4-2018

Safety Return on Investment (ROI): The Broader Adoption of Rotorcraft CFIT-Avoidance Technology

Isaac Nderitu Munene

SAFETY RETURN ON INVESTMENT (ROI): THE BROADER ADOPTION OF ROTORCRAFT CFIT-AVOIDANCE TECHNOLOGY

By

Isaac Nderitu Munene

A Dissertation Submitted to the College of Aviation
in Partial Fulfillment of the Requirements for the Degree of
Doctor of Philosophy in Aviation

Embry-Riddle Aeronautical University
Daytona Beach, Florida
April 2018

SAFETY RETURN ON INVESTMENT (ROI): THE BROADER ADOPTION OF ROTORCRAFT CFIT-AVOIDANCE TECHNOLOGY

By

Isaac Nderitu Munene

This Dissertation was prepared under the direction of the candidate's Dissertation Committee Chair, Dr. Mark A. Friend, and has been approved by the members of the dissertation committee. It was submitted to the College of Aviation and was accepted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy in Aviation

Mark A. Friend, Ed.D.
Committee Chair

Bruce A. Conway, Ph.D.
Committee Member

Antonio I. Cortés, Ph.D.
Associate Dean, School of Graduate Studies

Irwin Price, Ph.D.
Committee Member

Alan J. Stolzer, Ph.D.
Dean, College of Aviation

Cass D. Howell, Ph.D.
Committee Member (External)

Michael P. Hickey, Ph.D.
Dean of Research and Graduate Studies

April 26, 2018
Date

ABSTRACT

Researcher: Isaac Nderitu Munene

Title: SAFETY RETURN ON INVESTMENT (ROI): THE BROADER ADOPTION OF ROTORCRAFT CFIT-AVOIDANCE TECHNOLOGY

Institution: Embry-Riddle Aeronautical University

Degree: Doctor of Philosophy in Aviation

Year: 2018

This dissertation provided a method of estimating the potential return on investment (ROI) that could be achieved if operators were to adopt the readily available controlled flight into terrain (CFIT) avoidance technology more broadly. Previous research explored the costs and benefits of different safety initiatives but did not evaluate from an operators' perspective. For the operators, a private ROI that excludes societal costs and benefits was therefore considered the suitable metric. For the rotorcraft industry, the ROI estimation methodology was not readily available, and this study sought to fill that gap. The purpose of this study was to estimate the potential ROI by determining the costs associated with the outcomes of CFIT-accidents, the costs of adopting the technology, the current accident rate, the benefits expressed as costs avoided through a reduction in the number of accidents, and application of the appropriate ROI formula.

The dissertation was conducted as a mixed method study that used qualitative data from historical CFIT-related accident reports to identify the accident outcomes and estimate the associated accident costs plus the available quantitative data to estimate the CFIT-avoidance technology adoption costs. The accident cost categories were based on categories used in airline research and modified for the rotorcraft industry. Using the formula, ROI = Net benefits divided by safety technology adoption costs, ROI values

were generated in multiple iterations of the Monte Carlo simulation. The net benefits were evaluated as the difference between the potential accident costs avoided with a reduction in CFIT accidents and the technology adoption costs.

The simulation results for the three rotorcraft categories showed that the turbine-single would experience the highest ROI, followed by the piston category and the twin-turbines. When all rotorcraft categories were considered, the ROI was positive but could turn negative if the technology adoption costs grew by a factor of more than three. The broad range in the ROI values for both the piston and single-turbine categories were largely driven by the high variation of the individual cost categories, especially the direct costs: occupant death and injuries, aircraft damage, and leasing costs.

From the results of the study, it was recommended that CFIT-avoidance technology should be more broadly adopted by piston and single-turbine rotorcraft operators. For twin-turbines, the adoption should be evaluated against the impact of the regulatory changes for helicopter air ambulance (HAA) operations, which may reduce the number of accidents and generate a positive ROI before further action from operators. Future research should focus on validating the methodology by using it as a starting point for evaluating the ROI for safety initiatives that have already been implemented, whether technology or operational programs. The industry should also improve the methodology by defining or proposing better processes for estimating rotorcraft accident costs, especially indirect costs estimated to be the of the same magnitude as the direct costs. The rotorcraft industry should find ways to make costs data, such as accident investigation costs, more accessible in order to apply the ROI estimation methodology to achieve more accurate results.

DEDICATION

This work is dedicated to my wife, son, mom, dad, and siblings for all the many years of support, love, and encouragement. You inspired me to pursue all my goals and interests in the aviation industry. You have all in your own unique way pushed me to see what is possible and to work for it. I also want to include my extended family, friends, and mentors who have been an important part of this journey through your unwavering support and advice.

ACKNOWLEDGEMENTS

I wish to extend my sincere appreciation and gratitude to my Committee Chair, Dr. Mark Friend, for his patient guidance and excellent leadership through the dissertation process and mentorship on aviation safety. Thank you for accepting to be my Committee Chair. I would also like to thank my esteemed dissertation committee members: Dr. Bruce Conway, Dr. Irwin Price, and Dr. Cass Howell. Your much-needed feedback on the dissertation and patience were instrumental to the completion of this dissertation. Your knowledge of economics, systems engineering, and aviation safety continuously challenged me to improve the research work product.

I would also like to extend my gratitude to my program advisor, Dr. Dothang Truong, who was always readily available to provide guidance, encouragement, and advice. To all my classmates and professors, I do appreciate the manner in which you all made courses enjoyable and informative. I would like to extend my sincere thanks to the College of Aviation and the entire Embry-Riddle Aeronautical University team for creating a PhD program that made it possible to achieve one of my goals in aviation safety.

To my wife, Rose, son, Collins, my parents, Ephantus and Ruth Munene, my siblings, friends, and entire extended family, thank you. Your patience, love, encouragement, and support made this dissertation possible. I look forward to spending more time with you all. I would also like to thank my colleagues at Bell and Textron Inc. who have made my journey in aviation safety and graduate school an enjoyable one.

TABLE OF CONTENTS

Page

LIST OF TABLES

Page

Table

LIST OF FIGURES

Page

Figure

CHAPTER I

INTRODUCTION

In his commentary in the America Helicopter Society (AHS) International's March/April 2015 issue of *Vertiflite*, the long-term Executive Director, Michael Hirschberg, reiterated the need for civil helicopter operators to adopt technologies that are certified, readily available, and affordable in order to mitigate most of the top safety issues. He emphasized five core technologies: (1) Enhanced Ground Proximity Warning Systems (EGPWS)/ Helicopter Terrain Awareness Warning Systems (HTAWS), (2) flight data monitoring devices, (3) helicopter operations monitoring program systems, (4) radar altimeters for light helicopters, and (5) onboard aircraft performance monitoring and calculating systems. As an industry leader, he was emphasizing the findings of the study by the European Helicopter Safety Team (EHEST) which listed the 15 "highly promising" technologies that could potentially mitigate most of the safety issues facing the helicopter industry (National Aerospace Laboratory (NLR), 2014).

The Specialist Team Technology (ST Technology), a sub-team of the European Helicopter Safety Implementation Team, was created to assess the potential of different technologies to mitigate the safety issues identified by the European Helicopter Safety Analysis Team (EHSAT). The EHSAT analyzed more than 300 accidents and identified the different accident / incident causes and contributing factors referred to as the Standard Problem Statements (SPSs). The team developed a tool and used it to link the different technologies to the SPSs, and using a scoring or rating system, determined the most advantageous technology for each safety issue. Two rating elements, Impact and Applicability were used. *Impact* was a measure of how well the given technology could mitigate the specific SPS, and *Applicability* was a measure of whether the said technology could be utilized for a specific SPS at its current technology readiness level and cost. Due to the large number of SPSs identified, only the Top 20 were considered. The technologies were rated as: slightly promising, moderately promising, and highly promising. According to the National Aerospace Laboratory (2014), of the 15 highly promising technologies, five are promising in mitigating the mission risk presented by terrain or obstacles:

i) Enhanced Ground Proximity Warning System / Terrain Awareness and Warning System (EGPWS/TAWS)
   - System provides warnings of obstacle hazards such as ground and towers.

ii) Laser Radar Obstacle and Terrain Avoidance System
   - System uses an eye-safe laser capable of detecting objects as thin as wires, thus making it useful for wire strike prevention.

iii) Digital Map
   - System displays digital maps with elevation and obstacle information.

iv) Passive Tower-based Obstacle Collision Avoidance System
   - Units located on utility and power line towers detect air traffic entering a predefined warning zone and activate warning lights to illuminate the tower and do not require any installations in the helicopter.

v) Radar Altimeter for Altitude Measurement
   - System for small helicopters, consisting of one single unit containing both transmitter and receiver antennas as well as processing unit.

Though these technologies are readily available to operators, adopting them requires the investment of additional resources beyond the initial aircraft acquisition costs for aircraft already in service. For operators, the decision to invest resources in safety relies heavily on their ability to build a credible business case for it, thus the need for an evaluation of the return on investment (ROI) or cost-benefit analysis.

As the competitiveness in the global business environment continues to intensify, executives are evaluating the contribution of their individual products, services, and programs to the overall corporate fiscal performance. The executives' goal is to identify factors that impede or enhance productivity and growth. Safety performance and management has been identified as a critical factor to an organization's reliability, reputation, operational effectiveness, fiscal performance, and competitiveness (Fernández-Muñiz, Montes-Peón, & Vázquez-Ordás, 2009; Flight Safety Foundation, 2012). According to Porter and Kramer (2006), in the automotive industry, Volvo has actively chosen to make vehicle safety a central element of its competitive position, while Toyota has done the same with the environmental safety benefits of its hybrid technology. Rotorcraft manufacturers, through the introduction of different safety technologies, have sought to gain the same competitive advantage over their counterparts while reducing the occurrence of aircraft incidents and accidents. The adoption of these technologies is therefore important to the manufacturers and the industry as a whole.

Rotorcraft Safety

Rotorcraft safety continues to be a major concern for the aviation industry. The importance of addressing this subject is highlighted by the National Transportation Safety Board's (NTSB) action of placing the enhancement of public helicopter safety on its

Most Wanted List of 2015 (NTSB, 2015). The International Helicopter Safety Team (IHST) was set up in late 2005 by government regulators, manufacturers, and helicopter operators with the goal of reducing the number of global helicopter accidents by 80 percent by 2016 and eventually to zero (U.S. Joint Helicopter Safety Analysis Team, 2011).

Controlled flight into terrain. A *Controlled flight into terrain (CFIT)* is defined as an accident where an aircraft in good working condition, while still under the control of the crew, is unintentionally flown into terrain, man-made obstacles, or water, with no prior awareness on the part of the crew of the impending collision (Ishihara, 2005). In a study of the helicopter emergency medical services (HEMS) CFIT accidents between 1992 and 2004, Ishihara (2005) observed that 84% of the accidents occurred during night time, 58% in visual meteorological conditions (VMC), 80% during the cruise phase, and 79% involved terrain. The reduction of CFIT accidents requires the industry understanding the extent of the problem, proposing mitigation solutions, and adopting the said solutions.

A 2015 White Paper was prepared for the rotorcraft industry by the Helicopter Association International (HAI), the AHS International, General Aviation Manufacturers Association (GAMA), and Aircraft Electronics Association as a proposal to modify the requirements of Part 14 Code of Federal Regulations (CFR) 27 single-engine instrument flight rules (IFR) certification. The team observed that during the period between 2001 and 2013, Part 27 single-engine helicopters across the world were involved in 194 accidents related to inadvertent flight into instrument meteorological conditions (IMC) or CFIT with 133 resulting in fatalities. Over the same period, multi-engine Part 27 or Part

29 rotorcraft worldwide were involved in 54 accidents related to IMC, CFIT, or IFR with 40 resulting in fatalities. According to the NTSB, 60 percent of all CFIT accidents are fatal (Sandel Avionics, 2012).

The U.S. Joint Helicopter Safety Analysis Team (JHSAT) (2011) has observed that in the 523 U.S. registered helicopter accidents occurring in calendar years 2000, 2001, and 2006, a pilot's decision to continue Visual Flight Rules (VFR) when indications of deteriorating weather were presented frequently resulted in the pilot entering inadvertent IMC. Accidents that occurred after continued flight in such marginal or deteriorated weather conditions were commonly a result of a collision with obstacles or terrain. When operating in a low altitude environment, the inability to detect wires as well as the loss of situational awareness was also observed as a problem that resulted in inadequate clearance from the ground and strikes to trees and obstacles in the rotorcraft's flight path.

In a 2006 report, the NTSB concluded that for 17 of the 55 accidents it considered, the pilots might have avoided terrain if TAWS was installed. It further concluded that the use of TAWS would enhance the safety of emergency medical services (EMS) operations in night and adverse weather conditions by helping prevent CFIT accidents. The NTSB issued the Safety Recommendation A-06-15, proposing the Federal Aviation Administration (FAA) require EMS operators to install TAWS and ensure their flight crews are capable of using it. In 2008, the FAA published Technical Standards Order C194, Helicopter Terrain Awareness and Warning System, in readiness for the rulemaking process for EMS TAWS requirements to start (NTSB, 2009).

By the end of 2008, the NTSB realized the safety recommendation on TAWS would not be adequate as the number of accidents began to rise again after the reduction achieved between 2004 and 2007. For flight safety improvements to be realized, a final rule mandating the installation and use of TAWS in air medical services flights would therefore be required. In April 2009, before the House Committee of Transportation and Infrastructure, then FAA Director of Flight Standards, John Allen, announced that the agency had initiated the formal rule-making process to address this issue (FAA, 2009a). In 2012, the FAA released guidance outlining the technical requirements for the installation of TAWS on all HEMS aircraft, now more commonly referred to as helicopter air ambulance (HAA), and in 2014 the final rule was released (FAA, 2014a).

In February 2014, the FAA made amendments to the Title 14 CFR Parts 91, 120, and 135 introducing new requirements for the HAA operators, commercial helicopters, and Part 91 helicopter operations. Under Part 135 rotorcraft operations, each HAA rotorcraft is to be equipped with a radio altimeter, HTAWS, and flight data monitoring system. Additionally, the pilots must be instrument rating holders and can demonstrate their capability of maneuvering the aircraft safely out of inadvertent instrument meteorological weather conditions (FAA, 2014a). In May 2014, the FAA released Advisory Circulars 27-1B Change 4 and 29-2C Change 4 to formalize the requirements for the installation of the equipment on all HAA operations aircraft (FAA, 2014b; FAA, 2014c).

According to the FAA, by 2014 there were 75 air ambulance companies operating approximately 1,515 helicopters in the United States. Since 2004, the FAA has been promoting different initiatives to reduce HAA accidents after determining that 62 accidents, which resulted in 125 fatalities between 1991 and 2010 could have been mitigated by adopting the technologies mandated in 2014. This number did not include accidents involving non-HAA commercial helicopters. From 2011 through 2013, a total of 16 helicopter accidents resulting in 39 fatalities occurred (FAA, 2014d). The number of accidents is an indication of why the FAA and the IHST emphasize the need for a faster adoption of different safety technologies within the whole industry.

Return on Investment (ROI)

Improving rotorcraft safety requires cooperation between the government and the industry, which is made up of rotorcraft manufacturers and operators. The government improves safety by enhancing safety regulations, while the industry develops the required technologies to satisfy those regulatory requirements. As stated earlier, the adoption of CFIT-avoidance technology will require the investment of financial resources beyond the initial aircraft acquisition and current operational costs for aircraft already in service. The decision to invest resources in safety requires the equipment manufacturers, operators, or government to understand the economic value of doing so. A cost-benefit analysis (CBA) or an ROI analysis can facilitate the decision making (Stone, 2005). Selecting the best method for making the assessment is based on the perspective and goals of the party performing the analysis.

