspections are both dangerous and expensive due to labor and insurance costs. Maintenance and inspection personnel already risk falling during the tower inspections and maintenance checks they perform that are too infrequent for both what management and personnel desire as well as what the increased system strain demands. The solution is: us.

Our company helps ski lift maintenance personnel, inspection personnel, and ski lift management who experience risk of injury from falling while conducting ski lift inspections when they climb lift towers and must remember location and severity of defects inspected to complete paperwork when they get back to the ground by providing a safer, more accurate, and faster UAV system that can archive component data and perform inspections more frequently at a lower cost due to insurance and labor savings resulting in fewer workplace incidents and reduced liability costs, a reduction in inspection costs, and methods to track failure progression of components better than the current risk-prone inspections that require climbing the towers that could be increased from only 5 times a year to weekly as ski lift operational periods expand into the summer.



Ski Resorts can save money by reducing:

- **Labor**
  50% Reduction of Personnel Required
- **Inspection Time**
  74% Reduction of Labor Hours
- **Insurance Costs**
  Save $8,500 on average in the US
- **Worker's Compensation**
  Save 20% in Worker's Compensation

Figure 68: Resort Motivations

12.2 Business Model

INSPEX generates profit through commission as a vendor for DJI drones as well as FLIR Thermal and HD GoPro Cameras. INSPEX also generates profit through a data management and analysis subscription for image processing and storage. There is no other company in the United States that provides both UAV systems and image data management, which collects data for Ski Lift failure analysis across the industry.

What a Purchase Includes:

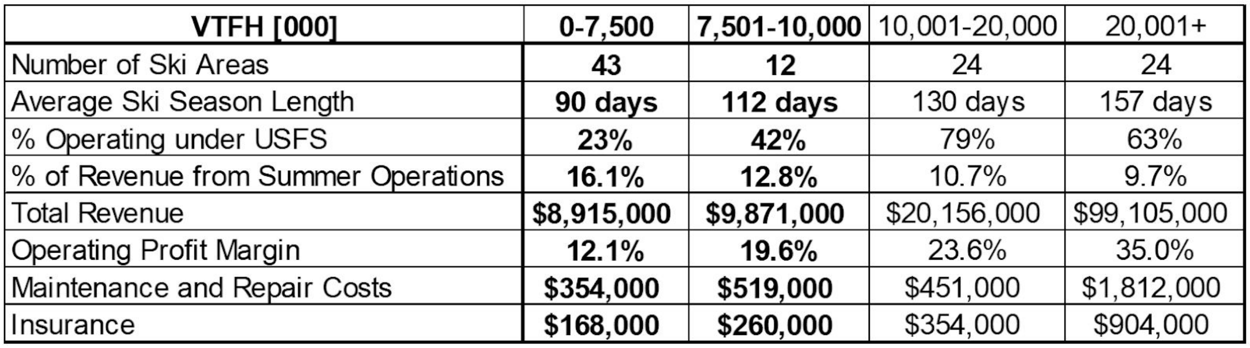
- Integrated Digital UAV Inspection System (complete with thermal and HD cameras and preloaded software)
- Recommended FAA Part 107 Schools/Training Resources
- Subscription (based on quote, starting at $2000/month):
  - Inspection Report
  - Data analysis and predictive failure progression report
  - OpenCV Image Processing
  - Amazon Web Services Cloud Storage for 2 months worth of high definition inspection video stored at a time (data and reports can be stored for longer)
- Operational Consultation
- Annual personnel retraining
- Regulatory update

What a Purchase Does Not Include:

- Drone Insurance (Recommended): quoted to cost $1000/year for liability, hull, and malicious damage
- Part 107 Exam(s): $150 each, depending how many it takes to pass
- Drone operation training (recommended): $500

12.3 Market Analysis

The target market for a ski lift inspection system consists of smaller ski resorts that are less likely to be subject to US Forest Rules and have a lower operating profit margin. The percentage of maintenance and repair costs for smaller resorts is 4% of their total revenue, compared to 2% for larger resorts. Therefore, these resorts would benefit the most from a cost reduction for lift inspections and maintenance. Smaller ski resorts are classified based on a VTFH between 0-10,000. Based on the NSAA Economic Analysis Report, fifty percent of Ski Resorts in the US have a VTFH less than 10,000. Therefore, the primary target market for our ski lift inspection system consists of approximately 260 ski resorts compared to the total of 521 ski resorts in the United States. Larger resorts could be also targeted because they have longer ski seasons that cannot be interrupted due to safety concerns. Fifty percent of US Ski resorts are considered large. Economic characteristics from the NSAA Economic survey for resorts of each size category are summarized in the table below.



VTFH [000]	**0-7,500**	**7,501-10,000**	10,001-20,000	20,001+
Number of Ski Areas	**43**	**12**	24	24
Average Ski Season Length	**90 days**	**112 days**	130 days	157 days
% Operating under USFS	**23%**	**42%**	79%	63%
% of Revenue from Summer Operations	**16.1%**	**12.8%**	10.7%	9.7%
Total Revenue	**$8,915,000**	**$9,871,000**	$20,156,000	$99,105,000
Operating Profit Margin	**12.1%**	**19.6%**	23.6%	35.0%
Maintenance and Repair Costs	**$354,000**	**$519,000**	$451,000	$1,812,000
Insurance	**$168,000**	**$260,000**	$354,000	$904,000

Figure 69: NSAA Economic Analysis Survey Response Summary

12.4 Marketing and Sales Strategy

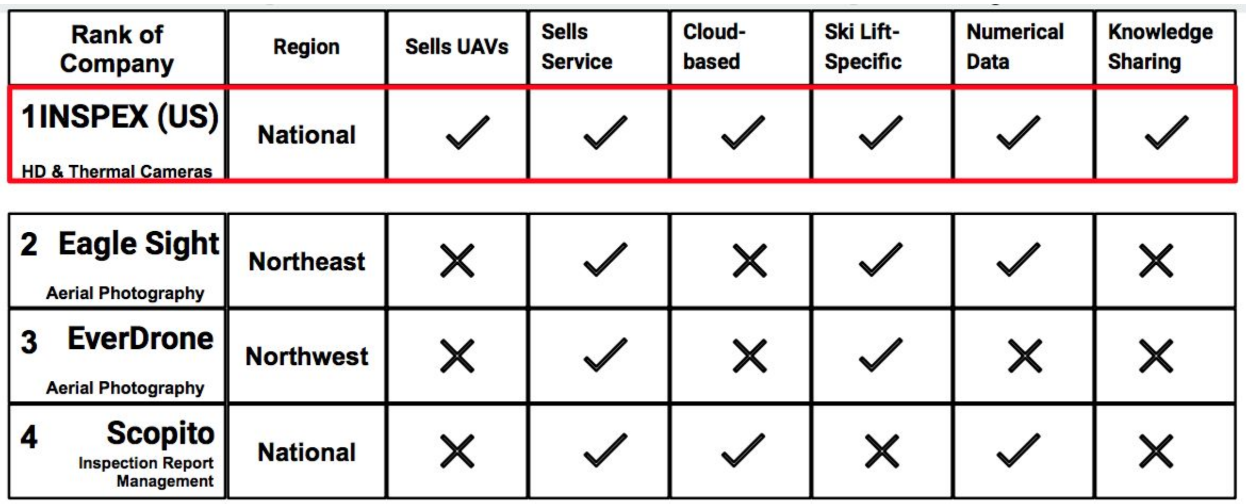
To enter the market, members of the National Ski Areas Association (NSAA) and geographic clusters will be targeted. The NSAA is headquartered in Colorado, which is one of the largest geographic clusters in the US. The state of Colorado is an industry hub and role model for safety and regulation for the entire country. By demonstrating the integrated system at several conferences and seminars shown in the table below, exposure to industry decision-makers will increase visibility and boost sales. Involvement with regulatory bodies such as the Colorado Passenger Tramway Safety Board will help the system become standard for the industry. The NSAA will also be publishing an article about INSPEX for their bi-monthly magazine, which has over 700 ski resort industry subscribers.

Date	**Opportunity**	**Location**
April 2018	NSAA Lift Maintenance Seminar	Massachusetts
May 2018	NSAA Convention	Marco Island, Florida
May 2018	Rocky Mountain Lift Association	Colorado
January 2019	Western Winter Conference	Snowbird, Utah
February 2019	Eastern Winter Conference	Killington, Vermont

Figure 70: Demonstration Opportunities

12.5 Market Competition and Competitive Advantage

INSPEX is one-stop shop for UAVs and a Cloud-based Inspection Service that specializes in ski lifts for visual and numerical data analysis. The cloud-based inspection data management company Scopito is limited in data collection capability and mass image processing as it is not an automated system nor designed for ski lifts. Other ski lift inspection companies such as Eagle Sight and EverDrone are limited in availability to the number of pilots available within the region that they can serve. They also lack experience with maintenance procedures or mechanical problems. INSPEX offers a platform for knowledge sharing in an industry that operates in a fix-as-you-go corrective maintenance philosophy with little knowledge on ski lift failures and few numeric tolerances for component failure. Our engineers can provide knowledge and expertise that aerial photographers cannot and should not provide. A side by side comparison of INSPEX and other competition can be found in the table below.



Rank of Company	Region	Sells UAVs	Sells Service	Cloud-based	Ski Lift-Specific	Numerical Data	Knowledge Sharing
1 INSPEX (US) HD & Thermal Cameras	National	✓	✓	✓	✓	✓	✓
2 Eagle Sight Aerial Photography	Northeast	✗	✓	✗	✓	✓	✗
3 EverDrone Aerial Photography	Northwest	✗	✓	✗	✓	✗	✗
4 Scopito Inspection Report Management	National	✗	✓	✓	✗	✓	✗

Figure 71: Competition Comparison

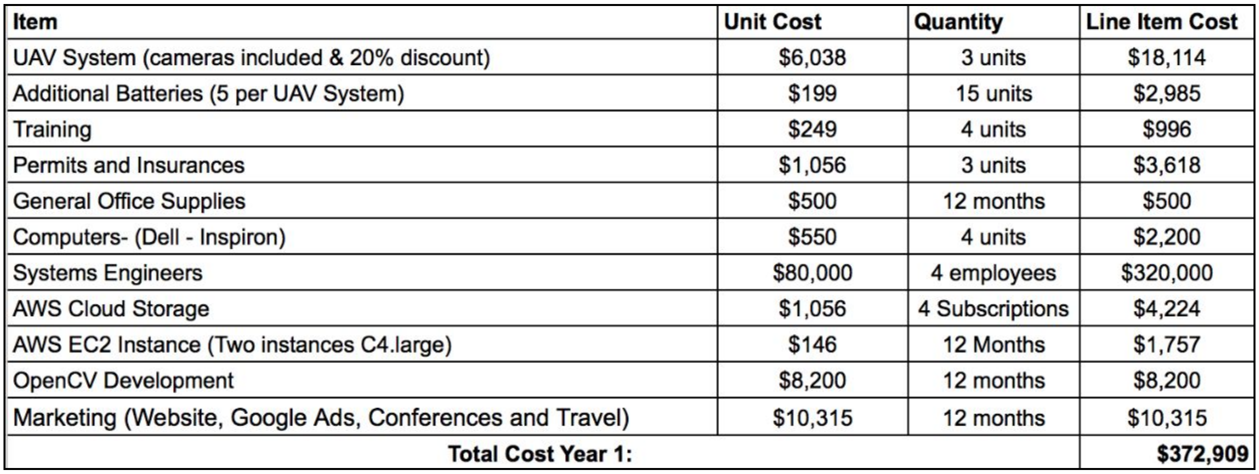
If a resort were to purchase a UAV from another vendor or buy an integrated system, they would pay several thousand dollars more. No other company offers an integrated system that comes preloaded with software for cloud-based data management and predictive analytics. A cost summary can be found in the table below.