A *CBA*, also known as a benefit-cost analysis, is an examination of the costs associated with the implementation of projects or activities and the benefits realized from them. All costs and benefits are examined regardless of who bore the costs or realized the benefits: the producer, the consumer, or a third party. The comparison is made in the same unit of measurement, usually a monetary unit like dollars. A CBA can be used to evaluate different programs or solutions to determine the one for which the benefits exceed the costs and allocate the resources accordingly. Performing this type of analysis can become difficult when identifying and valuing the benefits (FAA, 1998; Guzman & Asgari, 2014). For government outputs, through regulation or otherwise, a CBA may prove to be adequate for the purpose of evaluating the alternatives, but since they are not sold under market conditions, their value to consumers, the benefits they provide, become difficult to determine (FAA, 1998). It is therefore necessary to identify how the benefits are to be determined and evaluated for each specific CBA. A CBA as a public sector investment appraisal approach that provides information to decision-makers on the economic viability of different alternatives and their benefits to the community (Civil Aviation Safety Authority, 2010) differs from an ROI analysis that focuses on private investments.

ROI, by definition, is the ratio of gain to investment and measures the return, cost savings, profit, or cost avoidance that result from a given use of money (Feldman, Jazouli, & Sandborn, 2009). ROI is the monetary benefit derived from having spent money on developing, changing, or managing a product or system. It is an economic measure used to evaluate the efficiency of an investment (Chang, Sandborn, Pecht, Yung, & Wang, 2015). An ROI analysis is also considered to be a type of CBA conducted from an investor's perspective (Stone, 2005). Westerlind (2004) suggests that an ROI analysis can be used as a financial measurement to develop a company's business case and increase management and investor confidence. According to Banks, Reichard, Crow, and Nickell (2009), individuals in the Prognostic and Health Management (PHM) technology field usually reference the reduced maintenance costs, increased operational availability, and improved safety based on anecdotal evidence to respond to prospective customers' questions on the benefits of implementing the technology. They suggest that such an answer only provides an understanding of the practical benefits but not a justification for investing in the equipment, and an ROI analysis would be appropriate.

It has been observed that the adoption of a voluntary safety improvement process such as a Safety Management System (SMS) that increases business costs, depends on the proposer's ability to demonstrate its economic viability. Though the implementation costs of such programs or processes can be easily identified, the benefits can be more difficult to identify and quantify, as there is no one accepted approach or standard for the aviation industry. Industry leaders therefore need to be incentivized to adopt solutions like SMS through the application of generally accepted economic models in the valuation of the output or benefits (Stolzer, Halford, & Goglia, 2008). The adoption of CFIT-avoidance equipment, beyond the HAA operations, is voluntary and therefore requires the identification and quantification of the expected benefits. Canada's Department of Transport used a CBA when making the case for amending the regulatory requirements to expand the adoption of TAWS equipped with Enhanced Altitude Accuracy function to all private turbine-powered and commercial aircraft with six or more passenger seats. According to the Department of Transport, this action would cost $59 million and provide $216 million in benefits by avoiding additional safety costs with a reduction in CFIT accidents. The effort was expected to yield a net benefit of $157 million over a 10-year implementation period (Department of Transport, 2011). If this change was not mandated for operators, understanding the ROI would have been critical in determining whether to voluntarily adopt the technology. For rotorcraft operators, an ROI analysis can provide some insight into the financial implications of broadly adopting the CFIT-avoidance technology.

A review of available aviation safety literature indicated that a gap exists on models or methods used for performing an ROI analysis for the adoption of a given aircraft technology or equipment as a safety intervention. Research emphasis has been on safety management systems or programs (Lercel, Steckel, Mondello, Carr, & Patankar, 2011; Schmidt, Schmorrow, & Figlock, 2000; Taylor, 2000). Of the research performed, the CBA which considers the public costs and benefits was the method of choice. Examples include a CBA on accident safety costs for airline aircraft (Cavka & Cokorilo, 2012), airport security (Stewart & Mueller, 2013), aviation security (Stewart & Mueller, 2014), and the U.K. offshore helicopter industry (Mitchell, 2006). For broader adoption of CFIT-avoidance technology, going beyond the CBA and performing an ROI analysis that considers the private costs and benefits can facilitate decision making for the industry (operators and helicopter manufacturers) who are likely to invest in the required resources.

Significance of the Study

For close to a decade, as previously stated, the 80% reduction of helicopter accidents has been a key objective of the IHST. The NTSB, FAA, and European Aviation Safety Agency (EASA) have worked closely as partners toward the improvement of aviation safety across the globe. They have continued to highlight the need to accelerate the adoption rate of safety technology in order to reduce the number of accidents. The FAA has used mandates to facilitate the adoption of the technology in some operations such as the HAA, but a gap exists when other operations are considered.

This study sought to provide operators and rotorcraft manufacturers (the industry) with a method of estimating the potential ROI that can be achieved when the industry is in the process of making the decision to voluntarily adopt rotorcraft safety technologies. For this study, the ROI was considered from the rotorcraft manufacturers' and operators' perspective, as they will be actively investing financial resources for the integration of the technology into the fielded fleet. Rotorcraft manufacturers were also to be considered operators as they are involved in flight training and flight test operations. The ROI methodology applied in this study can be used in the future to evaluate whether new or existing technologies, like those identified in the NLR (2014) report, provide a ROI for those investing the resources to implement them. The results of an ROI analysis can facilitate better and timely decision making and justification of resource allocation, planning, and implementation of safety improvements by the industry.

Statement of the Problem

Improving safety within any industry requires the investment of various resources that come with financial implications for the organizations involved. Research has shown that organizations focusing on the well-being and safety of their workforce by building a culture of health yield a greater value for their investors (Fabius, Thayer, Konicki, Yarborough, Peterson, Isaac, Loeppke, Eisenburg, & Dreger, 2013). Additionally, safety is considered an indicator of an organization's performance, such as enhancing product quality and plant performance. Improving safety or the perception of improving safety could be good business (Veltri, Pagell, Behm, & Das, 2007).

To improve rotorcraft safety, resources must be invested, and organizations are expected to show the added value for their benefactors or investors. Existing research does not provide a methodology of estimating the potential ROI when aircraft equipment or technology is adopted by operators. To encourage the adoption of the CFIT-avoidance technology beyond the HAA operations, the researcher will explore the ROI that could potentially be achieved with the implementation of the safety recommendations issued by the NTSB in 2005 and in line with the recent mandates issued for HAA operations. An ROI is a suitable metric by which the industry can determine if an investment in the broader adoption of CFIT-avoidance technology is advisable. Since the operators (customers) and rotorcraft manufacturers would be considered investors in this case, a private ROI analysis would be suitable, where the tangible financial benefits are considered. The societal benefits are usually considered when a CBA is being performed. A private ROI excludes costs and benefits where the public (society) and the government are the sole beneficiaries (Landau, Weisbrod & Alstadt, 2010). Taylor (2000) provides an example of a private ROI by evaluating the different approaches of implementing maintenance resource management (MRM) concepts by an airline. The benefits and costs considered did not include those external to the organization (societal). For the rotorcraft industry, gaps exist in ROI estimation techniques related to the adoption of safety technology (especially for the CFIT-avoidance technology) and understanding of the financial impact of the operators opting to voluntarily adopt the technology. The focus of existing research has been mostly on CBAs, and this study sought to provide a method of performing the ROI analysis.

Purpose Statement

The purpose of this study was to estimate the potential ROI that could be achieved if the readily available CFIT-avoidance technology was more widely adopted by the helicopter industry using actual helicopter accidents and the safety costs associated with their outcomes. The study estimated the ROI likely to be achieved with the broader adoption of the CFIT-avoidance technology by:

i. Determining and evaluating the costs associated with accidents of different helicopter categories including, but not limited to: loss of aircraft, damage to aircraft, loss of crew and passengers, accident investigation costs, loss of investment, and crew replacement costs;

ii. Determining and evaluating costs associated with adoption of the CFIT-avoidance technology including: equipment acquisition, installation, training, and lifecycle support (sustainment);

iii. Determining the CFIT accident rate (probability of occurrence) by helicopter category;

iv. Determining and evaluating the benefits associated with the accident costs likely to be avoided as a result of the adoption of the CFIT-avoidance technology for operators and rotorcraft manufacturers; and,

v. Applying the appropriate formula to estimate the ROI likely to be achieved with the broader adoption of the CFIT-avoidance technology.

Research Questions

The research involved the application of an appropriate financial formula to estimate the potential ROI that can be achieved with the broader adoption of CFIT-avoidance technology within the rotorcraft industry. The ROI was estimated from the rotorcraft manufacturers' and operators' perspective for they would bear the responsibility of investing resources when equipping their respective aircraft. Manufacturers were considered investors based on their involvement in rotorcraft operations for development, production, and training purposes. For this study, the accidents examined occurred between January 2005 and December 2015, the period since EGPWS/TAWS for rotorcraft became available (Kraemer, 2002). The research addressed the following questions:

a) What are the estimated costs likely to be experienced by rotorcraft operators as a result of a CFIT accident?

b) How can operators estimate the potential ROI for the broader adoption of safety technology such as the CFIT-avoidance technology?

c) Do the ROI results support the adoption of CFIT-avoidance technology beyond the mandated HAA operations?

Delimitations

The study did not attempt to address the ROI on CFIT-avoidance technology adoption in different regions of the globe. Rather, it focused on general aviation helicopter operation accidents within the United States. The historical accident data reports prepared by the NTSB and FAA for helicopter CFIT events were used to determine the probability of future CFIT accidents occurring, the costs associated with such accidents, and costs likely to be incurred when adopting the technology to avoid future accidents. The accident reports were retrieved from the NTSB Aviation Accident Database. For the ROI analysis, all commercial helicopter operations were considered. The period of interest for the data was from January 1, 2005, through December 31, 2015. The accident reports considered had a finalized status identifying the probable cause and safety recommendations, where applicable.

While five technologies were identified for mitigation of CFIT accidents, only the EGPWS/TAWS, laser radar obstacle and terrain avoidance system, digital map, and radar altimeter were considered for adoption. This purposefully limited technology adoption to those technologies that would be installed on the aircraft where an operator would incur the cost. The cost of installing equipment such as the passive tower-based Obstacle Collision Avoidance System would be incurred by the government, as it is not installed onboard the aircraft.

Limitations and Assumptions

This research focused on the potential ROI to be achieved on the adoption of CFIT-avoidance technology. It considered the safety costs associated with a CFIT accident and the probability of occurrence based on the accidents that occurred during the period of interest. When performing an ROI analysis or a CBA, costs associated with the aircraft accidents to be considered depend on whether they are social or private costs. The cost categories considered included those identified under the Aviation Safety Targets for Effective Regulation (ASTER) project conducted by the National Aerospace Laboratory NLR (2001) for the European Commission. For the ROI analysis, the accident cost categories were limited to those directly related to the accident outcomes; for example, loss of aircraft use, loss of resale value, and loss of revenue are private costs. Costs such as site contamination and clearance, loss of baggage, and airport closure were not considered, as they are considered public costs. It must be noted that the ASTER cost categories were reflective of those of an airline aircraft accident and were scaled to that of accidents in rotorcraft operations by adopting the appropriate values for each category of costs. The accident costs considered for this study were those incurred in an accident that is operational (intended flight) and primarily were a result of the aircraft coming into contact with an obstacle or terrain while the pilot still had control. Ideally the aircraft should not have been experiencing other anomalies such as engine or structural failure.

The aircraft accident reports may not explicitly state in the safety recommendations that the installation of the CFIT-avoidance equipment could have prevented the accident. Therefore, for this specific study it was assumed that the installation of the equipment on all the identified accident helicopters would have more than likely helped to prevent the eventual accident. The accident reports included in the analysis were factual reports, that is, the accident investigation had been completed.

The costs associated with a helicopter accident or the adoption of the different CFIT-avoidance technology will vary by the source and category. A detailed analysis of each category was performed. As the technology already exists, it was assumed that all costs associated with the research, development, and production of the pieces of equipment were already factored into the retail price. The method used to extract the cost data from the different data sources such as websites, catalogs, quotes, and databases of the various vendors, original equipment manufacturers, customer service facilities, and operators depended on how the data are stored. These sources can vary over time, and therefore, the data were limited to the time they were extracted with no consideration given to future updates. It was also assumed that the method used to estimate the ROI would be flexible enough to allow iterative estimates to be made for future analysis.

An additional assumption was that the safety initiatives implemented by the organization, for example the SMS, would not be the leading factor for the reduction in the CFIT accident rate. Though these safety initiatives can be considered confounding variables, the definition of a CFIT accident suggests that without the information presented by the CFIT-avoidance equipment, the pilot while still in control of the aircraft, is unlikely to be aware of the impending collision. It was also assumed that the reduction on the accident rate would largely be achieved by the industry adopting the available CFIT technology.

Definitions of Terms

Accident	An occurrence associated with the operation of an aircraft that takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage (CFR Title 49 830.2).
Accident costs	Also referred to as *aircraft safety costs* are the costs an operator is likely to experience as the direct or indirect consequences of an accident. *Direct costs* are those primarily related to the aircraft airframe and occupants and include: deaths, injuries, aircraft physical damage, loss of resale value, aircraft loss of use, and loss of baggage. *Indirect costs* are those costs related to other consequences of the accident including: search and rescue costs, costs of airline immediate response, costs of accident investigation, loss of investment

income, increased costs of insurance, and costs of loss of reputation (Cavka & Cokorilo, 2012).

Accident outcomes These are the observable and measurable effects or consequences of an accident. These outcomes include severity of injuries or number of deaths of crew and passengers, severity of aircraft damage, extent of damage to environment and infrastructure, and injury or death to civilians on ground.

CFIT An accident that occurs when an airworthy aircraft is flown under the control of a qualified pilot, into terrain, water surface, or obstacles, with inadequate awareness on the part of the pilot of the impending collision (FAA, 2003). These accidents to some extent can be attributed to the pilot's lack of awareness of the aircraft's altitude relative to proximate terrain and obstacles and usually occur when the pilot cannot visually ascertain terrain / obstacles in prevailing flight conditions (FAA,2007).

CFIT-avoidance Technology

Refers to a component or system that, when installed in aircraft, has the potential to mitigate the occurrence of a CFIT accident (including water and obstacles). For the purposes of this study, wire strikes were included relative to the equipment configuration under consideration.

Industry For the purpose of this study, the industry was considered as the rotorcraft manufacturers and operators. Rotorcraft manufacturers perform development test, training, sales demonstration, post-maintenance, and production (ferry) flights and are exposed to the same risk of incurring a CFIT.

ROI The monetary benefit to the investor resulting from an investment in the development, change, or management of a product or system. In safety, the ROI is a means of measuring the benefit of investing financial resources to the improvement of safety.