	Buy a Drone:		Both:	Buy a Service:		
Company	ARMUS	UAS THERMALS	INSPEX	Eagle Sight	EverDrone	Scopito Image Processing
Cheapest Thermal Drone System	$15,999	$12,950	$8,500	N/A	N/A	N/A
Drone Inspection Service	N/A	N/A	$2,000 per month	$3,000 per month	$3,000 per month	$778 per month

Figure 72: Competition Cost Comparison

12.6 Business Costs

Startup costs include the cost to acquire the technology including hardware and software development as well as marketing and labor costs. Software development requires two employees, while hardware development and data collection requires one employee. The remaining employee will be dedicated to marketing. A summary of startup costs for year one can be found below.

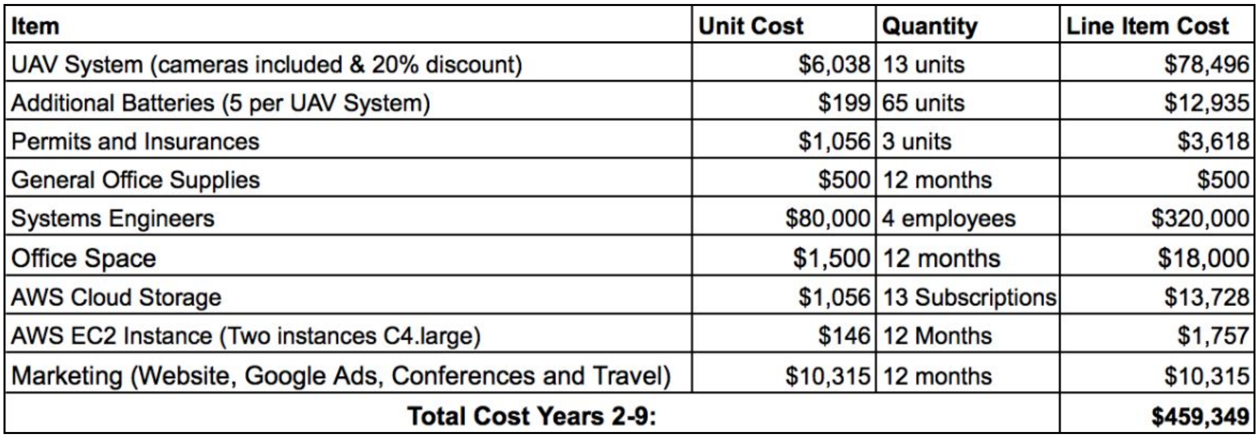


Item	Unit Cost	Quantity	Line Item Cost
UAV System (cameras included & 20% discount)	$6,038	3 units	$18,114
Additional Batteries (5 per UAV System)	$199	15 units	$2,985
Training	$249	4 units	$996
Permits and Insurances	$1,056	3 units	$3,618
General Office Supplies	$500	12 months	$500
Computers- (Dell - Inspiron)	$550	4 units	$2,200
Systems Engineers	$80,000	4 employees	$320,000
AWS Cloud Storage	$1,056	4 Subscriptions	$4,224
AWS EC2 Instance (Two instances C4.large)	$146	12 Months	$1,757
OpenCV Development	$8,200	12 months	$8,200
Marketing (Website, Google Ads, Conferences and Travel)	$10,315	12 months	$10,315
Total Cost Year 1:			**$372,909**

Figure 73: Startup Cost Summary

Business costs are based on quotes for equipment, insurances, image processing, and cloud storage. Purchases for businesses and resale receive a 20%

discount for all DJI UAVs. Larger ski resorts that have several lifts would require multiple inspection systems and a higher level subscription to be purchased. For the purpose of market penetration and cost estimation, one system and one small subscription per ski resort was used as the baseline of sales. Due to the size of some geographic clusters and existing industry relationships, we expect exponential growth (at a rate of 6%) starting at 5% market penetration (13 ski resorts) annually. Annual operating costs depend on the number of units sold. An example of operating costs can be found in the table below.

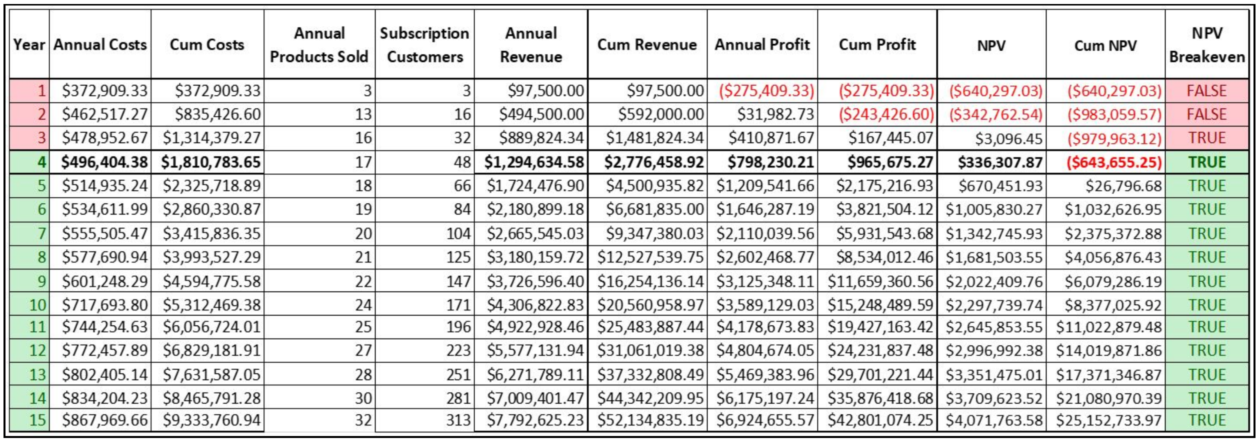


Item	**Unit Cost**	**Quantity**	**Line Item Cost**
UAV System (cameras included & 20% discount)	$6,038	13 units	$78,496
Additional Batteries (5 per UAV System)	$199	65 units	$12,935
Permits and Insurances	$1,056	3 units	$3,618
General Office Supplies	$500	12 months	$500
Systems Engineers	$80,000	4 employees	$320,000
Office Space	$1,500	12 months	$18,000
AWS Cloud Storage	$1,056	13 Subscriptions	$13,728
AWS EC2 Instance (Two instances C4.large)	$146	12 Months	$1,757
Marketing (Website, Google Ads, Conferences and Travel)	$10,315	12 months	$10,315
Total Cost Years 2-9:			**$459,349**

Figure 74: Operational Cost Summary

12.3 Revenue Projection

Revenue projection is based on the number of products sold each year in addition to cumulative and continuing customers for the sale of subscriptions. The total investment required for the first year is $372,909. The cumulative profit projection for year 5 is $715,354. In 15 years, the cumulative profit projection becomes $33 million.



Year	Annual Costs	Cum Costs	Annual Products Sold	Subscription Customers	Annual Revenue	Cum Revenue	Annual Profit	Cum Profit	NPV	Cum NPV	NPV Breakeven
1	$372,909.33	$372,909.33	3	3	$97,500.00	$97,500.00	($275,409.33)	($275,409.33)	($640,297.03)	($640,297.03)	FALSE
2	$462,517.27	$835,426.60	13	16	$494,500.00	$592,000.00	$31,982.73	($243,426.60)	($342,762.54)	($983,059.57)	FALSE
3	$478,952.67	$1,314,379.27	16	32	$889,824.34	$1,481,824.34	$410,871.67	$167,445.07	$3,096.45	($979,963.12)	TRUE
4	**$496,404.38**	**$1,810,783.65**	17	48	**$1,294,634.58**	**$2,776,458.92**	**$798,230.21**	**$965,675.27**	**$336,307.87**	**($643,655.25)**	**TRUE**
5	$514,935.24	$2,325,718.89	18	66	$1,724,476.90	$4,500,935.82	$1,209,541.66	$2,175,216.93	$670,451.93	$26,796.68	TRUE
6	$534,611.99	$2,860,330.87	19	84	$2,180,899.18	$6,681,835.00	$1,646,287.19	$3,821,504.12	$1,005,830.27	$1,032,626.95	TRUE
7	$555,505.47	$3,415,836.35	20	104	$2,665,545.03	$9,347,380.03	$2,110,039.56	$5,931,543.68	$1,342,745.93	$2,375,372.88	TRUE
8	$577,690.94	$3,993,527.29	21	125	$3,180,159.72	$12,527,539.75	$2,602,468.77	$8,534,012.46	$1,681,503.55	$4,056,876.43	TRUE
9	$601,248.29	$4,594,775.58	22	147	$3,726,596.40	$16,254,136.14	$3,125,348.11	$11,659,360.56	$2,022,409.76	$6,079,286.19	TRUE
10	$717,693.80	$5,312,469.38	24	171	$4,306,822.83	$20,560,958.97	$3,589,129.03	$15,248,489.59	$2,297,739.74	$8,377,025.92	TRUE
11	$744,254.63	$6,056,724.01	25	196	$4,922,928.46	$25,483,887.44	$4,178,673.83	$19,427,163.42	$2,645,853.55	$11,022,879.48	TRUE
12	$772,457.89	$6,829,181.91	27	223	$5,577,131.94	$31,061,019.38	$4,804,674.05	$24,231,837.48	$2,996,992.38	$14,019,871.86	TRUE
13	$802,405.14	$7,631,587.05	28	251	$6,271,789.11	$37,332,808.49	$5,469,383.96	$29,701,221.44	$3,351,475.01	$17,371,346.87	TRUE
14	$834,204.23	$8,465,791.28	30	281	$7,009,401.47	$44,342,209.95	$6,175,197.24	$35,876,418.68	$3,709,623.52	$21,080,970.39	TRUE
15	$867,969.66	$9,333,760.94	32	313	$7,792,625.23	$52,134,835.19	$6,924,655.57	$42,801,074.25	$4,071,763.58	$25,152,733.97	TRUE

Figure 75: Financial Projection Table

Based on the expected market penetration and net present value (NPV), the first three years will end in a loss, followed by a breakeven (profit) for year 4 and thereafter. A graph of projections for the first five years of business can be found in the table below.