List of Acronyms

AHS	America Helicopter Society
AIS	Abbreviated Injury Scale
ASTER	Aviation Safety Targets for Effective Regulation
CASR	Center for Aviation Research
CBA	Cost-benefit analysis
CFIT	Controlled Flight into Terrain
CFR	Code of Federal Regulations
DALY	Disability Adjusted Life Year
DMC	Direct Maintenance Cost
DOC	Direct Operating Cost
EASA	European Aviation Safety Agency
EGPWS	Enhanced Ground Proximity Warning System

EHEST	European Helicopter Safety Team
EHSAT	European Helicopter Safety Analysis Team
EMS	Emergency Medical Services
FAA	Federal Aviation Administration
FAMS	Federal Air Marshal Service
FCW	Forward Collision Warning
FFDO	Federal Flight Deck Officer
FH	Flight Hours
GA	General Aviation
GAJSC	General Aviation Joint Steering Committee
GAMA	General Aviation Manufacturers Association
GPS	Global Positioning System
HAA	Helicopter Air Ambulance
HAI	Helicopter Association International
HC	Human Capital
HEMS	Helicopter Emergency Medical Services
HLY	Healthy Life Years
IFR	Instrument Flight Rules
IHST	International Helicopter Safety Team
IMC	Instrument Meteorological Conditions
IPSB	Installed Physical Secondary Barrier
IQR	Interquartile Range
MFD	Multi-function Display

MRM	Maintenance Resource Management
MTBF	Mean Time Between Failures
NLR	National Aerospace Laboratory
NTSB	National Transport Safety Board
OBSS	Onboard Safety Systems
OSHA	Occupational Safety and Health Administration
PHM	Prognostic and Health Management
QALY	Quality Adjusted Life Years
ROHSEI	Return on Health, Safety, and Environment Investments
ROI	Return on Investment
SAR	Search and Rescue
SMS	Safety Management System
SPS	Standard Problem Statement
SRM	Safety Risk Management
TABC	Time-Driven Activity-Based Costing
TAWS	Terrain Awareness Warning System
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
VOLY	Value of Statistical Life Year
VOSL	Value of Statistical Life
WTP	Willingness to Pay

CHAPTER II

REVIEW OF THE RELEVANT LITERATURE

This literature review provides an overview of the ROI analyses or cost-benefit assessments as applied within the aviation industry of the costs associated with aviation accidents, benefits associated with safety improvements, and a summary of CFIT-avoidance technology. Though the purpose of this study is to estimate the ROI that can be achieved from broadly adopting the CFIT-avoidance technology, it is useful to understand how costs and benefits have been identified when CBAs have been performed with respect to the aviation industry. As previously described, a ROI is considered as the ratio of gain to investment and measure of the "return", cost savings, profit, or cost avoidance that results from a given use of money (Feldman et al., 2009), and therefore understanding the costs is important. For the broader adoption of any given technology, the ROI can be assessed at the industry level, and, in this case, the industry will be defined as an entity comprising of rotorcraft manufacturers and operators.

As helicopter operations have progressively become more complex and challenging, manufacturers and operators have continued to take advantage of technological improvements to provide pilots the operational flexibility they need. The introduction of new and advanced computerized aircraft systems has increased safety levels by reducing pilots' workload and increasing operational capabilities (Tsang & Vidulich, 2004).

A continuing challenge for the aviation industry and others is the ability to adopt new technology in a cost effective and timely manner. This challenge is a result of operators trying to achieve a safety and economic equilibrium that is dictated by the productivity and profitability limits set within contemporary transport analyses. It is therefore necessary to develop a method of assessing the costs of safety in the event of an accident, and the benefits that may be realized on making the necessary investments in safety improvements (Cavka & Cokorilo, 2012).

In today's competitive environment experienced at a global level, all businesses have to demonstrate their profitability and value to shareholders by decreasing their overhead costs and operating expenses (Jervis & Collins, 2001). The various segments of these businesses are expected to demonstrate their value to the organization as the business continues to evolve in a fast-paced environment. One of the value propositions is that a competitive advantage may be created by an organization through investments for improved product, health, and environmental safety. Safety managers therefore need a decision tool to help them determine which elements of a safety program will offer the best ROI (Jervis & Collins, 2001). For rotorcraft manufacturers, these elements of a safety program include safety technology developed and integrated into its fleet as well as their customers' fleet to mitigate a specific safety hazard or improve aircraft operations for pilot and crew. With rotorcraft manufacturers also being operators, they are likely to incur the same costs as their customers if they lost an aircraft in an accident during flight test, production, or training activities. By investing in new safety technologies for their fleet, they experience the same benefits.

The continued growth of aviation activity around the world comes with a risk of an increase in the number of incidents and accidents currently being experienced. This possibility highlights the need to develop and adopt safety technology in a proactive manner. The adoption of new safety technology requires a thoughtful process for its introduction into the market since its adoption will depend on:

1) How easy it is to integrate into existing aircraft systems and its performance;
2) If it meets the customers' needs;
3) The existing socio-economic conditions; and,
4) The opinion of leaders and stakeholders (Tang, 2006).

Adopting any new safety technology requires the investment of resources in aircraft equipment. Understanding the value proposition for such pieces of equipment to each stakeholder group is important. For one customer group, the adoption of the equipment may be a high value proposition, while for another it's a losing one (Marais & Weigel, 2006). Cost issues can influence the commitment of resources for safety efforts in complex environments. In aviation and medical practice where the teams highly interact with technology, safety is paramount (Helmerich, 2000). In order to propose the broader adoption of safety technology, one needs to understand the costs involved, the issues that may arise, and to perform a cost benefit analyses or ROI analysis. This can be done at an industry or organizational level.

Return on Investment

The goal of performing an ROI analysis is to evaluate the impact an investment has on owners of an organization or industry. Impact can be assessed in terms of the benefits and costs resulting from the investment as observed from the perspective of the investor or individual performing the analysis. The versatility and simplicity of the ROI metric makes it a useful tool for developing a company's business case and increasing the management and investors' confidence (Westerlind, 2004). Returns or benefits can be in three forms: economic, socio-economic, and social. Economic returns are the financial returns created by the investment; socio-economic returns are savings the state or society realizes, while social returns are the less tangible effects such as an increased sense of self-esteem and personal independence (Krlev, Munscher, & Mulbert, 2013). For the adoption of the CFIT-avoidance technology, the tangible costs and benefits can be evaluated from the industry's perspective, and a review of past research can facilitate the identification of those that are applicable.

A review of current research showed that safety ROI research has been focused more on the operations aspect than the aircraft equipment and technology one. CBAs that account for societal or public costs and benefits have been used to determine whether technology and aircraft equipment changes being mandated for safety improvements would not have a negative financial impact. The most prominent research on safety ROI resulted in the development of the ORC Network Occupational Safety and Health Group software named ORC Return on Health, Safety, and Environment Investments (ROHSEI). This software has been widely used by companies, government agencies, and educational institutions to evaluate and communicate the business value of HSE investments specific in projects and the overall business (Linhard, 2005).

The ROHSEI process considers both direct and hidden impacts on business performance. Direct impacts are those easily identified and quantifiable impacts that include capital, production downtime, and personnel time. These impacts are assessed using various cost parameters such as: property damage, production downtime, design and engineering time, and operational personnel time, among others. Hidden impacts are those that affect business performance and include: worker productivity, product quality, and customer satisfaction. They are more difficult to identify and quantify as they are associated with the project in question and require feedback to the analysis team from the individuals involved (Linhard, 2005).

Johnson and Avers (2012) described a process for predicting and / or measuring the safety and financial ROI for human factors safety interventions. Using the ROI calculator developed by the FAA and Booze, Allen, Hamilton Consulting, the researchers demonstrated how an individual with technical expertise to identify the benefits and investments associated with the safety intervention can evaluate the ROI. With the accident and incident data available from a large maintenance organization where fatigue was found to be a contributory factor, the researchers calculated the ROI. The company identified the costs involved in delivering fatigue training to employees and estimated the expected benefits from a reduction in equipment damage and injuries. An ROI of 312% over six quarters was calculated using the calculator's basic formula:

ROI = [(Net Returns or Benefits) – Investment (Cost)] / [Investment (Cost)]

where: Net Returns or Benefits = Estimated Return (Benefits) * Probability of Success

The Center for Aviation Research (CASR) performed a study to illustrate the business benefits of a Safety Management System (SMS) by developing an analytical framework through which the various types of costs associated with the SMS are accounted for (Lercel et al., 2011). Using the macro-to-micro analytical framework, the business benefits of safety programs were evaluated. At the macro-level, an analysis of the stock value of an airline after a major accident showed that the value of the airline could depreciate by as much as 25% and take over a year to recover. At the mid-level, the analysis showed that financial benefits of safety programs can only be realized when a program is sufficiently targeted toward a specific behavioral change. At the micro-level, the researchers used examples to illustrate how the costs and safety benefits of a particular safety invention can be tracked, and the desired return is not always achieved within the first year but over a period that is dependent on different factors. The safety investment model presented in their research portrayed the SMS as a combination of multiple safety initiatives with varying rates of return, risk, and period of return (Lercel et al., 2011). When applied broadly, these SMS initiatives can include the adoption of safety technology.

Stewart and Mueller (2013) performed a cost-benefit analysis of aviation security measures employed to prevent attacks on airports and their associated facilities to determine the optimal security measures. The three measures evaluated were the Federal Air Marshal Service (FAMS), the Federal Flight Deck Officer (FFDO) Program, and the installed physical secondary barrier (IPSB). Consideration was given to the threat likelihood, costs of security measure, hazard likelihood, risk reduction, and expected losses. The cost-effectiveness of the measures was compared using three criteria: (1) net present value, (2) benefit-to-cost ratio, and (3) break even analysis, to assess where the risk probability becomes too high for the measure to be cost effective. The researchers found that the IPSBs and FFDO programs were cost effective if the annual attack probability exceeded 0.5% and 2% respectively. A reduction in the FAMS budget was also found to be a viable policy alternative. These results provide a basis for making the right risk management decisions for these security measures.

Stewart and Muller (2014) further performed a cost-benefit analysis of measures designed to provide enhanced protection for airport terminals and their associated facilities. In this study, four significant threat scenarios were considered:

1) a large truck bomb,
2) a curbside car bomb,
3) a luggage or vest bomb, and
4) a public grounds shooting attack.

The protective measures included:

1) the addition of permanent vehicle search points,
2) check-in and screening personnel,
3) curbside blast deflection and shatterproof glass,
4) training airport police rapid response team to special weapons and tactics standards,
5) directing vehicles to remote lots,
6) eliminating lanes closest to the terminal,
7) adding support columns for upper level roadways,
8) searching all luggage entering terminals, and
9) adding 30 handheld bomb sniffers and bomb sniffing dogs.

To evaluate the costs-effectiveness of these measures, the researchers applied risk-based decision theory with the same three criteria in their previous research as described earlier plus Monte-Carlo simulation methods to propagate the hazard likelihood. The researchers found that the attack probabilities would have to be much higher than the levels observed at that time to justify the additional protective measures and the investment of financial resources.

One of the most critical functions of original equipment manufacturers and operators is to ensure their assets such as combat vehicles and aircraft are available for operations when needed. To achieve a high operational availability, the operation, maintenance, and logistic support of the assets should be effectively managed. The utilization of Prognostic and Health Management (PHM) technology allows the operators to acquire detailed health information to facilitate the achievement of the set operational availability goals (Banks et al., 2009). A cost-benefit analysis was found to be useful in supporting the estimation of the expected ROI for a customer who is considering adopting PHM technology. The research showed the relationship between a CBA and ROI when the ROI was to be used as a decision metric. Banks et al. (2009) provided a general methodology for conducting the cost-benefit analysis with the following considerations:

- the scope of the PHM system,
- the upfront or acquisition and installation costs,
- the life-cycle costs (spares and maintenance),
- projected usage profile of the platform, and
- planned depot overhauls and scheduled maintenance overhauls.

An estimated payback period for the PHM technology and its impact over the asset's lifecycle was also determined. The ROI calculation was based on the formula:

$$ROI = (\text{Benefit Gain} - \text{Technology Cost}) / \text{Technology Cost}$$

Jervis and Collins (2001) applied the Analytical Hierarchy process as a tool for determining which safety program elements offer the best ROI. The authors considered the Occupational Safety and Health Administration (OSHA) Voluntary Protection Programs as the model safety program for which the process can be applied due to their comprehensive safety management approach. The research focused on six managerial safety program elements:

a) management leadership and employee involvement,
b) worksite analysis,
c) hazard prevention and control,
d) safety and health training,
e) documentation review, and
f) occurrence of bargaining agent.

The results showed that the hazard “prevention and control” and “management leadership and employee involvement” elements provided the highest benefit-to-cost ratio. These are generally considered the basic requirements for a successful safety program.

ROI analyses or cost-benefit analyses for safety systems have been performed in other industries. In the road transport industry, three onboard safety systems (OBSS): lane departure warning (LDW), roll stability control (RSC), and forward collision warning (FCW) for Class 7 and 8 trucks were analyzed for their economic and cost benefits (Department of Transport, 2013). The direct and indirect benefits associated with a reduction in crashes from the use of OBSS were compared with the costs of deploying each system. The costs were associated with the technology acquisition, installation, maintenance, replacement, and training. The benefits included the tax deduction savings associated with the OBSS investment, operational, environmental, labor compensation, property damage, legal settlement, court costs, medical related costs, monetized value of pain and suffering, and lost productivity. The results showed that the estimated benefits of LWD and RSC systems outweighed the estimated costs, while no significant difference was observed for the FCW system. The LWD and RSC systems benefits to the carrier outweighed the costs by a factor (benefits-to-costs ratio) of 14.69 to 4.95 and 12.50 to 4.7 respectively. The FCW system benefits-to-costs ratio was not determined as the benefits were found not to be a statistically significant factor (Department of Transport, 2013).

A review of the existing literature on ROI as detailed above showed that for the aviation, in the same manner as other transport sectors, CBAs had been extensively used to determine the benefits of adopting safety technology. In aviation, when the ROI methodology has been used, it has been limited to operations. To address the existing gap on performing ROI analysis on rotorcraft safety improvements, this research reviewed the different economic models that can be applied with the goal of proposing an applicable method of evaluating the safety costs and benefits of broadly adopting the CFIT-avoidance technology.

Performing an ROI evaluation. In the aviation industry, various economic models have been applied to estimate the benefits achieved by implementing safety improvements. To inform and encourage organizations to be early adopters of Safety Management Systems, Whealan-George (2013) reviewed the different economic models that can be used to estimate the potential benefits. These models are:

1) Accounting Approach: The basic direct accounting approach applied by Friend (2011) and Skydel (2011) estimates the total business costs with and without safety interventions based on historical data and probability of occurrence. This direct approach does not take into account how an industry's business operation constantly changes over time, thereby skewing the estimated savings.
2) Time-Driven Activity-Based Costing (TABC): a proprietary financial methodology developed by John Cox of Safety Operating Systems and Triant Flouris to estimate an airline's safety costs. The TABC captures costs associated with any organizational activity that has an impact on safety (Rosenkrans, 2011). The organization can identify the variable and fixed costs that safety officers can adjust to simulate their business and predict their cost saving on safety initiatives.
3) FAAs Return on Investment simulator: An FAA accounting worksheet and PowerPoint training course used for estimating the benefits of expended costs on safety initiatives and the probability of the identified safety events occurring. The output from the ROI simulator facilitate the conversations between safety and financial specialists on the expected ROI over a period of six quarters by presenting the pre- and post-safety intervention values (Rosenkrans, 2011). The outputs consist of these five graphs: (1) investments and returns over time; (2) investment profile; (3) financial return profile; (4) probability of success; and (5) total safety events over time. The FAA accounting worksheet utilizes the formula:

ROI = {[(estimated return or benefits * probability of success as a percentage) – (investment costs)]/ (investment costs)}

4) Cost-benefit analysis using historical data: This model was applied by the FAA when it determined that Part 121 operators could benefit from implementing a SMS for their organizations. The FAA determined the economic value by assuming a 50% reduction on the losses from the 172 accidents that could have been wholly or partially prevented by the adoption of an SMS due to its formalized and intensive nature of addressing safety issues (Whealan-George, 2013).
5) Cost-optimization algorithms combined with probable-risk: A simulation with budget constraints and failure probabilities allows an organization to determine which events or precursors to events can be addressed in order to achieve greater cost savings. Addressing lower level events reduces the probability of the costly high level critical failure occurring (Whealan-George, 2013).
6) Analytical Hierarchical Process: Though not fully an economic model, the process breaks down complex processes into sub-processes and assigns them numerical values representing their weighting, priority, and significance levels. This approach in a safety improvement environment requires an individual, based on their experience and knowledge, to detail the elements of the safety improvement and prioritize them by their perceived benefit of its application. The intangible (indirect) benefits can be difficult to quantify, and the process can become time consuming (Jervis & Collins, 2001; Whealan-George, 2013).
7) Simulation model using system dynamics and data mining: This model employs a system dynamics approach incorporating human decision making and system drift over a period of time leading to an accident. Charles-Owaba and Adebiyi (2006)

employed the model for a pre- and post-safety program evaluation of a manufacturing organization.