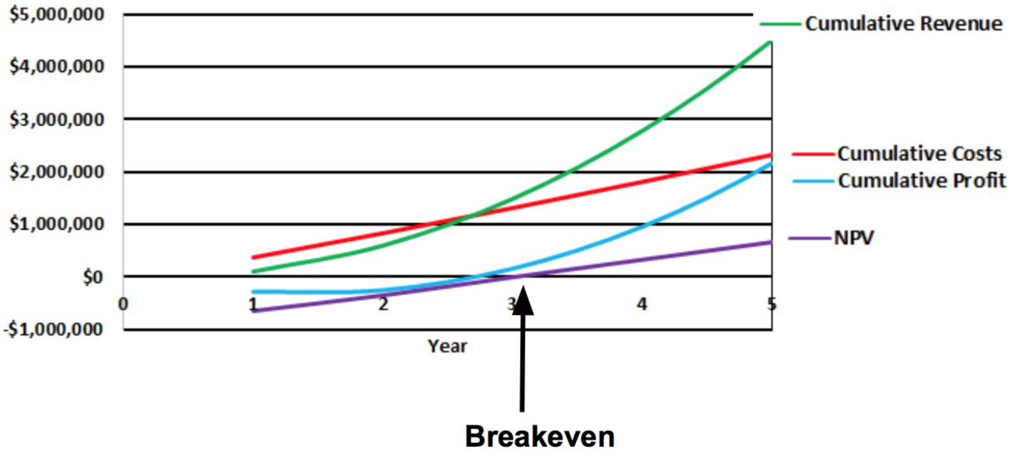


Figure 76: Revenue, Cost, and Profit Projection for 5 Years

The return on investment (ROI) for expected market penetration is 480% for year 5. Optimistic and pessimistic revenue projections end with an ROI of 640% and 260% for year 5 respectively. A summary of expected, optimistic, and pessimistic returns can be found in the table below for year 5, 10, and 15.

	Expected	Optimistic	Pessimistic
5 year ROI	480%	640%	260%
10 year ROI	3990%	4580%	3090%
15 year ROI	11380%	12840%	9250%
Breakeven	**Year 4**	**Year 3**	**Year 4**

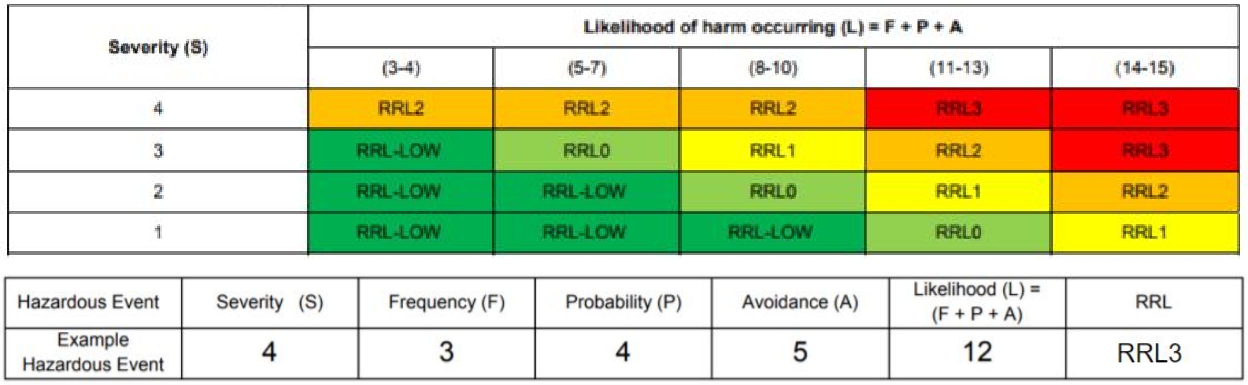
Figure 77: Expected, Optimistic, and Pessimistic Return on Investment

13.0 Future Work: Predictive Analytics and Audio Inspections

Predictive Analytics is the use of data, statistical algorithms, and machine learning techniques to identify the likelihood of future outcomes based on historical data. Behavior regarding the frequency of inspection for each type of component can be monitored. Ski lift manufacturers would also be able to track quality control for replacement parts based on individual component lifespans. The measurements taken during an inspection may be used to predict when a lift falls within range of risk. Due to the battery limitations of the aerial platform, this solution would provide a methodology to optimize and shorten the inspection times for a particular lift by tracking failure progression.

Applications of predictive analytics also include image processing algorithms to obtain motion patterns for dynamic lift system analysis. Audio inspections for wheel and bearing squeaking can also be included for predictive analysis and failure progression analysis. Predictive analytics can be used in conjunction with the current method, the aerial platform, or the tower platform to determine periods of high risk when there is more demand on the system or when components are the most brittle and have the highest probability of failure. The frequency of inspection is dependent on both the probability of failure and the availability of the inspection system. Inspections should especially be performed when the probability of failure increases during the most demanding winter months.

ANSI Lift Standards have pre-existing definitions for risk reduction that can be used to classify the level of risk for a lift based on data from inspections. If the level of risk is too high, the lift should be closed for repair. The severity (S) of possible harm and the likelihood (L) of harm occurring will be used as measures for the required risk reduction level defined by ANSI and respective inspection frequency [15]. The severity of possible harm is based on historical accidents and their respective number or injuries and fatalities. The likelihood is based on the frequency (F) of the hazardous situation (the probability of the component failure), the probability (P) of occurrence for the hazardous event (the probability of the respective accident), and the probability (A) of avoiding or limiting harm.

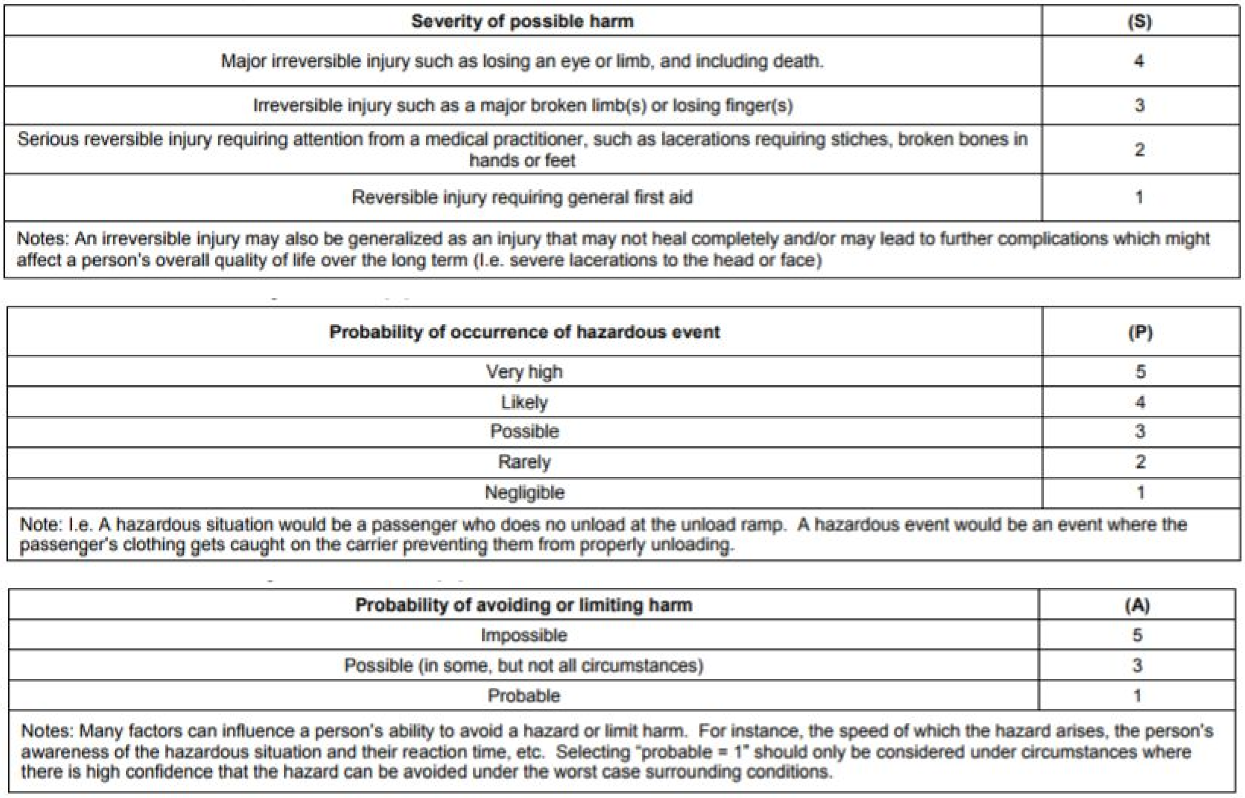


Severity (S)	**Likelihood of harm occurring (L) = F + P + A**				
	(3-4)	(5-7)	(8-10)	(11-13)	(14-15)
4	RRL2	RRL2	RRL2	RRL3	RRL3
3	RRL-LOW	RRL0	RRL1	RRL2	RRL3
2	RRL-LOW	RRL-LOW	RRL0	RRL1	RRL2
1	RRL-LOW	RRL-LOW	RRL-LOW	RRL0	RRL1

Hazardous Event	Severity (S)	Frequency (F)	Probability (P)	Avoidance (A)	Likelihood (L) = (F + P + A)	RRL
Example Hazardous Event	4	3	4	5	12	RRL3

Figure 78: Risk Reduction Level Matrix and Sample Calculation [15].

Given that failures and accidents are random stochastic processes, the frequency of inspections serves as the statistical process control, which will also reduce the probability of component failures and accidents. The probability (A) of avoiding or limiting harm will be defined by failure progression and whether or not the set inspection frequency is sufficient to track degradation before a more catastrophic failure occurs. The scales defined by ANSI Standards for these probabilities are shown in the tables below. Thresholds for reliability for each of the following scales can be determined through inspection data analysis based on age, operating hours, manufacturer, and component trends for failure.



Severity of possible harm	(S)
Major irreversible injury such as losing an eye or limb, and including death.	4
Irreversible injury such as a major broken limb(s) or losing finger(s)	3
Serious reversible injury requiring attention from a medical practitioner, such as lacerations requiring stiches, broken bones in hands or feet	2
Reversible injury requiring general first aid	1
Notes: An irreversible injury may also be generalized as an injury that may not heal completely and/or may lead to further complications which might affect a person's overall quality of life over the long term (I.e. severe lacerations to the head or face)	

Probability of occurrence of hazardous event	(P)
Very high	5
Likely	4
Possible	3
Rarely	2
Negligible	1
Note: I.e. A hazardous situation would be a passenger who does no unload at the unload ramp. A hazardous event would be an event where the passenger's clothing gets caught on the carrier preventing them from properly unloading.	

Probability of avoiding or limiting harm	(A)
Impossible	5
Possible (in some, but not all circumstances)	3
Probable	1
Notes: Many factors can influence a person's ability to avoid a hazard or limit harm. For instance, the speed of which the hazard arises, the person's awareness of the hazardous situation and their reaction time, etc. Selecting "probable = 1" should only be considered under circumstances where there is high confidence that the hazard can be avoided under the worst case surrounding conditions.	