8) Baldrige Performance of Excellence Model: This model is used to estimate the net social value of improved quality performance. It would therefore require the social value of the benefits of safety improvements to be defined beyond the basic financial terms.

9) Contrarian view of safety at any costs and modeling benefits: This economic view suggests that the safety has already reached a long term economic equilibrium despite the various methods of measuring benefits (Vasign, Fleming, & Tacker, 2008). They were in the opinion that economic models may not necessarily be the best method of evaluating the economic benefits of an SMS as the intangibles such as passenger reaction, labor reaction, liability risks, and government enforcement are difficult to measure.

The economic models described above provide different approaches to estimating the ROI or cost-benefits associated with the safety interventions under consideration. The safety specialist has to decide which model to utilize depending on its applicability, its complexity, the available resources, scope of the study, and the costs and benefits under consideration. Understanding the costs and benefits associated with the adoption of CFIT-avoidance technology will be critical to performing a more representative ROI. Benefits and costs the rotorcraft industry may experience include the avoidance of future accident safety costs and reduction in insurance costs, as discussed herein.

Accident Safety Costs

Reducing the losses experienced by an organization or industry is the first goal of introducing safety technology. These losses can be measured in terms of costs of lives, time, material, and equipment, depending on the type of industry. Huang, Leamon, Courtney, DeArmond, Chen, and Blair (2009) designed a study to explore the perceptions of corporate financial decision makers on the impact of safety on a company's financial performance. The researchers estimated that for every dollar spent on direct costs associated with occupational injuries, $2.12 was spent on indirect costs, while the return on every dollar invested on safety was $4.41 based on the 5,840 fatal and 4.1 million non-fatal occupational injuries that were reported in 2006 in the U.S. private industry. This ROI suggests that a company should consider investing the right amount of financial resources to address the most critical safety concerns for its industry. This also requires a good understanding of the costs which are to be incurred or avoided for each initiative.

The responsibility of providing evidence to an organization's management showing how investing in safety can be worthwhile and how it can be accomplished lies with the safety professional (Friend, 2011). The safety professional should therefore provide quality information to assist management in making decisions. This information not only includes the costs, but also the intangible elements such as the enhancement or loss of reputation, positive versus adverse publicity, and goodwill from the public and employees. In providing the ROI information to management, the safety practitioner must consider the losses that may occur, the risk (exposure to the losses), and costs associated with those losses that occur (Friend, 2011).

In aviation, past aircraft safety cost-benefit analyses have identified two cost categories: direct and indirect costs (Čavka & Čokorilo, 2012; Čokorilo, Gvozdenović, Vasov, & Mirosavljević, 2010). These cost-benefit evaluations were based on the cost implications defined by the National Aerospace Laboratory (2001) as shown in Table 1. The costs of these accidents were determined primarily on the aircraft type and level of damage. In these two studies, the A320-200 and A380 aircrafts were considered, and the same cost categories can be scaled down to reflect costs of a helicopter accident.

Table 1

Accident Safety Costs

Direct Cost Category	**Cost Description**
Aircraft physical damage	Minor (15% damage) Moderate (50% damage) Major (80% damage) Disaster (100% damage) Catastrophic (100% damage)
Possible loss of resale value	5-10% of aircraft market value (for partial losses)
Aircraft loss of use	Monthly lease cost x assumed months to replace
Aircraft loss of investment return	Part of aircraft loss of use
Site contamination and clearance	Wide body: 1.2-2.8 M€ Narrow body: 0. 7-1.3 M€ Smaller aircraft: 0.13-0.2 M€
Airline costs for delay	Wide body: 22 € x number of passengers on flight Narrow body: 20 € x number of passengers on flight

Airport closure	Airport disruption depends on severity of the accident. Only applicable if accident occurs on or close to the runway.
Deaths and injuries	Value of a Statistical Life (VOSL): 1-2.64 M€ VOSL differs per country. Value of injury is 13% of VOSL.
Loss of staff investment	Replacement cost per pilot: 45000 €
Loss of baggage	Underfloor cargo carried on passenger flights: 110000 € Personal baggage on passenger flights: 45000 €

Indirect Cost Category	**Cost Description**
Search and Rescue (SAR) costs	Average SAR costs: 0.6 M€
Airline immediate response	Average costs per accident: 0.5-3 M€
Cost of accident investigation	State: 0.1-100 M€ Airline: 1 M€ Manufacturer: 1 M€
Third party damage	Third party death and injury: use similar VOSL as in passenger death and injury + third party physical damage
Loss of investment income	These costs are reflected in insurance premiums.
Increased cost of insurance	Loss of 20% insurance discount for airline involved
Loss of reputation	Airline loss of turnover: 0-380 M€ (Huge range. Loss to society is far less than to airline, since major part of reduced demand will shift to other airline.) Manufacturer (Likely that airlines will buy aircraft from other manufacturers.)

Note. Adapted from "Aviation Safety Targets for Effective Regulation, a Consolidated Report," by National Aerospace Laboratory, NLR, 2001.

According to the NLR (2001), the most significant determinants of costs arising from aircraft accidents are aircraft damage, death and injury of occupants, and loss of reputation of an airline (operator). The magnitude of these direct and indirect costs is directly linked to the severity of an accident where severity is determined by the level of damage and number of deaths or injuries to the occupants. In the NLR analysis, the accident severity scheme shown in Table 2 was used to model the effects of accident severity on the level of cost. From this analysis, it’s expected that in a catastrophic accident, an aircraft will be completely damaged and at least 80% of the occupants will perish. CFIT accidents are more generally considered to have a catastrophic outcome due to the nature of the events.

Table 2

Accident Classification Severity Scheme

Level	**Damage [%]**	**Death [%]**
Catastrophic	100	80
Disaster	100	30
Major	80	0
Moderate	50	0
Minor	15	0

Note. Adapted from “Aviation Safety Targets for Effective Regulation, a Consolidated Report,” by National Aerospace Laboratory, NLR, 2001.

Aircraft physical damage. The actual costs arising from the damage of an aircraft can vary greatly depending on the age of an aircraft, extent of damage, and financial inflation. To determine the average loss of aircraft value with age, actual cost figures for individual aircraft were collected. The costs were normalized to obtain an "index" for the relative degree of damage expressed as a percentage of the aircraft total damage as shown previously in Table 2 (NLR, 2001). The cost value for the aircraft physical damage can be determined by multiplying the aircraft's market value and the corresponding damage ratio (Čavka & Čokorilo, 2012). For rotorcrafts, the market value (residual value) at any given period can be found in the Helivalue$, Inc. Helicopter Blue Book.

Possible loss of resale value. Loss in resale value of an aircraft involved in an accident amounts to approximately 5-10% of its market value. The losses are determined by the degree of severity of the accident from minor, moderate, major, and disaster to catastrophic. The disaster and catastrophic severities bear a complete loss of resale value (NLR, 2001). In their research, Čavka & Čokorilo (2012) assumed a possible loss of resale value of 5% for the minor, moderate, and major categories. A helicopter's market value can be determined from the Helicopter Blue Book.

Aircraft loss of use. These are costs incurred when the accident aircraft is not available for flight operations and necessitates the leasing or purchase of a replacement aircraft. The monthly leasing costs are expressed as a percentage of the average market value and the estimated number of months the lease would last or before a new replacement aircraft is introduced. This period was determined to be usually between six to twelve months for the airline jets (Čavka & Čokorilo, 2012). Consideration should be given to this cost category if a rotorcraft operator plans to use a leased aircraft until the repair of the accident aircraft is complete or one obtains a new aircraft.

Occupants' deaths and injuries. The injury and death of crew and passengers in an aircraft accident is an unfortunate outcome, and determining the value of a life that is lost or the quality of life that will be lived is considered to be a difficult and undesirable task. Even with this difficulty, the industry has made attempts to determine the value on which to compensate families for the loss of or injury to their loved ones. Monetizing these health impacts is a means of comparing benefits of a reduction in risk against the costs and helps facilitate quicker and more consistent decision making. To this end, different methods as highlighted by the European Commission (2009) have been used to determine these values. They include:

a) Quality Adjusted Life Years (QALY): This method uses available information on improvements in health / life quality combined with the duration of that improvement for its values. A year of life in perfect health is counted as 1.0, and the value decreases for years of less than perfect health based on a value that represents an average among different social groups. A common discount factor is used to discount future life years.

b) Disability Adjusted Life Year (DALY): This is the negative value of the QALY. It measures the number of quality adjusted years that are lost in comparison to the benchmarking scenario. For aviation accidents, the resulting disabilities would be compared to similar outcomes for other accidents. DALY and QALY should lead to comparable values if performed correctly (European Commission, 2009).

c) Healthy Life Years (HLY): This approach measures the number of quality adjusted remaining life years per person and with future years discounted and weighted across individuals. When using the remaining life expectancy as the upper bound for summation, the HLY value should be comparable to the QALY value, as HLY is essentially a summation of the QALYs (European Commission, 2009).

d) Cost of Illness: A measure comprised of only the medical expenses related to the incidence of an illness, and the lower the rate of occurrence, the saved expenses constitute a benefit. If the risk option results in a higher occurrence of the illness, the expenses are considered direct costs. This measure is limited as it does not account for the indirect costs to society such as loss of labor hours (European Commission, 2009).

e) Human Capital (HC): As a measure of the loss of social welfare, this method attempts to measure the loss of future earnings as a result of disability or premature death. The potential shortfall of this method is the different values given to lives based solely on projected future earnings, the likely exclusion of individuals outside of the workforce by assigning a value equal to zero, and the individual’s preferences for safety not being reflected. Adopting average monetary values for individuals outside the workforce can ease these concerns (Andersson & Treich, 2011).

f) VOSL: defined as the monetary value of an improvement in safety to achieve a risk reduction that would prevent one statistical death or injury. It is derived from an individual’s Willingness to Pay (WTP) for reduced risk and the reduction (European Organisation for the Safety of Air Navigation, 2015). VOSL, as an economic measure commonly used by governments, is also considered not to adequately represent the value of a life but the risk, as it is derived from market decisions. Basing the VOSL on perceived risk can introduce bias as the level of risk may vary with the perceptions of each individual (Viscusi, 2005). Estimating the VOSL is considered challenging due to the limitations in identifying the worker and job characteristics that may be correlated with the job and how the workplace risks are to be measured (Lee, 2012). A method commonly used to quantify an individual's perception of the utility of safety improvements when facing fatality risks is the maximum utility theory, and the determined value is referred to as the subjective value of statistical life (Andersson, 2007; Yang, Liu, & Xu, 2016). The utility of safety improvements results in a reduced fatality rate that together with the income of individuals that benefit can be used to determine the social value of statistical life. These safety improvements are assumed to have been implemented using collected taxes (Yang, Liu, & Xu, 2016). The different methods of determining VOSL create challenges, and therefore the choice of VOSL will be dependent of the type of study being performed.

g) Value of Statistical Life Year (VOLY): Generally, VOLY is a measure of the WTP for an increase of one additional year of life expectancy, and, like the VOSL, does not measure the quality of life. A major concern with the application of the VOLY, just like VOSL, is how to monetize a life without appearing to be unethical when every individual's life is considered priceless. The two measures should reflect a change in risk or safety levels (European Commission, 2009).

h) Value of Statistical Injury: defined as the monetary value of an improvement in safety to achieve injury risk reduction that would prevent one statistical injury (Andersson & Treich, 2011). These values of improvement are represented as a percentage of VOSL depending on the severity of the injury as categorized on the

Abbreviated Injury Scale (AIS). The injuries are classified into six categories ranging from AIS Code 1 for minor injuries to AIS Code 6 for fatal injuries. The valuation of each injury level is related to the loss of quality and quantity of life resulting from an injury typical of that level and as a fraction of a fatality (EUROCONTROL, 2015; FAA, 2016).

The availability of different measures for the monetized value of a life lost or injury incurred in an accident provides options for an economic analysis. Each measure has its limitations, but cost-benefit models have increasingly used the VOSL, a value that includes an element of indemnity together with a society's WTP to avoid a statistical fatality (NLR, 2001). For aviation related economic analysis, the FAA and EUROCONTROL have adopted the VOSL measure.

Scuffham, Chalmers, O'Hare, and Wilson (2002) estimated and compared the direct and indirect costs of general aviation accidents. Consideration was given to medical treatment, damage to aircraft and property, and accident investigation costs for direct costs and HC and WTP approaches for indirect costs. The HC approach considered the value of lost production from employed work and household activity. For the WTP approach, the Land Transport Safety Authority's estimated values of a society's willingness to pay to avoid a fatality or injury were considered. The direct and indirect costs associated with aircraft accidents shown in Table 1 together with those related to the integration of the technology can be appropriately modified and employed in estimating the ROI likely to be achieved on the adoption of CFIT-avoidance technology from an operator and manufacturer perspective. Due to the limited information available on the earnings or injuries for the crew and passengers lost or injured in rotorcraft accidents, the ROI analysis will adopt the recommended VOSL and VSI values recommended by the U.S. Department of Transport (2015). The U.S. Department of Transport has determined that the recommended VOSL for its analyses in 2015, based on existing data, should be $9.4 million. With the WTP being difficult to estimate for an entire range of disabilities that could be incurred in a transport accident, the Department has rated injuries in terms of severity and duration on a scale of QALYs as compared to the alternative of perfect health. The scores were grouped according to the AIS to yield coefficients that can be applied to the VOSL to assign each injury class a value corresponding to a fraction of a fatality, as shown in Table 3.

Table 3

Relative Disutility Factors by Abbreviated Injury Scale (AIS)

AIS Level	**Severity**	**Fraction of VSL**
AIS 1	Minor	0.003
AIS 2	Moderate	0.047
AIS 3	Serious	0.105
AIS 4	Severe	0.266
AIS 5	Critical	0.593
AIS 6	Unsurvivable	1.000

Note. Adapted from “Guidance on Treatment of the economic Value of Statistical Life (VSL) in Department of Transportation Analyses- 2015 Adjustment,” by U.S. Department of Transport, 2015.

To determine the value of any given injury, the applicable fraction of the VSL is multiplied by the 2015 VSL value of $9.4 million (U.S. Department of Transport, 2015).

CFIT-Avoidance Technology

Aircraft manufacturers, component manufacturers, and aircraft operators identify new products and technologies for integration into the industry in order to improve customer experience and safety. The integration of some of these technologies is done as a result of certification and operation regulation mandates where the main objective is to increase the reliability of safety critical systems (Anderson, 2013). These critical systems include those that have integrated the new technologies that target the reduction of rotorcraft CFIT accidents.

According to the FAA (2011), the number of fatal CFIT accidents between 2010 and 2012 represented a reduction of more than 50% over the preceding three-year period, 2007 to 2009. The General Aviation Joint Steering Committee (GAJSC) attributed this reduction in fatal accidents to the use of technologies such as global positioning system (GPS) with moving maps that provide traffic, terrain, and in-flight weather information. The GAJSC, at that time, further suggested that the implementation of new technologies such as the angle of attack indicators, ballistic parachutes, and terrain avoidance equipment would continue to further reduce the number of general aviation (GA) fatal accidents (GAJSC, 2012).

The emphasis on the adoption of CFIT-avoidance technology for rotorcraft operations can be traced back to the benefits observed for the fixed-wing fleet where the worldwide CFIT accident rate fell by 80 percent following the TAWS mandate (IHST, 2010). According to the FAA, TAWS has been considered by many in the airplane (fixed-wing) safety community as the single most important safety device introduced to prevent commercial fatal accidents in 20 years and has been voluntarily adopted in general aviation as part of GPS-based navigation systems (Department of Transportation, 2012). The FAA has mandated TAWS for HAA operations, but the anticipated safety benefits may extend to other operations in the industry when the technology is adopted broadly.