Table 79: Scale for Probabilities

To identify risk for a particular resort, the Vertical Transport Feet per Hour can be used for a preliminary estimate of visitors and speed to analyze risk. The number of people that ride a lift daily should be tracked using ticket data, so the approximate weight and stresses on the system can be taken into account. Then, periods of peak load can be identified to plan inspections and repair. Several resorts currently use RFID systems to track riders for economic analysis, but the technology would be beneficial to use for a more accurate estimate of the number of visitors. Periods of higher stress and lifts that run at higher speeds would require higher frequencies of inspection for risk reduction. For example, the period with the most customers and highest load tends to be during the winter months when components are also the most brittle. The level of risk reduction should be the highest during the winter months, so the frequency of inspections would be the highest.

14.0 Project Plan

14.1 Statement of Work

Background

Ski lifts are mechanical, electrical devices that operate in severe and changing weather conditions. They are a critical component of ski resorts. Bryce resort in Virginia would like to evaluate alternative designs to perform routine, periodic, inspections. Skylark Drones is interested in supplying their drones for use as one of the potential design alternatives. The National Ski Areas Association (NSAA) produces documentation for inspection of lifts and holds regional meetings each year to discuss lift maintenance. This project will present results of study at this meeting.

Objectives

The objective of this statement of work is developing a design alternative to perform routine, periodic, inspections on ski towers for Bryce Resort.

Scope of the Work

Unless otherwise specified, the team shall perform the following tasks:

1. Create a project plan
2. Meet the requirements of each deliverable on time

Period of Performance

The period of performance for the Ski Lift Maintenance/Inspection (INSPEX) project is 9 months with a start date of Aug 28, 2017 and an end date of May 18, 2018. All work is to be scheduled to completion within this time. Extensions to the schedule will not be considered.

The selected vendor for the INSPEX project will submit weekly individual time sheets with the total number of billing hours completed by each team member.

Place of Performance

The bulk of the work for the INSPEX project will be performed on site at George Mason University. Location of meetings with the vendor and client are to be determined.

Work Requirements

As part of the INSPEX project, the vendor is responsible for executing and completing the required tasks throughout the life of this project. The following is a list of these tasks:

Kickoff:

- Identify client's problem and needs
- Conduct preliminary research and gather data
- Present plan to client for approval

Requirements Phase:

- Work with Bryce Resort to gather requirements and maintenance procedures/regulations
- Develop originating requirements
- Derive mission requirements, functional requirements, design requirements, and simulation requirements

Design Phase:

- Develop design alternatives
- Derive high level design, detailed design, and simulation design
- Develop DoE and design proposal for Bryce Resort review and approval

Testing Phase:

- Test system validation
- Run simulation tests and results
- Analyze simulation results
- Confirm system verification
- Conduct sensitivity/cost/tradeoff analyses
- Compile a testing report to present to Bryce Resort for approval

Other Phases:

- Bryce Resort will be provided all finalized documentation of project plan

Deliverables/Milestones Schedule

Required Deliverables/Reports	Required Due Dates
Preliminary Project Plan	18-Sep-17
Requirements Development	02-Oct-17
Simulation Design	23-Oct-23
Simulation	22-Jan-18
Analysis	31-Jan-18
Testing	22-Mar-18

Table 80: Deliverables Schedule

Acceptance Criteria

The client named below verifies that the terms of this Statement of Work is acceptable. The parties hereto are each acting with proper authority by their respective companies.

Skylark Drone Research	INSPEX
Company name	Company name
Full name	Full name
Title	Title

Signature

Signature

Date

Date

14.2 Work Breakdown Structure (WBS)

The top level of the Work Breakdown Structure is Management, Research, Requirements, Design, Simulation/Testing, Analysis, and System Verification/Validation.

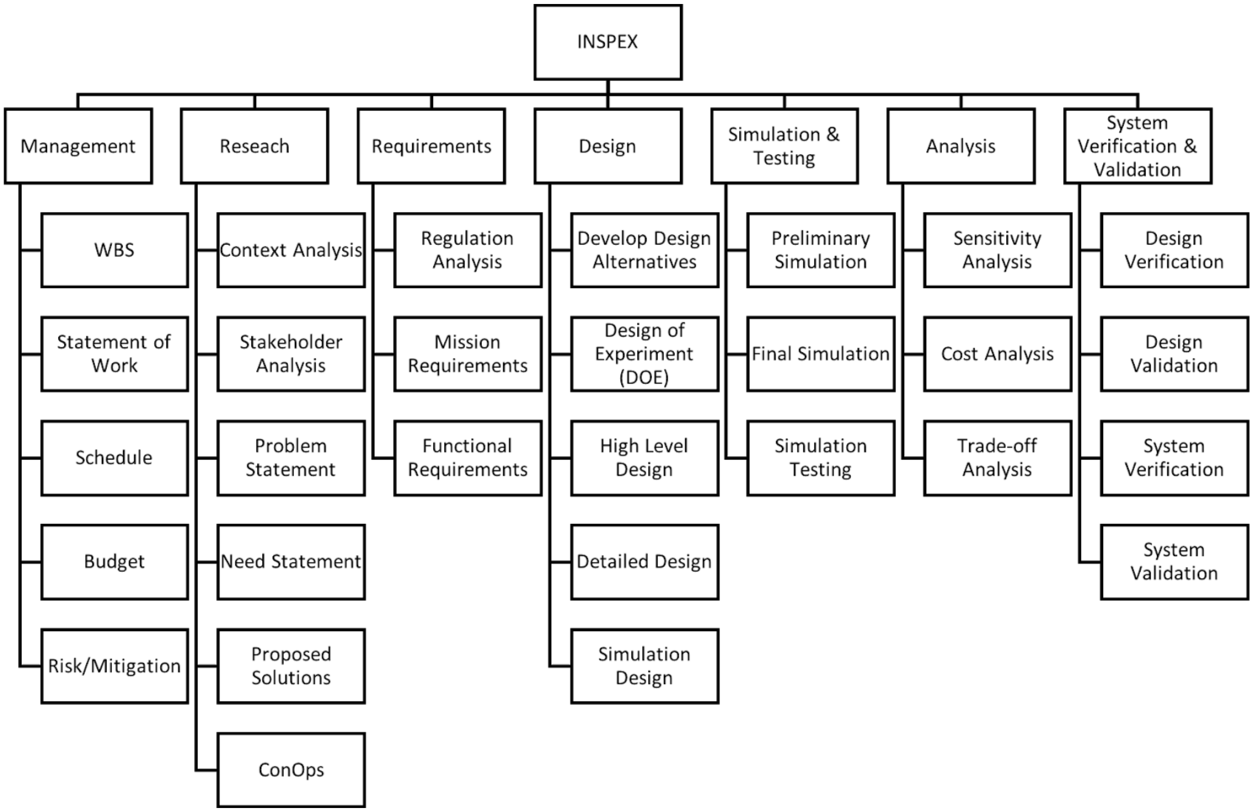
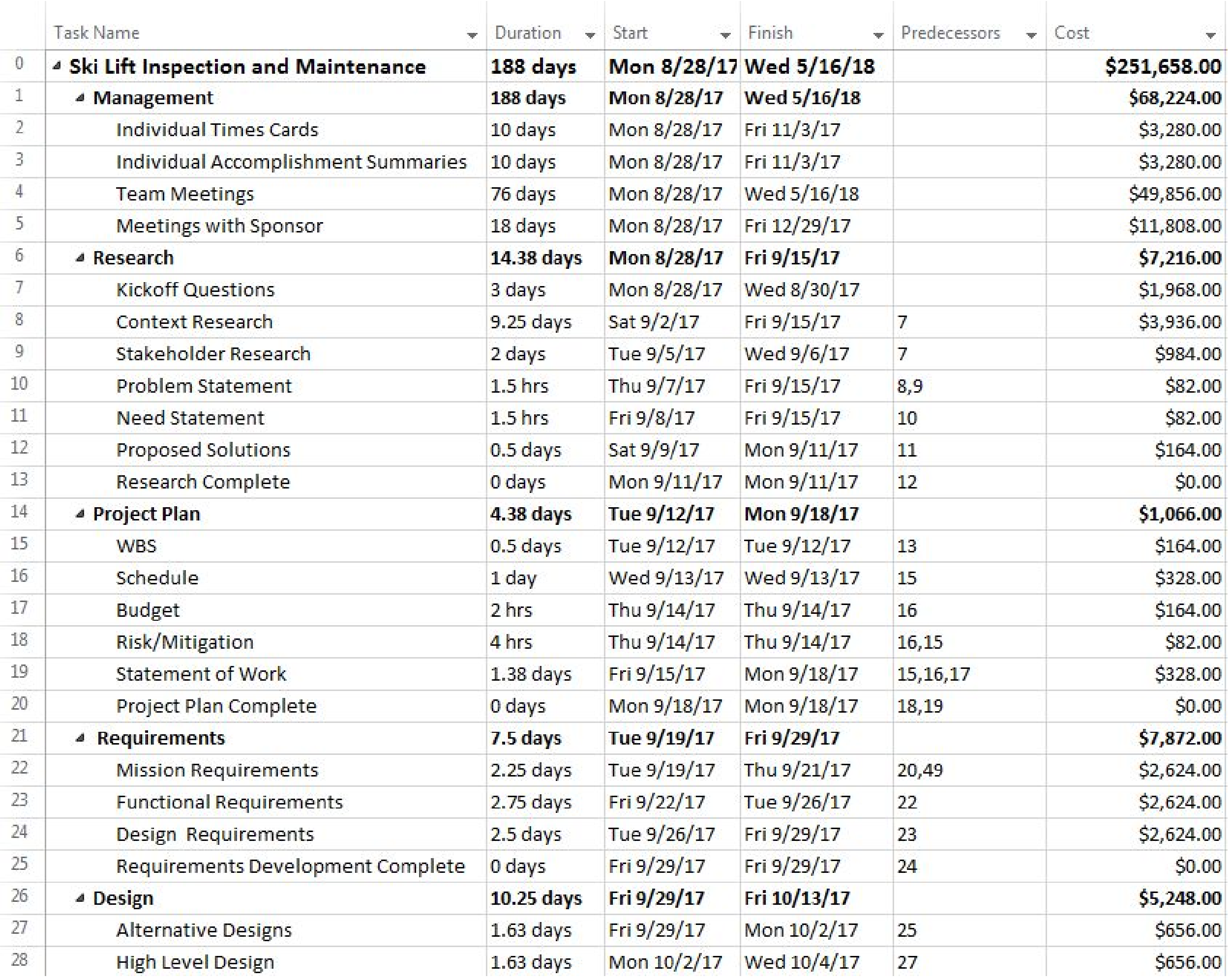