The U.S. Joint Helicopter Safety Analysis Team (2011) identified the installation of proximity detection systems as one of its Intervention Recommendations (IRs) for rotorcrafts accidents. The technology, it opined, would prove to be valuable in identifying ground obstructions as helicopters operate regularly in close proximity to obstacles. The CFIT-avoidance technologies recommended by the NLR (2014) are as follows:

a. Enhanced Ground Proximity Warning System / (Helicopter) Terrain Awareness and Warning System (HTAWS): The HTAWS provides a "look-ahead" function to detect terrain or obstacle conflicts by comparing the helicopter flight path to a terrain and obstacle database. The helicopter's position is based on the information provided by an onboard GPS receiver. Caution alerts (advisory in nature) and warning alerts (requiring pilot corrective actions) are generated if there are terrain and obstacle conflicts along the helicopter's flight path (Department of Transport, 2012). HTAWS that integrates data from a wire warning database system, for example WireWatch® and WireAware®, can reduce the likelihood of collision with transmission mast and power lines (Garmin, 2016a; Sandel Avionics, 2012). Examples of existing systems include the Honeywell MK XXI and XXII EGPWS, Garmin® HTAWS, and Sandel's ST3400H HeliTAWS®, as shown in Figures 1 and 2.

Figure 1. Honeywell EGPWS MK XXII. Retrieved from https://parts.seaerospace.com/product_images/35/20324/medium/mkxxii.jpg Copyright Southeast Aerospace. Adapted with permission.

Figure 2. Garmin® HTAWS (010-HTAWS-00). Retrieved from https://buy.garmin.com/en-us/us/p/72799 Copyright GARMIN. Adapted with permission.

b. Laser radar obstacle and terrain avoidance system: This system uses an eye-safe laser which is mounted on the helicopter's fuselage to provide information to the pilot through both displays and aural warnings on actively detected obstacles such as cables, trees, pylons, power lines, or rising terrain in the helicopter's flight path. The laser radar obstacle warning system comes with a higher probability of detection of thin wires, the real-time processing of the measured range image data, obstacle classification, and its visualization on the displays (Bers, Schulz, & Armbuster, 2005; Stevenson, Verdun, Stern & Koechner, 1994). Examples of existing systems include the Fairchild Control's HELLAS-A (Awareness) and Selex ES LOAM.

c. Digital map: This system is also referred to as a digital moving map and provides clear and precise information on the surrounding operational environment and can change or maintain an updated position in correspondence with the aircraft's current position. The moving map's information can be sourced from both database and sensor technology (Jones, 2002). The moving map systems are either standalone or integrated within the aircraft avionics suite and display the map images on a Multi-Function Display (MFD). The advanced systems can provide terrain and obstacle information to the pilot (NLR, 2014). Examples of existing systems include the Flight Management Systems, Israel Aerospace Industries, and Moving Terrain-MT Vision Air moving maps, as shown in Figure 3.

Figure 3. MT VisionAir X Heli: Retrieved from http://www.moving-terrain.de/lang-en/produkte/mt-visionair-x/mt-visionair-x-heli.html Copyright Moving Terrain Air Navigation Systems AG, Germany. Adapted with permission.

d. Radar altimeter: The radar altimeter is also referred to as a radio altimeter, and it measures the actual altitude of an aircraft with respect to the terrain by measuring how long it takes a beam of radio waves to reflect off the ground and return to the aircraft. The radar altimeter can be integrated with other systems to fulfill the requirements for advanced applications such as HTAWS and Terrain Collision Avoidance System operations (Garmin, 2016b; NLR, 2014). Examples of existing systems include Garmin's GRA™ 55 and 5500 (shown in Figure 4), Honeywell AA-300, Freeflight Systems TRA-3000, and TRA-3500 altimeters.

Figure 4. GRA™ 5500 Radar Altimeter. Retrieved from https://buy.garmin.com/en-US/US/p/135561 Copyright GARMIN. Adapted with permission.

Summary

A review of past literature shows that a gap exists within the body of knowledge for the aviation industry on how to estimate the expected ROI when adopting safety technology. The method of estimating an ROI should be predictive rather than a retroactive approach, as seen with the OBSS for road transport. Aviation accident data can be used to determine the probability of an accident occurring in the future and by the industry to set accident reduction targets to be achieved based on the expected performance of the available technology. This study offered a method of calculating the estimated ROI for adopting CFIT technology.

CHAPTER III

METHODOLOGY

Research Approach and Design

A review of the relevant literature supports the researcher's use of an expanded version of the formulas employed by Johnson and Avers (2012) in the ROI calculator for human factors safety interventions, ROI = [(Net Returns / Benefits) - Investment (Cost)] / (Investment Cost), and by Bank et al. (2009) for calculating the expected ROI for the utilization of PHM technology where ROI = [(Benefit Gain - Technology Cost) / Technology Cost] to estimate the potential ROI that can be achieved when rotorcraft CFIT-avoidance technology is broadly adopted. In research by the Department of Transport (2011), the benefits were considered to be the accident costs avoided with the installation of TAWS, and this study considered the same for the rotorcraft industry. These costs can be estimated by using the relevant NLR (2001) report cost categories as done by Cavka and Čokorilo (2012) and Čokorilo et al. (2010). Additionally, the adoption of the CFIT-avoidance technology is considered a SMS risk mitigation measure, and costs avoided can be estimated by applying decision analysis as done by Stewart and Muller for aviation security (2013) and airport security (2014). The expanded formula, which accounts for the cost savings likely to be realized with a reduction of the CFIT accident rate, is represented as Equation 1.

$$\text{ROI} = \frac{\text{Net Benefits}}{\text{Safety technology costs}} = \frac{[\text{Accident costs avoided} - \text{Safety technology costs}]}{\text{Safety technology costs}} \qquad (1)$$

where:

Net Benefits = Accident costs avoided through the adoption of CFIT-avoidance technology.

*Safety Technology Cost*s = Costs associated with the integration and usage of CFIT-avoidance technology on a rotorcraft.

The purpose of the study was to use historical rotorcraft accident reports and the safety costs associated with the accident outcomes to estimate the potential ROI that can be achieved if CFIT-avoidance technology is adopted more broadly. The study:

(a) identifies the outcomes of each CFIT-related accident (terrain, water, or obstacles and wires) occurring between January 1, 2005, through December 31, 2015;

(b) quantifies the value of the direct and indirect costs associated with each accident;

(c) determines the CFIT accident rate over the period of study, based on the number of CFIT accidents and flight hours accumulated;

(d) evaluates the CFIT accident rate (probability) with a reduction target range of 50% to 80%. The 50% target is based on the reduction observed in fixed-wing operations from the three-year period between 2007 to 2009 and the three year period between 2010 and 2012 (FAA, 2011). The 80% target is based on the IHST reduction target for the overall rotorcraft accident rate (USJHST, 2010).

(e) quantifies the costs associated with adopting the CFIT-avoidance technology; and

(f) employs the appropriate ROI equation in a Monte Carlo simulation to estimate the potential ROI that can be achieved if the CFIT accident rate is reduced by the 50% to 80% levels previously described.

This study employed a mixed methods research design performed in two phases. In the first phase, a qualitative assessment of the CFIT-related accident reports retrieved from the NTSB accident / incident database was performed to identify the accident outcomes (injuries, deaths, damage, etc.). At the beginning of each accident report, details of the accident that include: location, date and time, aircraft, aircraft registration, regulations under which the flight was conducted, aircraft damage, and injuries were provided. The injuries were categorized by severity to include fatalities. Within the report, the probable cause and findings section was also reviewed to verify that the accident was primarily a CFIT. The qualitative assessment was performed by the researcher to identify the accidents to be included in the analysis. The NTSB reports, based on subject matter experts' analysis, identified the probable cause and findings and provided a summary of the factual information with adequate detail for an individual with some appreciable aviation experience to determine whether a CFIT occurred and without the influence of factors such as mechanical or system failures. Since no further coding or classification of the data for causal factors was required, it was considered that the use of additional subject matter expert(s) was not necessary. The accident data from the database, which included information already contained in the accident reports, was also extracted into a Microsoft Excel® file for the calculation of the various accident safety costs as described in detail herein. The classification of the rotorcraft by engine type was done based on the manufacturer's designation and using the Aircraft Bluebook from the Aviation Week Network as a guide.

As part of the first phase, flight hours and fleet size data were retrieved from the FAA Aerospace Forecast Fiscal Year 2011-2031 and FY 2016-2036 reports (FAA, 2017). The flight hours from the FY 2011-2031 report were used to calculate the accident rates for the different rotorcraft categories. The hours from the FY 2016-2036 report were used to calculate the number of accidents that are likely to occur if the current accident rate remains unchanged and when the targeted reduction of between 50% and 80% is achieved. The number of accidents avoided was used to calculate the accident costs likely to be avoided for each rotorcraft category.

In the second phase, data searches and collection were performed to estimate the costs associated with the adoption of CFIT-avoidance technology. Data searches for aircraft manufacturer, equipment vendor, and training centers' catalogs, advertisements, quotes, or websites were done. Costs to install, operate, and maintain the equipment were considered. It was assumed that the equipment, when installed as part of an avionics suite, would have the capability to provide the pilot with the information that all four CFIT-avoidance technologies recommended in the NLR (2014) report would provide. For each piece of equipment, the costs to install, operate, and maintain it were collected. These costs were then averaged for each type of equipment and used for determining the technology adoption costs for all the identified CFIT-avoidance equipment. The cost estimates generated in both phases are combined to calculate the ROI with Equation 1. The graphical representation of the study's design is depicted in Figure 4.

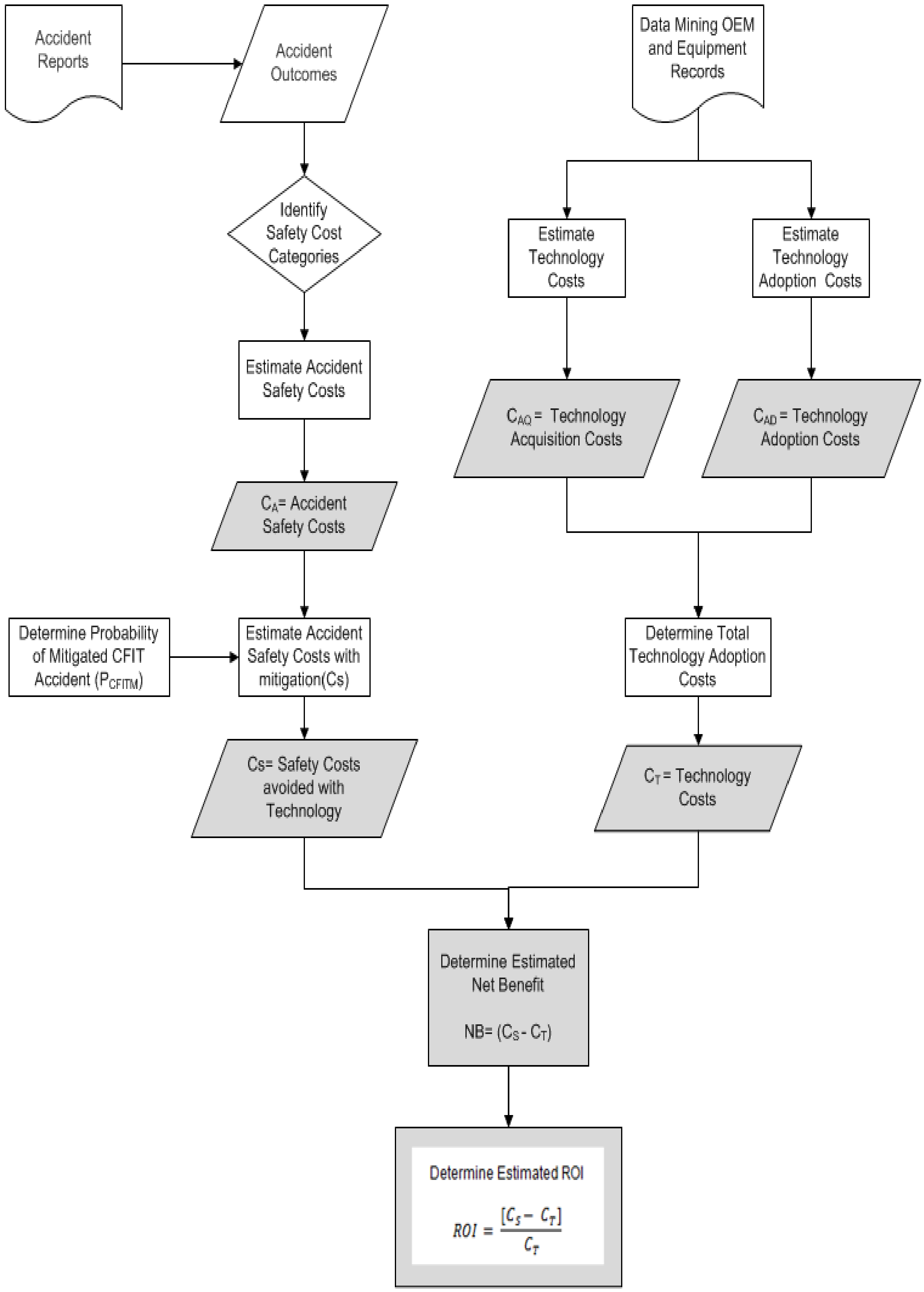

Figure 5. Return on investment research process.

Accident Safety Costs

Using the data retrieved for the variables listed in Table 4 and the criteria in Table 5, the direct and indirect aircraft safety costs associated with the outcomes of the accidents for each accident were evaluated. The cost category criteria applied were drawn from the NLR (2001) *Aviation Safety Targets for Effective Regulation* report together with the appropriate assumptions on aircraft accidents and safety costs as applied in studies previously described herein and referenced as *Rotorcraft Comments* in Table 5.

Table 4

Accident Data Variables Utilized in Aircraft Safety Costs Evaluation

Variable	Aircraft Safety Costs	Data Type
Make	Aircraft category	Qualitative
Model	Aircraft category	Qualitative
Engine Type	Aircraft category	Qualitative
Number of Engines	Aircraft category: turboshaft single or piston, turbine single, turbine twin, or heavy (based on number of engines and manufacturer’s or industry’s classification).	Quantitative
Aircraft Damage	Aircraft physical damage and loss of resale value (destroyed, substantial, or minor)	Qualitative
Total Fatal Injuries	Deaths and Injuries, Fatal	Quantitative
Total Serious Injuries	Deaths and Injuries, Serious	Quantitative
Total Minor Injuries	Deaths and Injuries, Minor	Quantitative
Total Uninjured	Deaths and Injuries, None	Quantitative

Table 5

Aircraft Safety Costs Criteria and Variable Name

Direct Costs			
Cost Category	**ASTER Cost Description**	**Rotorcraft Comments**	**Variable**
Aircraft physical damage	ASTER Handbook: Minor (15% damage) Moderate (50% damage) Major (80% damage) Disaster (100% damage) Catastrophic (100% damage); Percentages based on analysis of past accidents for larger aircrafts and are adopted for estimation purposes only.	For this analysis, the ASTER and NTSB categories are paired as follows: • Minor/Moderate: Minor • Major: Substantial • Disaster/Catastrophic: Destroyed. The costs are based on the market value of rotorcraft at time off accident.	C_D
Possible loss of resale value	5-10% of aircraft market value (for partial losses)	Applicable only to aircraft with minor damage and substantial damage (Čavka & Čokorilo, 2012). Costs will be based on 5% of market value of rotorcraft at accident date.	C_R
Aircraft loss of use	Monthly lease cost x assumed months to replace	Mid-size single engine rotorcraft (e.g. Bell 407) monthly lease of $85,000 (Fadali, Griswold, Packham, & Harris, 2011).	C_L
Aircraft loss of investment return	Part of aircraft loss of use	Part of rotorcraft loss of use	N/A
Site contamination and clearance	Wide body: 1.2-2.8 M€ Narrow body: 0. 7-1.3 M€ Smaller aircraft: 0.13-0.2 M€	Costs are incurred by the local or state emergency departments. Considered societal costs and not cost to operator.	N/A
Airline costs for delay	Wide body: 22 € x number of passengers on flight	Rotorcraft operations differ from airlines as majority of flights are	N/A

	Narrow body: 20 € x number of passengers on flight	non-scheduled and therefore delays will be considered to incur negligible costs.	
Airport closure	Airport disruption depends on severity of the accident. Only applicable if accident occurs on or close to the runway.	Rotorcraft CFIT accidents usually do not occur near the airport, and therefore airport closure costs will be considered negligible.	N/A
Deaths and injuries	Value of a Statistical Life (VOSL): 1-2.64 M€ VOSL differs per country. Value of injury is 13% of VOSL.	VOSL: $9.4 million. Value of injury, refer to Table 3 (Department of Transport, 2015).	C_F and C_I
Loss of staff investment	Replacement cost per pilot: 45000 €	Replacement costs for a rotorcraft pilot are difficult to determine. With an aircraft pilot average pay of $119,360 (BLS, 2016), the replacement costs are estimated to be $179,040 (1.5 times the average pay).	C_P
Loss of baggage	Underfloor cargo carried on passenger flights: 110000 € Personal baggage on passenger flights: 45000 €	Due to limited baggage space on rotorcrafts, these costs will be considered negligible.	N/A
Indirect Costs			
Cost Category	**Cost Description**	**Rotorcraft Comments**	**Variable**
Search and Rescue (SAR) costs	Average SAR costs: 0.6 M€	According to Čavka & Čokorilo (2012), indirect safety costs are difficult to estimate and predict and therefore recommend a percentage of the direct costs, depending on the type of accident and injury classification.	C_{IN}
Airline immediate response	Average costs per accident: 0.5-3 M€		
Cost of accident investigation	State: 0.1-100 M€ Airline: 1 M€ Manufacturer: 1 M€		

Third party damage	Third party death and injury: use similar VOSL as in passenger death and injury + third party physical damage	• minor: 5-15% (minor); • moderate: 25-40%; • major: 50-70%; • disaster: 85-110%; • catastrophic:90-140% Due to the variability observed in indirect costs in previous research, an indirect-to-direct cost ratio is usually recommended. Based on research by Manuele (2011) and OSHA (2007), a ratio of indirect to direct costs of 1:1 will be applied for this study.	
Loss of investment income	These costs are reflected in insurance premiums		
Increased cost of insurance	Loss of 20% insurance discount for airline involved		
Loss of reputation	Airline loss of turnover: 0-380 M€ (Huge range. Loss to society is far less than to airline, since major part of reduced demand will shift to other airlines.)		
	Manufacturer (Likely that airlines will buy aircraft from other manufacturers.)		

Note. Adapted from "Aviation Safety Targets for Effective Regulation, a Consolidated Report," National Aerospace Laboratory, NLR, 2001. Modified to add rotorcraft comments and define study variable.

Aircraft physical damage. The damage to an aircraft varies by the type of accident and its interaction with the environment at the time. According to the NLR report (2001), the severity of the accidents included in their research model that involved CFIT were found to be catastrophic in nature. This is an indication that a CFIT is more likely to result in the loss of the aircraft whether on impact with the terrain or by the resulting post-crash fire. To determine the value of the damage, the value of a similar aircraft at the time of the crash was retrieved from the industry's current primary sources of the data, the HeliValue$, Inc. Helicopter Blue Book, or Aircraft BlueBook and multiplied by the percentage associated with the level of damage as expressed by Equation 2.

$$C_D = \text{Aircraft Value} * \text{Damage Percentage (severity based)} \quad (2)$$

Possible loss of resale value. Collisions with obstacles such as transmission poles, wires, and towers that do not result in the loss of the aircraft require the operator to incur restoration costs. Čavka & Čokorilo (2012) have recommended estimating a loss in value of 5 percent on its value on the date of the accident. The value of the aircraft at that point was determined from the HeliValue$, Inc. Helicopter Blue Book or Aircraft Bluebook.

$$C_R = \text{Aircraft Value} * 0.05 \quad (3)$$

Aircraft loss of use. After an accident, an aircraft assessed to have experienced minor, moderate, or major damage is transferred to a facility for repairs. The unavailability of the aircraft will necessitate the leasing of another aircraft for the organization to meet its operational needs. The lease period is dependent on the extent of the damage to the aircraft under repair and type of aircraft. The costs associated with the lease can be estimated with Equation 4.

$$C_L = \text{Monthly Lease} * \text{Number of months} \quad (4)$$

The monthly lease costs will vary based on the aircraft type, age of the aircraft, and other conditions as determined by the lessor. For the study, the average monthly lease cost was determined by aircraft category and based on rates sourced from current aircraft leasing companies and applicable literature.

Death and injuries. A review of existing literature and current practices in various countries shows that the Value of a Statistical Life (VOSL) has been used when estimating the compensatory costs for occupational deaths and injuries. The safety costs associated with a fatality (C_F) were set at the 2015 VSOL level of $9.4 million and that of an injury, at the value evaluated with the application of the relative disutility factor to the VOSL. The relative disutility factor, previously given in Table 3, was based on injury severity as set by the U.S. Department of Transport (2015).

Loss of staff investment. In addition to the costs related to death and injury incurred in an aircraft accident, the operator is likely to incur additional costs for the replacement of crew. Replacement costs include the advertising, recruitment, interviewing, screening, hiring, management, and effective training of a pilot to accomplish the same duties as the deceased pilot. Due to the limited literature on the cost incurred when hiring a replacement rotorcraft, research on other fields was done. According to Boushey and Glynn (2012) of the Center for American Progress (CAP), the cost of replacing an employee earning $75,000 or less annually is approximately 20.4% of the base salary and 21.4% when all employees from the case studies reviewed are considered.

Applebaum and Milkman (2006) determined that high paying jobs at senior or executive levels tend to have high replacement costs as a percentage of the salary. They found that for a lower level executive at a consumer products company's corporate headquarters earning $125,000 dollars, the replacement cost is about $185,000. For a middle level manager earning $50,000 to $125,000, the cost ranged from $98,000 to $117,000. At a client services company, replacement costs were found to be about 1.5 times the base salary of an employee earning over $100,000. Considering the specialized training required for rotorcraft pilots and the estimated average pay for an aircraft pilot being $119,360 (BLS, 2016), this study employed a replacement cost of $179,040. This was equivalent to 1.5 times the average pay of a pilot.

Indirect costs. Unlike the direct costs, indirect costs (C_{IN}) are the hidden costs that result from internal systems of the organization adapting to the accident. According to the U.S. Occupational Safety & Health Administration (OSHA) (2007), indirect costs refer to the production time lost by the employee, fellow workers, and supervisors; unhappy customers; cleanup time; schedule delays; training new employees; overhead costs; legal fees; and increase in insurance costs. The costs identified in the ASTER report (NLR, 2001) and considered as indirect costs in previous research are difficult to estimate as are those identified by OSHA.

To facilitate the evaluation of safety costs, researchers have adopted an indirect to direct costs ratio, and they vary greatly. OSHA has a ratio of 1-to-1.1 when direct costs exceed $10,000 while Čavka & Čokorilo (2012) range the costs from 5 to 140 percent, dependent on the accident severity. Scuffham et al. (2002), using the Human Capital (HC) approach assigned a ratio of 1-to-4.9 and with the Willingness to Pay (WTP) approach assigned a ratio of 1-to-5.41 for accidents in New Zealand. Manuele (2011), in his quest to find a more reliable ratio, evaluated the different methods and sources used to determine the ratios found in existing literature.

A study by Manuele (2011) found that in some cases the ratios were based on decades-old data that do not reflect the growth of direct costs at a higher rate than indirect costs in recent times. Examples of the ratios included the 4:1 recommended by the Canadian Manufacturers and Exporters (Ontario Division) and Workplace Safety and Insurance Board in *The Business Results Through Health and Safety Guidebook*, ASSE's Journal of SH&E Research in which Choi (2006) suggested indirect costs were two to 20 times the direct costs, the U.S. Fish and Wildlife Service noted that $4 to $10 were spent on indirect costs for every dollar of direct costs, and the International Safety Equipment Association's estimated indirect costs were up to 30 times the direct costs. He opined that safety practitioners have commonly used the ratio 4:1 for indirect to direct costs of accidents to inform management on total accident costs and there was a need to rethink the ratio. It was observed that the ratio reduced as the direct costs continued to increase. Manuel (2011), using the available data, updated the calculations in the Stanford University's Department of Civil Engineering 1981 Technical Report No. 260 to the Business Roundtable and determined that a ratio of 0.8:1 of indirect to direct costs was more appropriate. He also argued that a safety professional assuming a ratio of 1:1 can be reasonably comfortable with it and should avoid using higher ratios for which supporting data is not available. Based on the research done by Manuele (2011) and OSHA (2007), this study applied a ratio of 1:1.

Safety costs (C_A) for each rotorcraft accident were calculated by totaling the costs in the different categories identified with the variables in Table 5 and as expressed with Equation 5.

$$C_A = (C_D + C_R + C_L + C_F + C_I + C_P + C_{IN}) \quad (5)$$

For a detailed evaluation of the expected ROI for CFIT accidents, the safety costs were evaluated with the assumption that the pieces of equipment are adopted within an integrated avionics suite with the capability to mitigate collision with terrain and objects such as wires, transmission towers, and poles. The goal of the IHST at its creation in 2005 was to reduce the number of accidents worldwide 80% by 2016. Current data shows that since 2006, an accident reduction of 24 percent to up to more than 50 percent has been achieved in key global regions, while the accident rate has decreased within a range of 40 to 60 percent. During this time, the worldwide fleet also grew by 30 percent (IHST, 2016).

In the fixed-wing world, as previously stated, CFIT accidents were reduced by 80% when TAWS was adopted and implemented. Aiming to achieve the same success as the fixed-wing segment, the probability of a CFIT occurring after the CFIT-avoidance technology has been adopted will be expected to reduce 20 to 80 percent from current accident levels. The probability of an accident (accident rate) during the period under consideration was determined by applying Equation 6.

$$\text{Rotorcraft CFIT accident rate} = \frac{\text{Number of CFIT related accidents}}{(\text{Number of flight hours}/100{,}000)} \quad (6)$$

The historical flight hours data for U.S. rotorcraft data over the same period were sourced from the USHST, the FAA, and the ASCEND database.

The calculated accident rate (probability) and accident safety costs were utilized to determine the estimated safety costs (C_S) that can be avoided as the CFIT-avoidance technology is adopted more broadly as mitigation for the accidents. Costs avoided with this risk mitigation strategy within a safety management system perspective were estimated by applying Equation 7.

$$C_S = C_A * P_{CFIT} * \Delta R * FHs \quad (7)$$

where:

P_{CFIT} = Probability of a CFIT-accident occurring.

ΔR = Reduction in CFIT-accident probability. Probability is expected to gradually decrease as the number of aircraft with the technology increases.

FHs=Projected fleet flight hours (January 2107 through December 2026).

Net Benefit. In a cost-benefit analysis, the established evaluation of the monetary difference between the pros (benefits) and cons (costs) on the implementation of a project or activity is termed as the net benefit (Guzman & Asgari, 2014). An ROI analysis in the same manner considers all tangible costs and benefits. By adopting CFIT-avoidance technology, the industry is expected to see a reduction in (or avoid) the accident safety costs being currently experienced. The net benefit for adopting collision avoidance equipment can be expressed as:

$$\text{Net Benefit} = (C_S - C_T) \qquad (8)$$

where:

C_T = Technology adoption costs.

Technology Adoption Costs

The adoption of rotorcraft safety technology, like any other technology, comes with costs. The costs are of two types: (1) non-recurring costs that include the initial cost of the equipment, its installation, and initial training for the users, and (2) recurring operational costs over the equipment's lifecycle (e.g. maintenance and proficiency training). To evaluate the costs that an operator is likely to experience, requests for information were made to the aircraft manufacturers, equipment vendors, and training centers on the current rates they were charging for the various services. Additionally, an analysis of the available pricing data from the catalogs, advertisements, vendor quotes, or websites of the equipment manufacturers and vendors was done. With the components being currently available to customers, it was assumed that the pricing associated with the acquisition and installation of the equipment has factored in the research and development costs and profit margins. These cost estimates should account for variability in pricing for the manufacturers or vendors (Department of Transport, 2013; Johnson & Avers, 2012). The CFIT-avoidance technology adoption costs, denoted as C_T, were determined by employing Equation 9.

$$C_T = (C_E + C_I + C_T + C_M) \tag{9}$$

where:

C_E = Equipment acquisition costs.

C_I = Equipment installation costs.

C_T = Training costs for users.

C_M = Recurrent maintenance costs.

The equipment under consideration for this study will have the capability to provide information on terrain, altitude, weather, and obstacles (transmission lines, masts, towers, structures, etc.). For example, an avionics suite with EGPWS/HTAWS that integrates obstacle data from a warning database system such as WireWatch® will be considered a comprehensive solution to mitigating CFIT accidents. According to Connor (2014), the leading avionics producers: Sandel, Garmin, and Honeywell, have created HTAWS equipment capable of producing warnings to pilots on wires, cables, and power lines when integrated into a helicopter's avionics suite. From these manufacturers, three types of HTAWS equipment will be considered: Sandel ST3400H-001 HeliTAWS, Garmin HTAWS 010-HTAWS-00, and Honeywell Mark XXI or XXII. Using data collected from the manufacturers, vendors, and approved installers, the technology adoption costs (C_T) for the equipment will be analyzed to determine the range for costs over which an operator is likely to incur to acquire and use any of the technology.

ROI Estimation

For the second phase, a Monte Carlo simulation was performed to estimate the ROI based on the selected criteria. The Monte Carlo Method or simulation was selected as a means of visualizing all the possible outcomes of the decisions that are made on the adoption of CFIT-avoidance technology. The Monte Carlo simulation is a computerized mathematical technique that allows one to account for risk in quantitative analysis and decision making and has been employed widely in the engineering, finance, and aviation industry projects (Blom, de Jong, & NLR, 2006; Henry, Schmitz, Kelbaugh, & Revenko, 2013; Wang, Chang, & El-Sheikh, 2012). The estimated ROI from the simulation will be based on Equation 1 which has been expanded with the safety cost categories.

Monte Carlo simulation. The simulation was performed in Microsoft Excel®. The variation represented by the possible reduction in the probability of occurrence of a CFIT accident, the technology adoption costs (C_T), and the aircraft safety costs (C_S) incurred in an accident influenced the ROI. To perform the simulation, the three variables applied in the ROI analysis were calculated and their ranges defined with a frequency distribution. The distribution for each variable was determined from the descriptive statistics. The C_S were calculated as a product of the number of accidents avoided with a reduction in the accident rate and the accident costs (C_A). The ROI values were calculated with the C_S and C_T as uncontrollable probabilistic inputs. The probability of a CFIT accident occurring was determined by the number of incidents divided by the flight hours accumulated over the given period of interest. A reduction of this probability by up to 80% when CFIT-avoidance technology is adapted was assumed to be in line with reduction achieved in the fixed-wing segment and target set by the

JHST for all rotorcraft accidents. The technology adoption costs, calculated using data from different vendors, suppliers, and manufacturers, were evaluated to determine the distribution using the descriptive statistics: minimum, median, and maximum values.