Figure 81: Work Breakdown Structure

14.3 Project Schedule

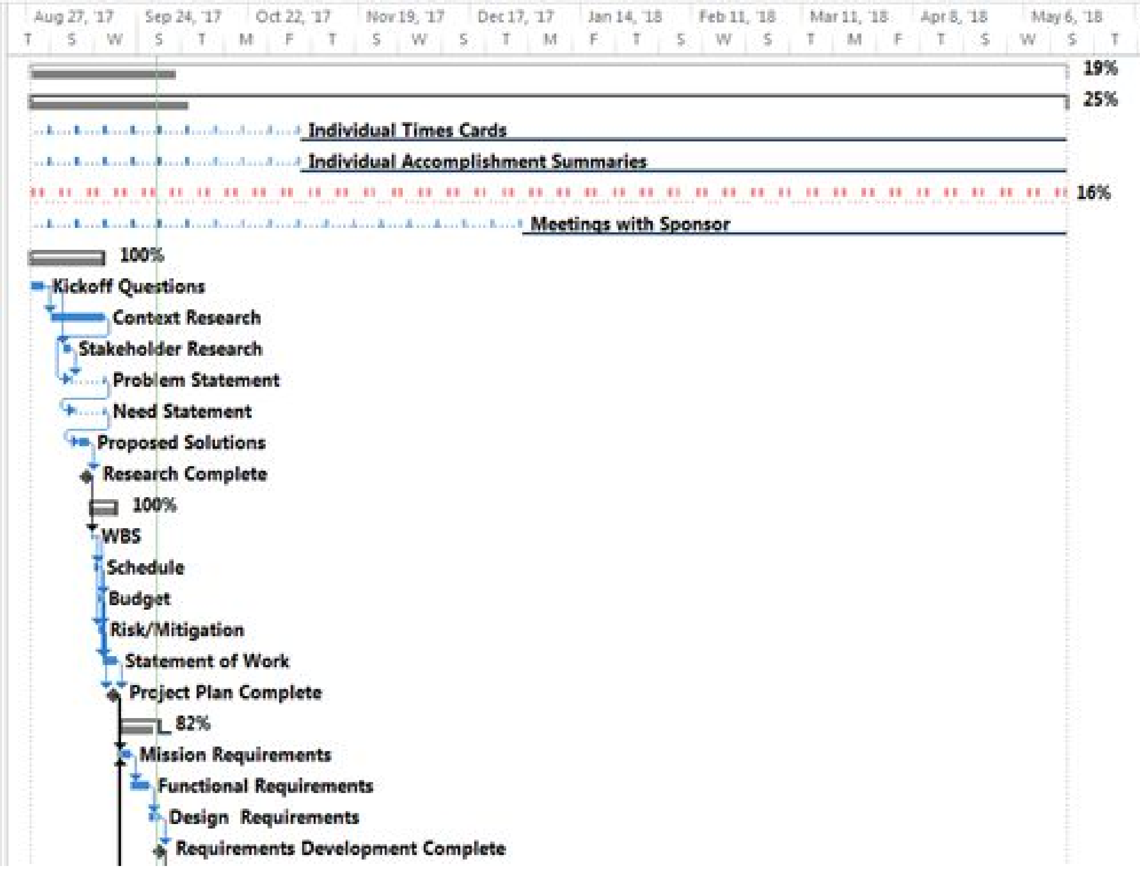


	Task Name	Duration	Start	Finish	Predecessors	Cost
0	**Ski Lift Inspection and Maintenance**	**188 days**	**Mon 8/28/17**	**Wed 5/16/18**		**$251,658.00**
1	**Management**	**188 days**	**Mon 8/28/17**	**Wed 5/16/18**		**$68,224.00**
2	Individual Times Cards	10 days	Mon 8/28/17	Fri 11/3/17		$3,280.00
3	Individual Accomplishment Summaries	10 days	Mon 8/28/17	Fri 11/3/17		$3,280.00
4	Team Meetings	76 days	Mon 8/28/17	Wed 5/16/18		$49,856.00
5	Meetings with Sponsor	18 days	Mon 8/28/17	Fri 12/29/17		$11,808.00
6	**Research**	**14.38 days**	**Mon 8/28/17**	**Fri 9/15/17**		**$7,216.00**
7	Kickoff Questions	3 days	Mon 8/28/17	Wed 8/30/17		$1,968.00
8	Context Research	9.25 days	Sat 9/2/17	Fri 9/15/17	7	$3,936.00
9	Stakeholder Research	2 days	Tue 9/5/17	Wed 9/6/17	7	$984.00
10	Problem Statement	1.5 hrs	Thu 9/7/17	Fri 9/15/17	8,9	$82.00
11	Need Statement	1.5 hrs	Fri 9/8/17	Fri 9/15/17	10	$82.00
12	Proposed Solutions	0.5 days	Sat 9/9/17	Mon 9/11/17	11	$164.00
13	Research Complete	0 days	Mon 9/11/17	Mon 9/11/17	12	$0.00
14	**Project Plan**	**4.38 days**	**Tue 9/12/17**	**Mon 9/18/17**		**$1,066.00**
15	WBS	0.5 days	Tue 9/12/17	Tue 9/12/17	13	$164.00
16	Schedule	1 day	Wed 9/13/17	Wed 9/13/17	15	$328.00
17	Budget	2 hrs	Thu 9/14/17	Thu 9/14/17	16	$164.00
18	Risk/Mitigation	4 hrs	Thu 9/14/17	Thu 9/14/17	16,15	$82.00
19	Statement of Work	1.38 days	Fri 9/15/17	Mon 9/18/17	15,16,17	$328.00
20	Project Plan Complete	0 days	Mon 9/18/17	Mon 9/18/17	18,19	$0.00
21	**Requirements**	**7.5 days**	**Tue 9/19/17**	**Fri 9/29/17**		**$7,872.00**
22	Mission Requirements	2.25 days	Tue 9/19/17	Thu 9/21/17	20,49	$2,624.00
23	Functional Requirements	2.75 days	Fri 9/22/17	Tue 9/26/17	22	$2,624.00
24	Design Requirements	2.5 days	Tue 9/26/17	Fri 9/29/17	23	$2,624.00
25	Requirements Development Complete	0 days	Fri 9/29/17	Fri 9/29/17	24	$0.00
26	**Design**	**10.25 days**	**Fri 9/29/17**	**Fri 10/13/17**		**$5,248.00**
27	Alternative Designs	1.63 days	Fri 9/29/17	Mon 10/2/17	25	$656.00
28	High Level Design	1.63 days	Mon 10/2/17	Wed 10/4/17	27	$656.00

	Task Name	Duration	Start	Finish	Predecessors	Cost
29	Detailed Design	1.63 days	Wed 10/4/17	Fri 10/6/17	28	$656.00
30	Trade-off Analysis	1.63 days	Fri 10/6/17	Mon 10/9/17	29	$656.00
31	Design of Experiment (DOE)	1.88 days	Mon 10/9/17	Wed 10/11/17	30	$1,312.00
32	Simulation Design	1.88 days	Wed 10/11/17	Fri 10/13/17	31	$1,312.00
33	Simulation Design Complete	0 days	Fri 10/13/17	Fri 10/13/17	32	$0.00
34	**Simulation**	**62 days**	**Fri 11/17/17**	**Mon 2/12/18**		**$81,344.00**
35	Preliminary Simulation	20 days	Fri 11/17/17	Thu 12/14/17	33	$26,240.00
36	Final Simulation	20 days	Fri 12/15/17	Thu 1/11/18	35	$26,240.00
37	Simulation Testing	22 days	Fri 1/12/18	Mon 2/12/18		$28,864.00
38	Simulation Complete	0 days	Mon 2/12/18	Mon 2/12/18		$0.00
39	**Analysis**	**30 days**	**Tue 2/13/18**	**Mon 3/26/18**		**$24,928.00**
40	Sensitivity Analysis	10 days	Tue 2/13/18	Mon 2/26/18	38	$5,248.00
41	Cost Analysis	10 days	Tue 2/27/18	Mon 3/12/18	40	$6,560.00
42	Trade-off Analysis	10 days	Tue 3/13/18	Mon 3/26/18	41	$13,120.00
43	Analysis Complete	0 days	Mon 3/26/18	Mon 3/26/18	42	$0.00
44	**Testing**	**35 days**	**Fri 2/16/18**	**Fri 4/6/18**		**$42,640.00**
45	Design Verification	11 days	Fri 2/16/18	Fri 3/2/18	38	$12,464.00
46	Design Validation	11 days	Mon 3/5/18	Mon 3/19/18	45	$14,432.00
47	System Verification & Validation	13 days	Tue 3/20/18	Thu 4/5/18	45,46	$15,744.00
48	**Presentations**	**151 days**	**Mon 9/18/17**	**Tue 4/17/18**		**$0.00**
49	Briefing 1 Complete	0 days	Mon 9/18/17	Mon 9/18/17	20	$0.00
50	Briefing 2 Complete	0 days	Mon 10/2/17	Mon 10/2/17	49,25	$0.00
51	Briefing 3 Complete	0 days	Mon 10/23/17	Mon 10/23/17	50,33	$0.00
52	Briefing 4 Complete	0 days	Mon 11/6/17	Mon 11/6/17	51	$0.00
53	Faculty Presentations	0 hrs	Fri 11/17/17	Fri 11/17/17	52	$0.00
54	Proposal Presentation	0 hrs	Wed 12/6/17	Wed 12/6/17	53	$0.00
55	Spring Semester Briefings	0 days	Tue 4/17/18	Tue 4/17/18		$0.00
56	**Documentation**	**99 days**	**Wed 12/6/17**	**Mon 4/23/18**		**$13,120.00**
57	Paper Finalization	5 days	Tue 4/17/18	Mon 4/23/18	47	$13,120.00
58	Proposal Final Report	0 days	Wed 12/6/17	Wed 12/6/17	54	$0.00
59	Draft Conference Paper	0 days	Wed 12/6/17	Wed 12/6/17	54	$0.00
60	**Competitions**	**0 days**	**Mon 5/7/18**	**Mon 5/7/18**		**$0.00**
61	Capstone Design Competition	0 days	Mon 5/7/18	Mon 5/7/18	55	$0.00