In the spreadsheet simulation setup, the initial conditions for the variables of each aircraft category: the rotorcraft accident costs, current CFIT-accident rate, projected flight hours for the period 2017-2026, and the technology adoption costs were added. Using the projected flight hours and accident rate, the number of accidents that are likely to be avoided was calculated. The accident rate value was randomly selected based on a 50 to 80 percent reduction of the current accident rate. This value was then multiplied with the C_A to generate the C_S value. The C_S value and a randomly selected C_T value were applied in the ROI formula. The process was repeated over 5,000 iterations in each simulation run to ensure that all possible values of C_S and C_T likely to be experienced with a 50 to 80 percent accident rate reduction with 25 to 75 percent of the fleet installing the CFIT-avoidance technology equipment were considered. For each rotorcraft category, the simulation was run several times and the results evaluated for consistency. The resulting ROI values were used to generate frequency distributions and boxplots to display the range over which operators or the industry are likely to achieve the ROI with the broader adoption of the CFIT-avoidance technology.

Population/Sample

The population for the study consisted of all accident reports on U.S. general aviation rotorcraft accidents that were determined to have resulted in a CFIT as defined for this study. The accidents considered occurred in the time period between January 1, 2005, and December 31, 2015. The accident reports considered had a finalized status identifying the probable cause and safety recommendations, where applicable. The start of the time period was selected to mark the 10-year period in which accident investigations for the accidents were expected to be complete and prior to the FAA mandated date for all HAA rotorcraft to have GPWS/TAWs installed.

Sources of the Data

The source of data was the NTSB accident / incident database which is considered the official U.S. government repository of the aviation accident reports generated from NTSB investigations. The study was limited to those events that were considered an accident, which by definition is an occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage (NTSB, 2013). The reports were grouped into three categories based on their status: preliminary, factual, and probable cause with the latter providing a detailed description of the accident and identifying the causal factors. The reports were also used to verify the accident outcomes, operations category by FAR, weather conditions, and rotorcraft information as retrieved from the NTSB Microsoft Access® database. The Helivalue$ Inc. Bluebook and the Aviation Week Network Aircraft Bluebook were utilized for determining the value of the rotorcraft at the time of the accident. To determine the CFIT-avoidance technology adoption costs, the relevant data by category were acquired from the equipment manufacturer and vendor websites, marketing material, industry publications, and related material through appropriate data searches.

Data Collection

The data required for the study was acquired from the NTSB Microsoft Access® database with the various coded information fields and downloaded to a Microsoft Excel® spreadsheet. The spreadsheet was modified with the addition of new fields for Aircraft Category (turboshaft or piston single, turbine single, turbine twin, and heavy) and Accident Type (Terrain or Obstacle). The accident reports in Portable Document Format (PDF) were retrieved and, together with the rotorcraft manufacturers' product data specification information, were also used to complete the fields. To retrieve the data, a search was performed through the NTSB accident database web search engine using key words and phrases that included: CFIT, terrain, obstacles, water, wires, wire strike, power line, and transmission lines. The reports were reviewed to determine if the accident met the criteria of a CFIT accident and was applicable to the study. For example, accidents resulting from a system failure or loss of control in flight were excluded.

To determine the safety costs associated with each accident, new fields were added for each safety cost category identified and calculated by applying the appropriate formulas and the values in Table 5. For each rotorcraft category, the descriptive analysis was performed, calculating the minimum, mean, median, and maximum values. The analysis function in the Microsoft Excel spreadsheet was used to perform the analysis.

The data required for the CFIT-avoidance technology adoption costs were acquired from the equipment manufacturer and vendor websites, marketing material, industry publications, and related material through appropriate data searches. The data was transferred into a Microsoft Excel® spreadsheet and the costs determined by applying the appropriate formulas. The data analysis function in the spreadsheet was used to perform the analysis.

Determining the probability or the accident rate of a CFIT accident was based on the number of hours flown by the commercial U.S. rotorcraft fleet. This information was retrieved from the FAA Aerospace Forecasts Fiscal Year 2011-2031 and 2016-2036 (FAA, 2017). The flight hours and number of accidents for each rotorcraft category were used to calculate the accident rate using Equation 6.

Reliability. The reliability of a study refers to the ability for one to obtain the same results in a consistent and repeatable manner. NTSB reports have been repeatedly used for various studies as the information provided by them is considered reliable, and reports follow a common reporting format. The report's narrative, probable cause and findings plus wreckage and impact information, was used to classify the accident as terrain or obstacle related. The accident reports in some cases though do not clearly state the primary cause when multiple causes or contributory factors were identified. Accidents were determined to be CFITs if the pilot still had control of the rotorcraft when collision with the terrain or obstacle occurred. Due to the population size, sampling was not done, and all reports were used for the analysis. The ASTER report has been used in previous studies and is considered reliable for defining the cost categories associated with aircraft accidents. The report was the work product of the ASTER Consortium led by the National Aerospace Laboratory NLR with input from select industry regulators and partners. Aircraft historical values and categories from the Helivalue$ Inc. Bluebook and the Aviation Week Network Aircraft Bluebook have been consistently used in the industry for varying analysis. The ROI methodology has been used in various forms in the transport industry and is adapted to the rotorcraft segment for this study.

Validity. The validity of a study refers to whether one is measuring what has been defined as the subject matter being measured. Internal validity was established by using a proven ROI formula that has been applied in various industries including aviation by CASR and FAA. The formula was modified for use in this study with variables (cost categories) defined in the NLR ASTER reports and applied in aircraft safety costs research on the Airbus A320. The ROI formula applied for the study can also be used for other aviation safety studies where determining the costs and benefits of equipment or technology acquisition is required. The external validity of the study, which refers to the ability to generalize the results to the entire population, was not considered a concern since the study employs the entire population of CFIT accidents. The derived ROI estimation methodology went beyond the cost-benefit evaluation of accident costs avoided by adopting safety technology, and its results advise the industry on the estimated value created by doing so. The methodology can be applied for other transport sector initiatives such as automotive safety and transport security equipment.

Content validity was established by utilizing the NTSB safety reports to determine whether the cause of the accident was a CFIT related to collision with terrain or obstacles. In cases where more than one probable cause of the accident may be identified, the CFIT should be the primary failure. The CFIT should not have been the result of a different preceding factor such as structural, system, or engine failure. Additionally, the Helivalue$ Inc. Bluebook and the Aviation Week Network Aircraft Bluebook were used to determine the rotorcraft category and values. These resources have been used in the industry for years for this purpose. By limiting the reports to the specified period between January 1, 2005, through December 31, 2015, consideration was given to a period where EGPWS / TAWS were available for use in some form and when the mandate had not been implemented.

Treatment of the Data

The data related to rotorcraft CFIT accidents for the period of interest was downloaded from the NTSB Microsoft Access® aircraft accident database to a Microsoft Excel® spreadsheet by performing a search using key words and phrases that included: CFIT, terrain, obstacles, water, wires, wire strike, power line, and transmission lines. The spreadsheet was edited to retain the data fields shown in Table 4. More data fields were added to facilitate the calculation of the aircraft safety costs represented by the variables in Table 5 and to identify the different categories of the rotorcrafts: reciprocating single / piston, turbine single, and turbine twin. The accident reports were reviewed to determine if the accident was primarily a CFIT accident not the consequence of another cause such as mechanical failure. The report's narrative, probable cause, findings, wreckage, and impact information was used to classify the accident as a CFIT and identify the outcomes such as fatalities, injuries, non-injuries, and airframe damage.

A second spreadsheet created for the calculation of technology adoption costs had fields for: the technology nomenclature, the equipment cost, training costs, installation costs, and recurring maintenance costs. The addition of more fields was dependent on additional cost categories that were determined critical to the adoption of the technology. The quantitative data was acquired from the equipment manufacturer and vendor websites, marketing material, industry publications, and related material through appropriate data searches. Using the data analysis function in the spreadsheet, the descriptive statistics were generated.

Descriptive statistics. Descriptive statistics were used in the study to determine the distribution of the variables for calculating the ROI: accident costs (C_A) and Technology costs (C_T). The C_S was calculated by multiplying the accident costs (C_A) with the number of accidents likely to be avoided with the adoption of the safety technology. Descriptive statistics were also used to gain an understanding of the individual cost categories of the accident costs. For the Monte Carlo simulation, a random value was selected from each variable's distribution, and the ROI was evaluated and results recorded. Multiple iterations of this calculation were performed with different randomly-selected values. The results of the ROI, in the form of a distribution, were used to describe the estimated ROI that can be achieved as the probability of a CFIT changes over time as a result of adopting the CFIT-avoidance technology.

Qualitative data. The qualitative data for the study were extracted from the NTSB accident investigation reports to advise the probable cause of the accidents. The probable cause and findings section of the accident reports documented all the causes. The accident reports with a CFIT outcome were retained and analyzed to determine that the CFIT was the primary probable cause or one of the probable causes and not a secondary outcome after a different cause such as mechanical failure. The qualitative data did not require further classification or coding as the accident outcomes and probable cause(s) were already determined by the NTSB accident investigators. A column was added in the spreadsheet in which the CFIT accidents were further categorized as obstacle, terrain, or wire-strike based on the report narrative. The review of the qualitative data ensured that only CFIT accidents were considered and grouped by the correct rotorcraft category, thereby improving the accuracy of the model. Rotorcraft categories were assigned based on the Helivalue$ Inc. Bluebook, Aviation Week Network Aircraft Bluebook, and the rotorcraft OEM grouping of each aircraft.

This mixed methods study used historical CFIT-related accident reports to identify accident outcomes and estimate the associated accident costs while also collecting available data to estimate the technology adoption costs to estimate the potential ROI that could be achieved when CFIT-avoidance technology is broadly adopted. The accident cost categories were based off categories used in previous research by Čavka & Čokorilo (2012) and modified for rotorcraft. The ROI formula, which is a ratio of the net benefits to the costs incurred to achieve those benefits was applied. The net benefits were calculated as the accident costs avoided by adopting the technology while the costs represented the costs likely to be incurred when acquiring, installing, and operating the equipment. The ROI results were generated as multiple iterations of a Monte Carlo simulation. The study considered different categories of rotorcraft and the results for each are discussed in the following section.

CHAPTER IV

RESULTS

The purpose of this study was to estimate the potential ROI that could be achieved if the readily available CFIT-avoidance technology is more widely adopted by the helicopter industry and a reduction in the accident rate was achieved. Accident reports were analyzed to determine whether they were CFIT related, based on FAA's (2003) definition of a CFIT accident as one that occurs when an airworthy aircraft is flown, under the control of a qualified pilot, into terrain, water surface, or obstacles, with inadequate awareness on the part of the pilot of the impending collision. In addition, the costs associated with the accident outcomes were evaluated, based on the applicable categories defined in Chapter 3. The accident reports examined were those from the time period between January 1, 2005, and December 31, 2015.

Treatment of the Data and Procedures

Accident reports were retrieved from the NTSB aviation accident database and used for this study (NTSB, 2017). To determine which reports were to be analyzed, queries using key search words were performed in the Microsoft Access® database for helicopter accidents within the period of interest. Terms used included: (a) *CFIT, (b) (H)TAWS, (c) wire strike, (d) terrain /ground (e) obstacles, (f) water, (g) power and transmission lines, (h) ground proximity, and (i) radar/radio altimeter.* The data returned from the queries were downloaded as Extensible Markup language (XML) files which were subsequently imported into a Microsoft Excel® file. A total of 1,760 records were imported.

The merged records were further reviewed by the researcher for quality (missing data) and to determine those to be retained for the analysis. The review revealed that the use of multiple search terms resulted in duplicate records for the same accident. Microsoft Excel® data tools were used to delete the duplicate records by comparing entries in the Event ID category of variables, reducing the number to 256. The accident reports, in PDF format, associated with these records were retrieved. For each report, the probable cause and findings were reviewed by the researcher to determine if the accident was CFIT related based on the analysis of the accident investigators. To facilitate the tracking of accidents that were to be excluded from the analysis, a new variable *Accident Type* was added. Accidents determined to be non-CFIT in the following categories were eliminated: (a) loss of control in flight, (b) loss of engine power, (c) dynamic rollover, (d) external load event, (e) mechanical failure, (f) in-flight collision, and (g) hard landing. A detailed look at the aircraft make and model showed that 16 were ex-military aircraft, for example, the UH-1 and OH-58 variants. These aircraft were remanufactured by an independent organization (not original equipment manufacturers). These aircraft were excluded from the analysis due to the limited information on the configuration and CFIT-avoidance equipment that would be appropriate for installation.

For the analysis, the technology adoption costs were evaluated with data collected from equipment manufacturer and vendor websites, marketing material, industry publications, and related material as needed. The accident costs were evaluated based on the set criteria for each category in 2016 U.S. dollars. Since future accident occurrence and equipment installation could not be attributed to a specific year within the ten-year period, the evaluation was based on the 2016 values. Therefore, general inflation or the aircraft and CTIF-avoidance equipment price inflation were not part of the evaluation.

Descriptive Statistics

A total of 112 accident records were retained and classified into three *Accident Type* categories: (1) CFIT, (2) CFIT-obstacle, and (3) wire strike. The categorization of the accidents in this manner allowed for the use of the CFIT-obstacle category to capture all non-terrain or wire collision related accidents in one group, for example, collision with poles, lighted tower, and highway markers. Figure 6 shows the distribution of the CFIT accidents, based on the prevailing weather conditions. Wire-strikes were the most prevalent. From the accident reports it was observed that in some accidents the pilots had an initial awareness of the presence of wires, and by losing sight of their location the rotorcraft wound up in a collision.

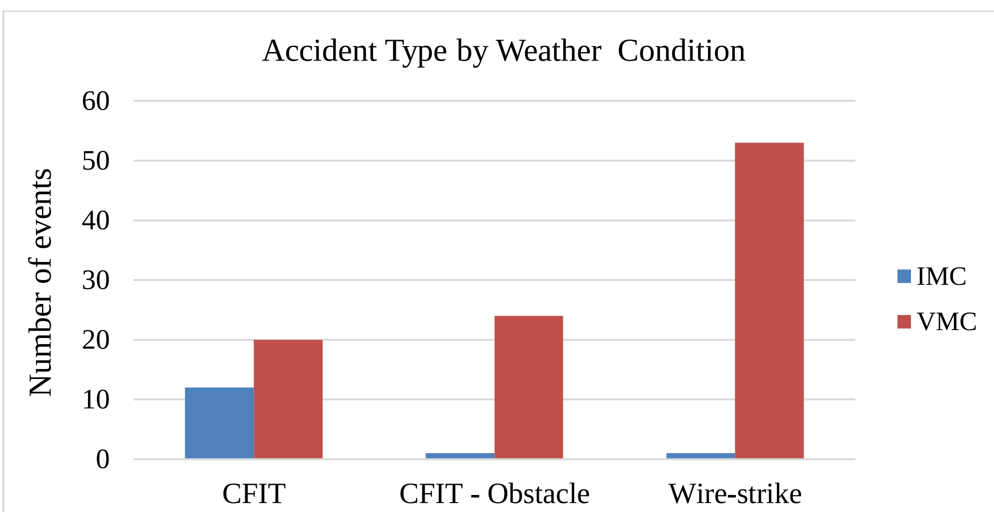

Figure 6. Accident type by weather condition.

The accident aircraft make, model, and engine type were used to categorize each into one of three groups: (1) Reciprocating or piston (light singles), (2) Turboshaft / Turbine single (light singles), and (3) Turboshaft twin or multi-engine turbine. The light singles were separated into turboshaft and reciprocating in order to better reflect the variation in accident and technology adoption costs. Turboshaft single category rotorcraft were found to have the highest number of accidents at 56, followed by the piston category with 46, and twin turbine with 10. Fifty-four percent of the analyzed CFIT accidents were fatal. Accidents involving piston rotorcraft were 67 percent fatal and 41 percent of single turbine accidents were fatal. Figure 7 illustrates the distribution of the accident aircraft by make and model and Figure 8 displays aircraft by engine type.