Figure 82: Project Schedule

14.4 Critical Path



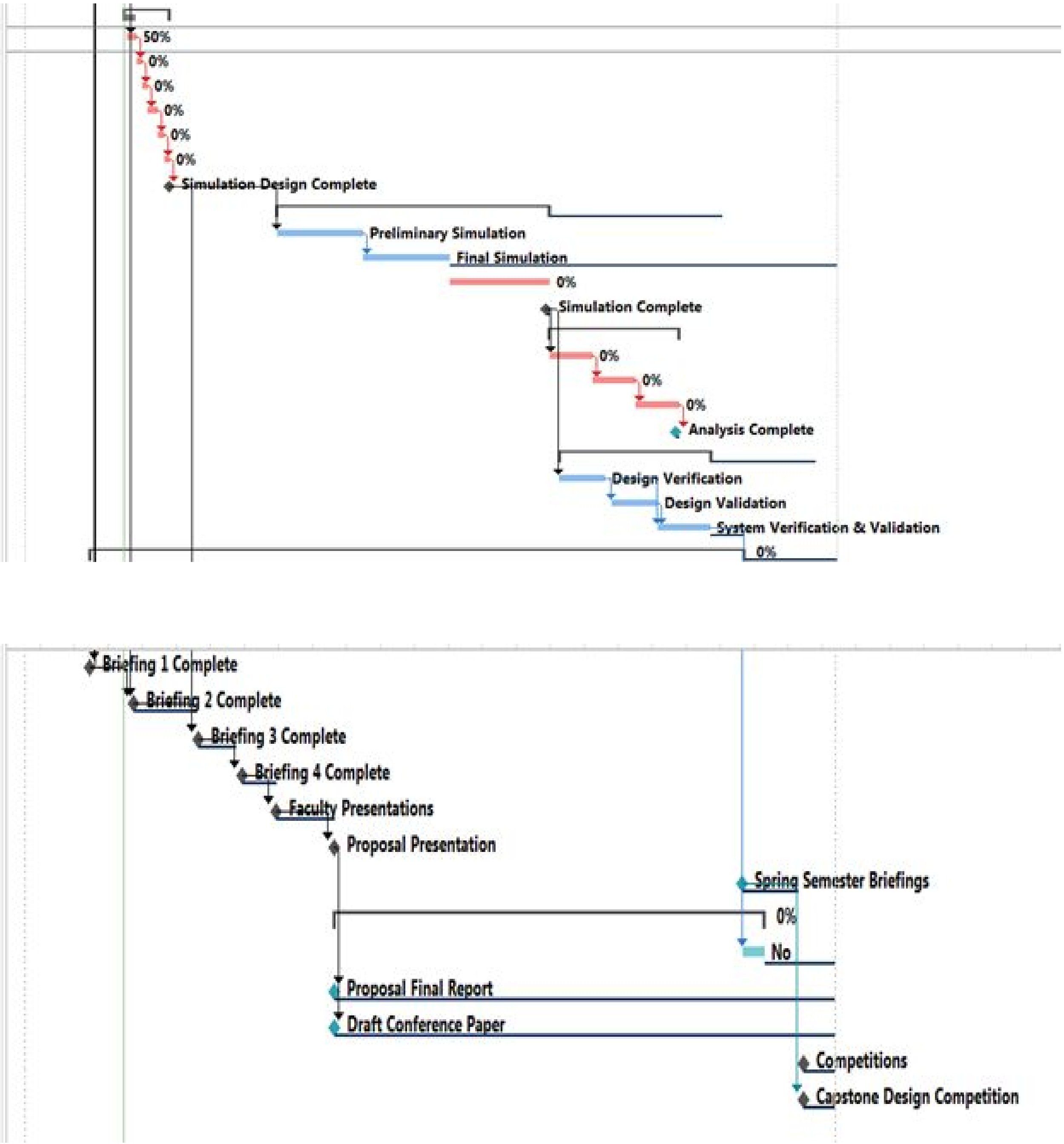


Figure 83: Critical Path

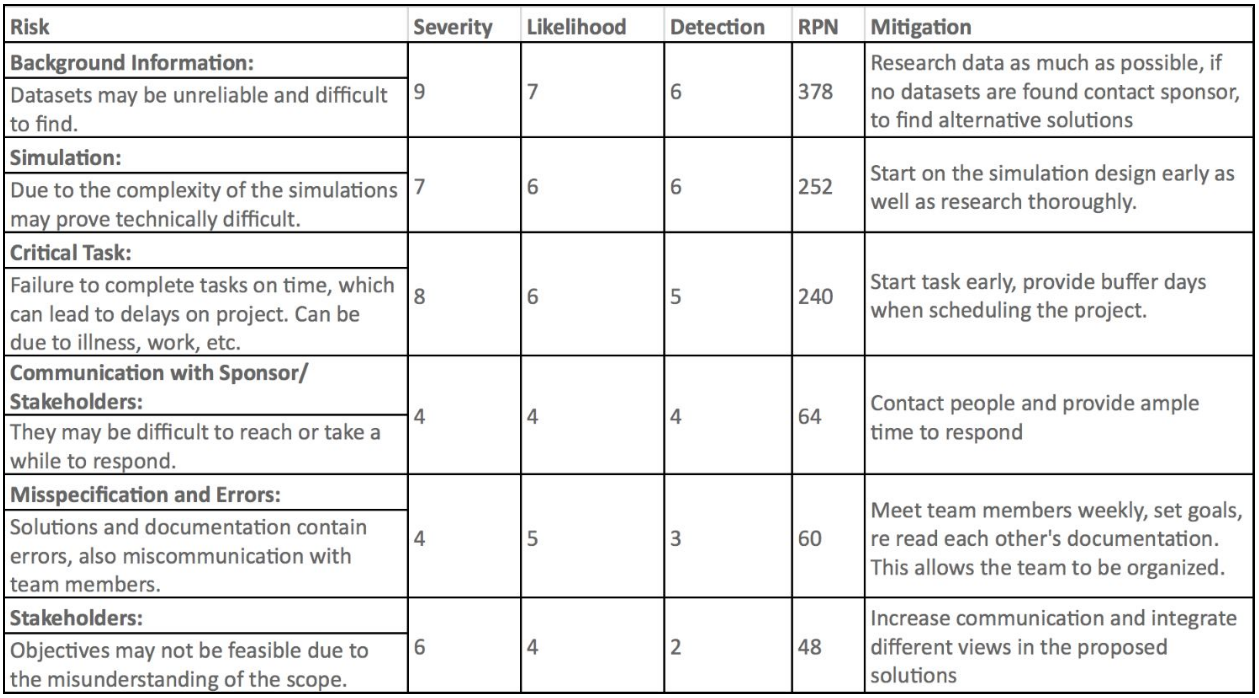
14.5 Budget

The average salary for an entry level Systems Engineer in Washington D.C. and Northern VA is approximately $80,000 per year [20][21]. Assuming 52 work weeks and 40 hours a week, this equates to $41/hour. We are implementing a multiplier of 2 for overhead cost making the total pay $82/hour per person. The total budget cost is based on 188 working days, weekends not included. The total number of work weeks equate to 37 weeks, working 80 hours per week in total. The total project cost is $251,740.00.

	Hours (hours per person)	Cost	Cost with Overhead
Optimistic	2,664 (18 hours)	$109,224.00	$218,448.00
Standard	3,070 (20 hours)	$125,870.00	$251,740.00
Pessimistic	3,356 (22 hours)	$133,496.00	$266,992.00

Figure 84: Project Budget

14.6 Project Risk Mitigation



Risk	Severity	Likelihood	Detection	RPN	Mitigation
Background Information: Datasets may be unreliable and difficult to find.	9	7	6	378	Research data as much as possible, if no datasets are found contact sponsor, to find alternative solutions
Simulation: Due to the complexity of the simulations may prove technically difficult.	7	6	6	252	Start on the simulation design early as well as research thoroughly.
Critical Task: Failure to complete tasks on time, which can lead to delays on project. Can be due to illness, work, etc.	8	6	5	240	Start task early, provide buffer days when scheduling the project.
Communication with Sponsor/ Stakeholders: They may be difficult to reach or take a while to respond.	4	4	4	64	Contact people and provide ample time to respond
Misspecification and Errors: Solutions and documentation contain errors, also miscommunication with team members.	4	5	3	60	Meet team members weekly, set goals, re read each other's documentation. This allows the team to be organized.
Stakeholders: Objectives may not be feasible due to the misunderstanding of the scope.	6	4	2	48	Increase communication and integrate different views in the proposed solutions

Figure 85: Project Risk Mitigation

Severity (S): 1(less severe) - 10 (very severe)

Likelihood (L): 1 (less likely to occur) - 10 (almost certain to occur)

Detection (D): 1 (able to detect before problem)-- 10 (almost unable to detect before it occurs)

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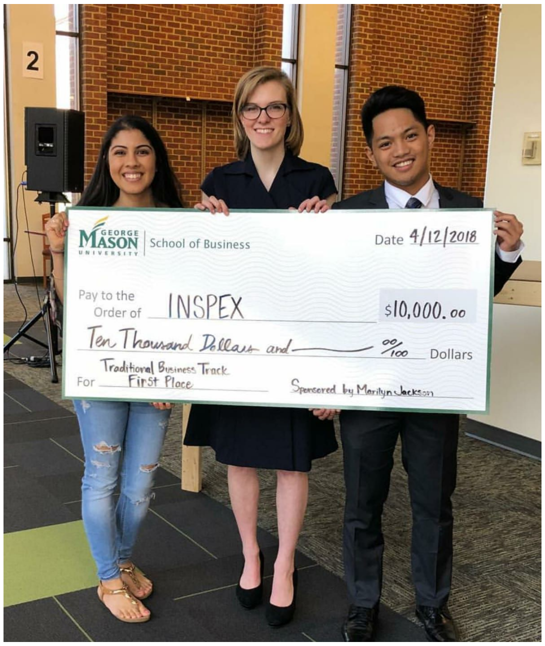
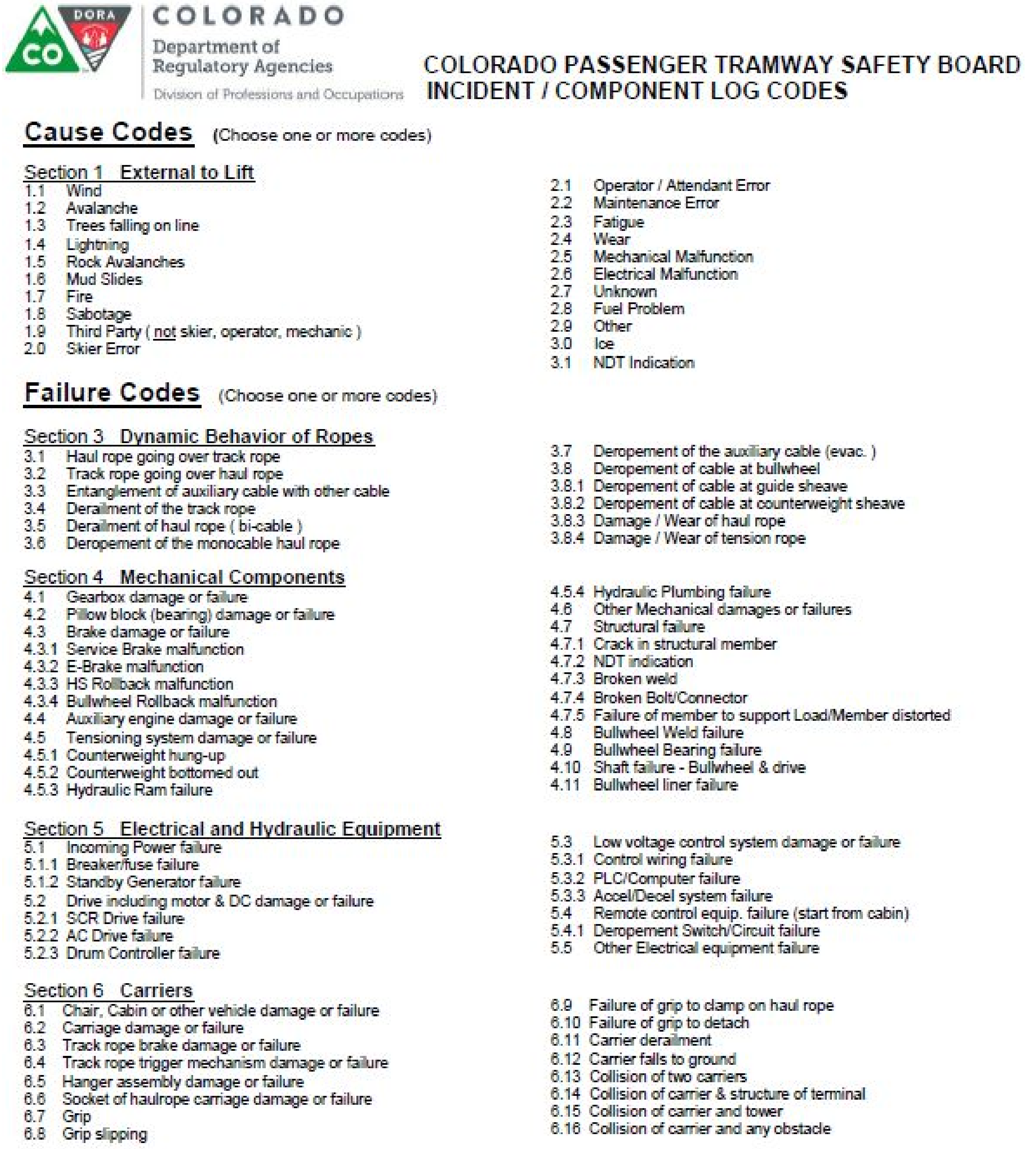
16.0 Appendix

16.1 Team Photos



16.2 Colorado Cause and Failure codes



COLORADO
Department of
Regulatory Agencies
Division of Professions and Occupations

COLORADO PASSENGER TRAMWAY SAFETY BOARD
INCIDENT / COMPONENT LOG CODES

Cause Codes (Choose one or more codes)

Section 1 External to Lift

1.1 Wind
1.2 Avalanche
1.3 Trees falling on line
1.4 Lightning
1.5 Rock Avalanches
1.6 Mud Slides
1.7 Fire
1.8 Sabotage
1.9 Third Party (not skier, operator, mechanic)
2.0 Skier Error
2.1 Operator / Attendant Error
2.2 Maintenance Error
2.3 Fatigue
2.4 Wear
2.5 Mechanical Malfunction
2.6 Electrical Malfunction
2.7 Unknown
2.8 Fuel Problem
2.9 Other
3.0 Ice
3.1 NDT Indication

Failure Codes (Choose one or more codes)

Section 3 Dynamic Behavior of Ropes

3.1 Haul rope going over track rope
3.2 Track rope going over haul rope
3.3 Entanglement of auxiliary cable with other cable
3.4 Derailment of the track rope
3.5 Derailment of haul rope (bi-cable)
3.6 Deropement of the monocable haul rope
3.7 Deropement of the auxiliary cable (evac.)
3.8 Deropement of cable at bullwheel
3.8.1 Deropement of cable at guide sheave
3.8.2 Deropement of cable at counterweight sheave
3.8.3 Damage / Wear of haul rope
3.8.4 Damage / Wear of tension rope

Section 4 Mechanical Components

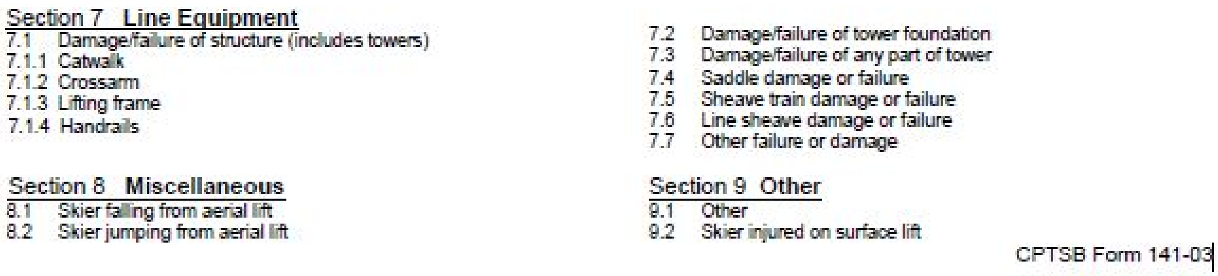
4.1 Gearbox damage or failure
4.2 Pillow block (bearing) damage or failure
4.3 Brake damage or failure
4.3.1 Service Brake malfunction
4.3.2 E-Brake malfunction
4.3.3 HS Rollback malfunction
4.3.4 Bullwheel Rollback malfunction
4.4 Auxiliary engine damage or failure
4.5 Tensioning system damage or failure
4.5.1 Counterweight hung-up
4.5.2 Counterweight bottomed out
4.5.3 Hydraulic Ram failure
4.5.4 Hydraulic Plumbing failure
4.6 Other Mechanical damages or failures
4.7 Structural failure
4.7.1 Crack in structural member
4.7.2 NDT indication
4.7.3 Broken weld
4.7.4 Broken Bolt/Connector
4.7.5 Failure of member to support Load/Member distorted
4.8 Bullwheel Weld failure
4.9 Bullwheel Bearing failure
4.10 Shaft failure - Bullwheel & drive
4.11 Bullwheel liner failure

Section 5 Electrical and Hydraulic Equipment

5.1 Incoming Power failure
5.1.1 Breaker/fuse failure
5.1.2 Standby Generator failure
5.2 Drive including motor & DC damage or failure
5.2.1 SCR Drive failure
5.2.2 AC Drive failure
5.2.3 Drum Controller failure
5.3 Low voltage control system damage or failure
5.3.1 Control wiring failure
5.3.2 PLC/Computer failure
5.3.3 Accel/Decel system failure
5.4 Remote control equip. failure (start from cabin)
5.4.1 Deropement Switch/Circuit failure
5.5 Other Electrical equipment failure

Section 6 Carriers

6.1 Chair, Cabin or other vehicle damage or failure
6.2 Carriage damage or failure
6.3 Track rope brake damage or failure
6.4 Track rope trigger mechanism damage or failure
6.5 Hanger assembly damage or failure
6.6 Socket of haulrope carriage damage or failure
6.7 Grip
6.8 Grip slipping
6.9 Failure of grip to clamp on haul rope
6.10 Failure of grip to detach
6.11 Carrier derailment
6.12 Carrier falls to ground
6.13 Collision of two carriers
6.14 Collision of carrier & structure of terminal
6.15 Collision of carrier and tower
6.16 Collision of carrier and any obstacle



Section 7 Line Equipment

7.1 Damage/failure of structure (includes towers)
7.1.1 Catwalk
7.1.2 Crossarm
7.1.3 Lifting frame
7.1.4 Handrails
7.2 Damage/failure of tower foundation
7.3 Damage/failure of any part of tower
7.4 Saddle damage or failure
7.5 Sheave train damage or failure
7.6 Line sheave damage or failure
7.7 Other failure or damage

Section 8 Miscellaneous

8.1 Skier falling from aerial lift
8.2 Skier jumping from aerial lift

Section 9 Other

9.1 Other
9.2 Skier injured on surface lift

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16.3 Simulation Code

A stochastic simulation was developed in java to compare inspection time. Safety, accuracy and availability was developed in excel.

16.3.1 Main

```
import org.apache.commons.math3.distribution.*;
import java.util.*;
public class Main{
  public static void main (String[] args){
    ArrayList<Double> list = new ArrayList<Double>();
    //  TowerObject t1 = new TowerObject(12.5,0.0);
    //height, distance from previous tower, vert dist from ground, # of sheaves uphill, # of sheave downhill
    TowerObject t2 = new TowerObject(12.5,0,0,6,6);
    TowerObject t3 = new TowerObject(11.78,73.152,7.49808,4,2);
    TowerObject t4 = new TowerObject(13.716,80.772,7.58952,6,2);
    TowerObject t5 = new TowerObject(15.88,85.344,8.50392,6,2);
    TowerObject t6 = new TowerObject(15.11,85.344,12.3444,6,6);
    TowerObject t7 = new TowerObject(13.97,79.248,17.8308,6,2);
    TowerObject t8 = new TowerObject(11.049,86.2584,22.58568,6,2);
    TowerObject t9 = new TowerObject(13.67,95.0976,21.61032,4,2);
    TowerObject t10 = new TowerObject(11.2,64.008,20.45208,8,6);
    LiftObject lift = new LiftObject(new TowerObject[] {t2,t3,t4,t5,t6,t7,t8,t9,t10});
    Inspection iUAV = new Inspection("UAV",
                                2,.3, //vertical speed
                                7,.3, //horizontal speed
                                3,.18, //inspection speed
                                1.3,8.46, //wind
```

```
                            300, 100, //set-up/battery change speed
                            lift);
  Inspection iHUMAN = new Inspection("Current Method",

             .5,.1, //vertical speed
            .67,.1, //horizontal speed based on average human walking speed ~3.1 mph w gear to carry
            .2,.07, //inspection speed ~1 mph
            1,1, //wind actually has no effect here
             (10*60), 100, //equipment set-up speed
              lift);
  double sum=0;
  ArrayList<Double> timesUAV = new ArrayList<Double>();
  int iterations = 1453; //1454 wind data points
  ArrayList<Double> groundspeedH = new ArrayList<Double>();
  ArrayList<Double> groundspeedI = new ArrayList<Double>();
  for(int k=0; k<iterations; k++){
    sum+= iUAV.time();
    timesUAV.add(iUAV.time());
    //groundspeedH.add(iUAV.normDist(iUAV.speed_horz_mean, iUAV.speed_horz_std)-(-.001 + 11
*iUAV.betaDist(iUAV.wind_mean, iUAV.wind_std)));
    //groundspeedI.add(iUAV.normDist(iUAV.insp_speed_mean, iUAV.insp_speed_std)-(-.001 + 11 *
iUAV.betaDist(iUAV.wind_mean, iUAV.wind_std)));
  }
  double sum2=0;
  ArrayList<Double> timesHUMAN = new ArrayList<Double>()
  for(int h=0; h<iterations; h++){
    sum2+= iHUMAN.time();
    timesHUMAN.add(iHUMAN.time());
  }
  double sumDiffsSquared = 0.0;
  for (double value : timesUAV)
  {
    double diff = Math.pow((value - (sum/iterations)),2);
    sumDiffsSquared += diff;
  }
  double sum2DiffsSquared = 0.0;
```

```
    for (double value2 : timesHUMAN)
    {
      double diff2 = Math.pow((value2 - (sum2/iterations)),2);
      sum2DiffsSquared += diff2;
    }
    System.out.println("Average Inspection Time for "+iUAV.inspection_method+": "+(sum/iterations)/60+" minutes");
    System.out.println("Standard Deviation of Inspection Times for "+iUAV.inspection_method+": "+Math.sqrt((sumDiffsSquared/(iterations-1)))/60+" minutes");
    System.out.println("Average Inspection Time for "+iHUMAN.inspection_method+": "+(sum2/iterations)/60+" minutes");
    System.out.println("Standard Deviation of Inspection Time for "+iHUMAN.inspection_method+": "+Math.sqrt((sum2DiffsSquared/(iterations-1)))/60+" minutes");
    System.out.println("Inspection UAV: "+iUAV.inspection_method+"\n"+timesUAV);
    System.out.println("Inspection HUMAN: "+iHUMAN.inspection_method+"\n"+timesHUMAN);
    //System.out.println("Ground H: "+groundspeedH);
    //System.out.println("\nGround I: "+groundspeedI);
  }
}
```

16.3.2 Counter

```
import java.io.*;
import java.util.*;
public class Counter {
  public static void main(String [] args) {
    // The name of the file to open.
    String fileName = "C:\\Users\\katie\\Desktop\\Spring 2018\\Code\\2014.txt";
    //String fileName = "C:\\Users\\katie\\Desktop\\Spring 2018\\Code\\2015.txt";
    //String fileName = "C:\\Users\\katie\\Desktop\\Spring 2018\\Code\\2016.txt";
    //String fileName = "C:\\Users\\katie\\Desktop\\Spring 2018\\Code\\2017.txt";
    // This will reference one line at a time
    String line = null;
    try {
      // FileReader reads text files in the default encoding.
      FileReader fileReader =
        new FileReader(fileName);
      // Always wrap FileReader in BufferedReader.
      BufferedReader bufferedReader =
        new BufferedReader(fileReader);
      int week = 0;
      int index = 1;
      ArrayList<Integer> i2014 = new ArrayList<Integer>();
      while((line = bufferedReader.readLine()) != null) {
       if(line.equals("1")){
        week++;
       }
       else{
        week=0;
       }
       if(index%7==0){
         i2014.add(week);
         week = 0;
        }
```

```
          index++;
        }
        System.out.println("Max: "+ Collections.max(i2014));
        System.out.println("Weeks: "+ i2014);
        System.out.println("Num Weeks: "+i2014.size());
        // Always close files.
        bufferedReader.close();
      }
      catch(FileNotFoundException ex) {
        System.out.println(
          "Unable to open file '" +
          fileName + "'");
      }
      catch(IOException ex) {
        System.out.println(
          "Error reading file '"
          + fileName + "'");
        // Or we could just do this:
        // ex.printStackTrace();
      }
    }
}
```

16.3.3 TowerObject

```
import org.apache.commons.math3.distribution.*;
public class TowerObject{
 public double height;
 public double distFromPrevTower;
 public double vertDistFromGround;
 public double numSheeveUp;
 public double numSheeveDown;

 public TowerObject(double height, double distFromPrevTower, double vertDistFromGround, double
numSheeveUp, double numSheeveDown) {
  this.height = height;
```

```
  this.distFromPrevTower = distFromPrevTower;
  this.vertDistFromGround = vertDistFromGround;
  this.numSheeveUp = numSheeveUp;
  this.numSheeveDown = numSheeveDown;
 }
}
```

16.3.4 LiftObject

```
import org.apache.commons.math3.distribution.*;
public class LiftObject {
 // Define Lift Characteristics --> how to format, csv? or .txt
 public TowerObject[] towers;
 public LiftObject() {
 // TowerObject[] towers = new TowerObject[0]; //may not be necessary
 }
 public LiftObject(TowerObject[] towers) {
  this.towers = towers;
 }
 public TowerObject get(int index){
    if (index >= towers.length){ //index can't be out of bounds
      throw new RuntimeException();
    }
    else{
      return towers[index]; //return the TowerObject value at the given index
     // return str;
    }
  }
  public void set(int index, TowerObject tower){
     if (index >= towers.length){ //index can't be out of bounds
      throw new RuntimeException();
     }
     else{
       towers[index] = tower; //set tower as the value at the given index
     }
  }
  public double getSize(){
```

```
    return this.towers.length;
  }
}
```

16.3.5 Inspection

```
import org.apache.commons.math3.distribution.*;
import java.util.*;

public class Inspection {
  public String inspection_method;
  public double insp_time;
  public double insp_cost;
  public double battery_life;
  public double speed_vert_mean;
  public double speed_vert_std;
  public double speed_horz_mean;
  public double speed_horz_std;
  public double insp_speed_mean;
  public double insp_speed_std;
  public double wind_mean;
  public double wind_std;
  public double setup_mean;
  public double setup_std;
  public LiftObject lift;
  public double wind_total=0;

  //constructor accepts a lift object and it's characteristics
  public Inspection (String inspection_method,
                    double speed_vert_mean, double speed_vert_std, // UAV or human climb/descend
                    double speed_horz_mean, double speed_horz_std, // UAV between tower or human
walking
                    double insp_speed_mean,double insp_speed_std,  //UAV maneuvering or human walking
on tower
                    double wind_mean, double wind_std,
                    double setup_mean, double setup_std,          //UAV setup or human harness
                    LiftObject lift) {
```

```
    this.inspection_method = inspection_method;
    this.speed_vert_mean = speed_vert_mean;
    this.speed_vert_std = speed_vert_std;
    this.speed_horz_mean = speed_horz_mean;
    this.speed_horz_std = speed_horz_std;
    this.insp_speed_mean = insp_speed_mean;
    this.insp_speed_std = insp_speed_std;
    this.wind_mean = wind_mean;
    this.wind_std = wind_std;
    this.setup_mean = setup_mean;
    this.setup_std = setup_std;
    this.lift = lift;
  }

  // CALCULATE TIME OF
INSPECTION~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~~~~~~~~~~~~~
  public double time() {
    double setup = normDist(setup_mean, setup_std); //set-up average (5mins=300secs)
    double total_inspection_time = setup;
    double runtime = 0; //how long the drone has been operating in one battery (seconds)
    int index = 0;
    double wind = -.001 + 11 * betaDist(wind_mean, wind_std);
    double tower_insp_time; //inspection time for each tower
    double batt_life=30*60; //capacity in seconds for each new battery
    //Inspecting with a UAV------------------------------------------------------------------------------------------
    if(inspection_method.equals("UAV")){
      for(TowerObject t : lift.towers){ //loop through towers
        if(tower_time(t,wind) < (batt_life*.7 - runtime)){ //it has enough time to inspect the next tower w
battery
          tower_insp_time = tower_time(t,wind); //calculate time to inspect a tower
          runtime+=tower_insp_time;
          total_inspection_time += tower_insp_time;
          tower_insp_time=0;
          index++;
```

```
    }

    else{ //replace battery
     runtime=0;
     double batt_change = normDist(setup_mean, setup_std);
     total_inspection_time+=batt_change; //battery change
     //System.out.println("Battery change on Tower"+(index+1)+ "\nChange time: "+ batt_change);
     tower_insp_time = tower_time(t,wind); //calculate time to inspect the tower
     runtime+=tower_insp_time;
     total_inspection_time += tower_insp_time;
     tower_insp_time=0;
     index++;
    }
   }
  }
  // Inspecting with the current method-----------------------------------------------------------------------------
  if(inspection_method.equals("Current Method")){
   for(TowerObject i: lift.towers){
    tower_insp_time = normDist(setup_mean,setup_std); // start w tower setup time, hook harness to twr
    tower_insp_time += (i.height/normDist(speed_vert_mean, speed_vert_std))*4 + //go up/down twr height

     (1.8288)/normDist(insp_speed_mean, insp_speed_std) + // walk 6 ft to left sheave

     (i.numSheeveUp*60) + //inspect uphill sheaves

     (4.1148/normDist(insp_speed_mean, insp_speed_std))*2 + //walk across top to other side ~13.5'

     (i.numSheeveDown*60) + //inspect downhill sheaves

     (2.286/normDist(insp_speed_mean, insp_speed_std)) + //walk back to ladder ~ 7.5'

     (4.1148/normDist(insp_speed_mean, insp_speed_std))*2 + //inspect structure -walk across top ~13.5'
```

```
          4*Math.sqrt((Math.pow(i.distFromPrevTower,2)+Math.pow(i.vertDistFromGround,2)))/
          normDist(speed_horz_mean, speed_horz_std); // climb down incl. go to next tower

        total_inspection_time+=tower_insp_time;
      }
    }
    return total_inspection_time;
  }

//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

  public double tower_time(TowerObject t, double wind){
    double upDown_speed = normDist(speed_vert_mean, speed_vert_std); //m/s
    double upDown_time = t.height/upDown_speed;

    double speed_vert1 = normDist(speed_vert_mean, speed_vert_std); // m/s
    double tower_clear1 = ((3.408)/(speed_vert1)); //second

    double insp_speed1 = normDist(insp_speed_mean, insp_speed_std); // m/s
    double across_tower1 =(10.2108)/normDist(.399,.102);//(insp_speed1-wind); //seconds  THIS IS
GRND SPEED FROM WIND DIST

    double insp_structure_speed1 = normDist(insp_speed_mean, insp_speed_std); // m/s
    double structure_insp_time1 = (6.7056)/(normDist(.399,.102));//insp_structure_speed1-wind);
//seconds THIS IS GRND SPEED FROM WIND DIST

    double travel_across_speed1 = (normDist(insp_speed_mean, insp_speed_std)); //m/s
    double travel_across_time1 = (6.4008)/(normDist(.399,.102));//(travel_across_speed1-wind);
//seconds  THIS IS GRND SPEED FROM WIND DIST

    double travel2center = (normDist(insp_speed_mean, insp_speed_std)); //m/s
    double travel2center_time = (3.68)/(normDist(.399,.102));//(travel2center-wind);// THIS IS GRND
SPEED FROM WIND DIST
```

```
    double distFromPrevTower_speed = (normDist(speed_horz_mean, speed_horz_std));
    double distFromPrevTower_time =
(t.distFromPrevTower)/(7*betaDist(2,4.94));//(distFromPrevTower_speed-wind); //seconds  THIS IS
GRND SPEED FROM WIND DIST

    double tower_insp_time =
      (upDown_time)*2 + //going up/down to tower height level

      (20*2) + //inspect wheel sides (once per side)

      (tower_clear1)*4 + //tower height clearance

      (across_tower1) + //go across above tower

      (structure_insp_time1) + //inspect tower structure

      (20*2) + //30 seconds to inspect top of sheave trains (10 seconds per sheave train)

      (travel_across_time1) + //travel speed across the structure

      (20*2) + //inspect side of tower

      (travel2center_time) + //go to center of tower


(Math.sqrt((Math.pow(t.distFromPrevTower,2)+Math.pow(t.vertDistFromGround,2))))/normDist(.67,.1
)+ //human operator travels to join up

      distFromPrevTower_time;

    return tower_insp_time;
  }

  public double normDist(double mean, double std) {
    Random rng = new Random();
    double ret = mean + std * rng.nextGaussian();
```

```
    //System.out.println(ret);
    return ret;
  }

  public double betaDist(double alpha, double beta){
    BetaDistribution b = new BetaDistribution(alpha, beta);
    double n = b.inverseCumulativeProbability(Math.random());
    return n;
  }

}
```

16.4 Youtube Video

Youtube Link: https://youtu.be/-8l0tEkVvRo