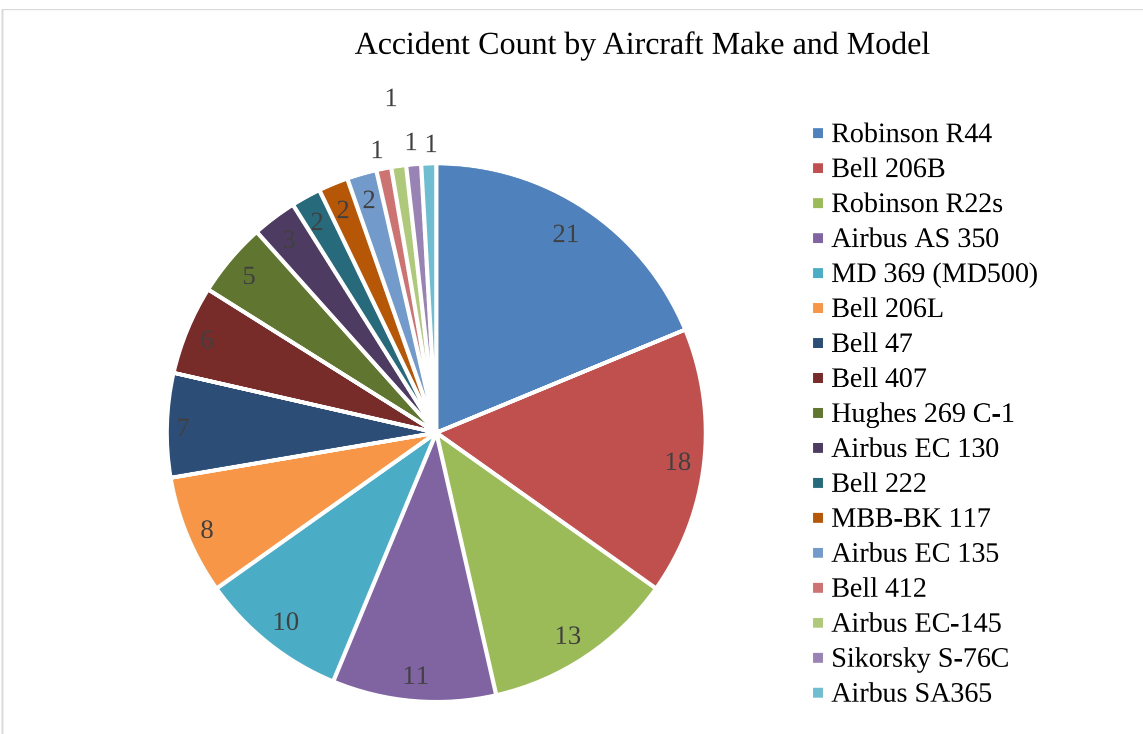

Figure 7. Accident count by aircraft make and model.

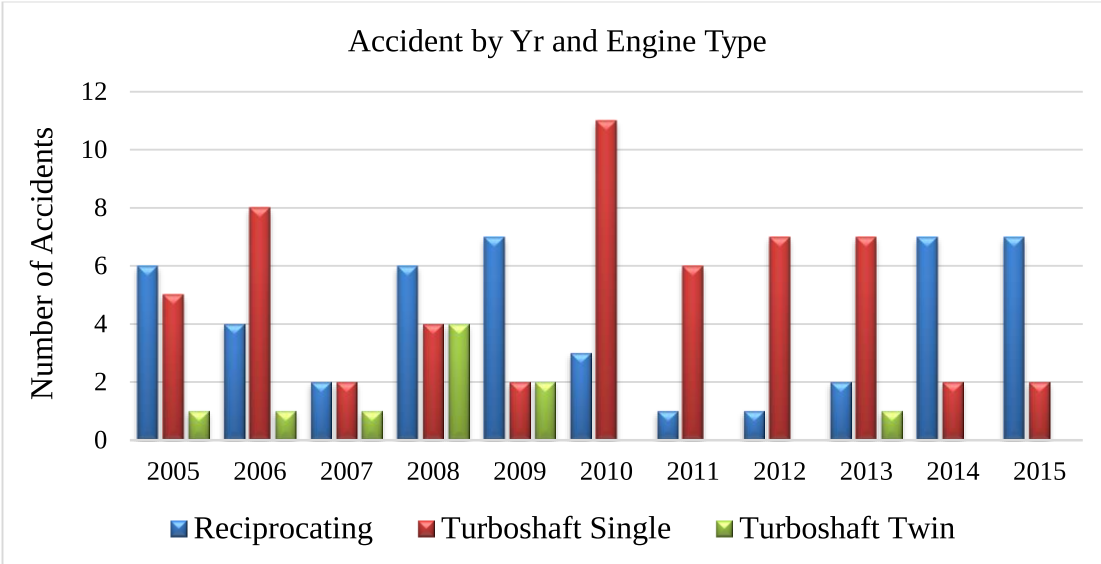

Figure 8. Accident by year and engine type.

The types of operations conducted at the time of the CFIT-related accident occurred were identified by the *Purpose of Flight* variable. From the review of the data records in Excel®, it was noted that the purpose of the flight was either missing or the description was generic. For the analysis, the *Purpose of Flight* descriptors such as *Other work use* and *Positioning,* where possible, were changed to provide a clearer indicator of the operation, while any missing ones were added. Aerial application and observation was used to group different low altitude operations including power line surveillance, crop dusting, crop freezing prevention, cherry drying, and film or television production. Public aircraft represents operations performed by government owned aircraft or aircraft leased or contracted from the private sector for non-law enforcement purposes. Aerial operations, personal, and HAA aircraft were the predominant operations during the occurrence of a CFIT related accident. The distribution of the accidents by the *Purpose of Flight* is shown in Figure 9.

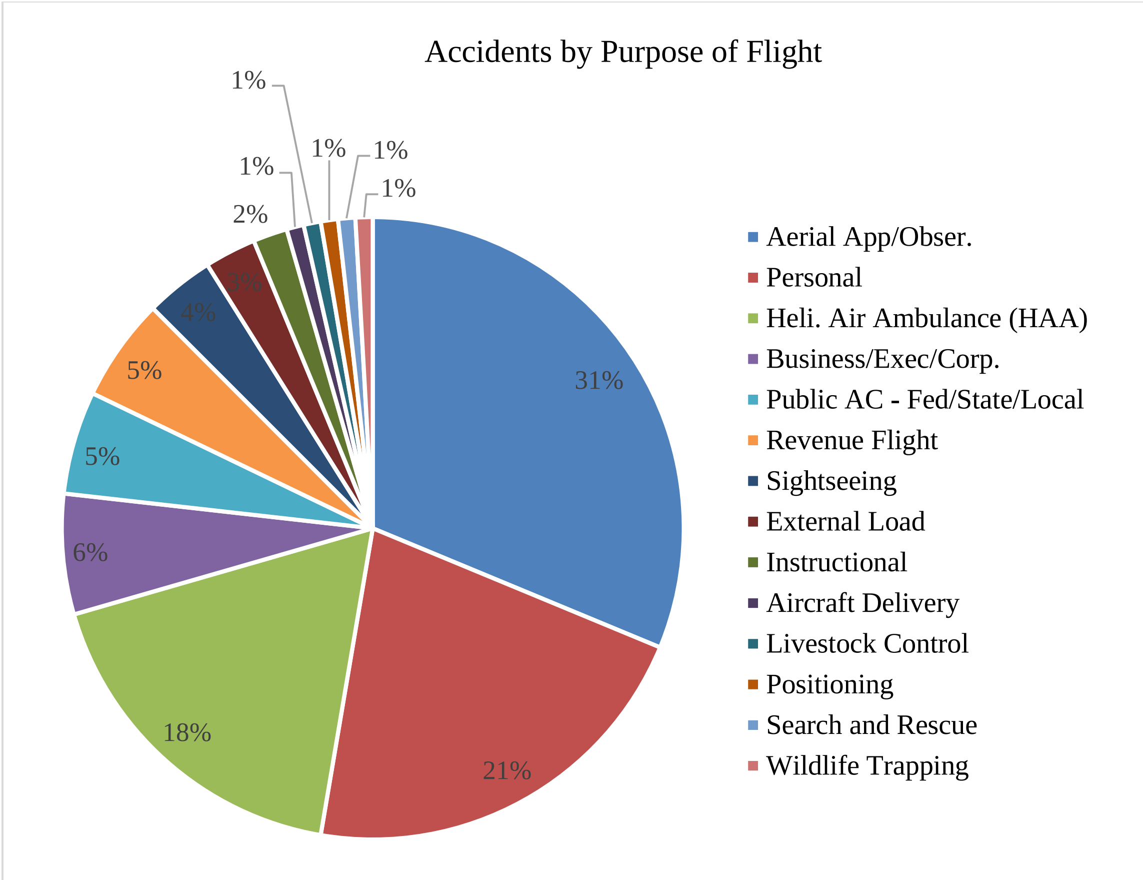

Figure 9. Accidents by purpose of flight.

The *Purpose of Flight* provides insight into the diverse operations that are undertaken by operators but not into the regulatory requirements the operators would have been required to meet. Rotorcraft are required to have specific equipment based on the operations they intend to perform and to do so in a safe manner. An analysis of the *Federal Air Regulations Description (FAR Description)* variable was done to identify under which regulations the operations were being performed and are shown in Figure 10.

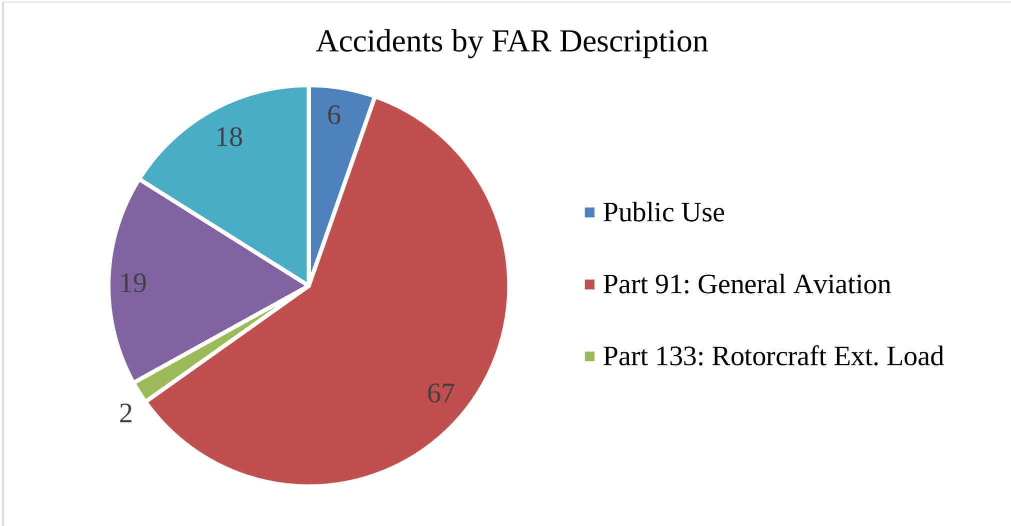

Figure 10. Accidents by FAR description.

Accident costs. To estimate the costs rotorcraft operators were likely to experience as a result of a CFIT accidents, columns were added to the Excel® spreadsheet for each cost variable identified in Table 5 (See Appendix A). Since the extracted data did not distinguish between pilot, passenger, or cabin crew fatalities, a column for pilot fatalities was added to separate them. Upon separation, the pilot fatalities were used to determine the pilot replacement costs (C_P) at a rate of $179,040 which was 1.5 times the average pay for a pilot in 2016 (BLS, 2016). In their research, Applebaum and Milkman (2006) determined that the replacement costs of employees making over $100,000 was 1.5 times the base salary. The aircraft damage costs (C_D) and loss in resale value (C_R) were evaluated using the market-based value of the rotorcraft in 2016 U.S. dollars. The aircraft model, series, and serial number were used to identify an aircraft within the same serial number range in the Helivalue$ Inc. Blue Book and its value. Where the Helivalue$ data was not available, the Aircraft Bluebook® value was used. These two sources are considered the rotorcraft industry's primary references of aircraft residual value for any given year.

The loss of use (C_L) cost was evaluated on the basis of an aircraft's category (engine type and size). All turbine singles were assigned the $85,000 monthly lease cost of a mid-size single engine rotorcraft, as previously given in Table 5. A monthly lease cost of $42,500 for piston singles and $212,500 for medium (twin-engine) rotorcraft were used for the simulation. The lease rates were estimated using the ratio of direct operating cost (DOC) of the Bell 47G (piston) and Bell 412SP (twin turbine) to the Bell 407 as evaluated in Conklin & de Decker's Aircraft Cost Evaluator (ACE). The DOC is considered a significant contributor to leasing costs and therefore can be an effective way of comparing operational costs of different rotorcraft. By comparing the DOCs, the ratio was used to estimate the leasing costs of the piston and twin turbine rotorcraft. The helicopter flight rate charts from the U.S. Department of Agriculture's Forest Service (2017) for helicopter services were used to validate the estimates. A conservative lease period of twelve months was determined by evaluating rotorcraft lead times, the period of time an operator would have to wait for a new or replacement aircraft from the manufacturer's production line. Aircraft lead times were found to range from 36 weeks to over 12 months depending on the aircraft size and customization requirements (Defence IQ, 2016; Duncan & Frank, 2007; Johnson, 2016;). In the meantime, a leased aircraft would perform the desired operations. The costs related to deaths and injuries and the indirect costs were also calculated. The accident costs, C_A, a sum of all the listed categories of costs for each accident was also calculated. Table 6 presents a summary of the accident costs for each category as analyzed for completeness, while Figure 11 shows the distribution of the C_A for each rotorcraft category as applied in the simulation model.

Table 6

Accident Cost Categories

R/C Category		Min	Max	Mean	Std. Dev.	Count
Piston	C_D	20,250	364,800	104,079	57,011	46
	C_R	0	22,800	5,509	4,241	46
	C_L	67,560	125,400	93,965	29,129	46
	C_F	0	37,600,000	6,947,826	9,593,279	46
	C_I	0	1,974,000	282,613	537,545	46
	C_P	0	358,080	77,843	104,412	46
	C_{IN}	110,060	37,994,540	7,511,836	9,609,346	46
	C_A*	220,120	75,989,080	15,023,672	19,218,693	46
Turbine-Single	C_D	139,200	2,240,000	515,028	393,409	56
	C_R	0	85,250	25,818	23,087	56
	C_L	1,020,000	1,020,000	1,020,000	0	56
	C_F	0	47,000,000	9,064,286	13,167,846	56
	C_I	0	2,961,000	501,557	879,645	56
	C_P	0	179,040	63,943	86,565	56
	C_{IN}	1,196,100	49,482,540	11,190,631	13,110,815	56
	C_A*	2,392,200	98,965,080	22,381,263	26,221,629	56
Turbine-Twin	C_D	432,000	2,560,000	1,419,900	784,505	10
	C_R	0	160,000	52,650	62,961	10
	C_L	669,600	1,173,600	952,890	171,780	10
	C_F	0	37,600,000	18,800,000	17,161,973	10
	C_I	0	987,000	197,400	416,156	10
	C_P	0	179,040	107,424	92,456	10
	C_{IN}	1,627,460	40,302,520	21,530,264	16,897,601	10
	C_A*	3,254,920	80,605,040	43,060,528	33,795,203	10

Note. C_D = Aircraft damage, C_R = Resale value loss, C_L = Loss of use (Leasing costs), C_F = Fatality/Death costs, C_I = Injury costs, C_P = Loss of staff (pilot replacement) costs, C_{IN} = Indirect costs, C_A = Accident costs. Costs evaluated in 2016 U.S. dollars. *Only C_A values utilized in ROI simulation model.

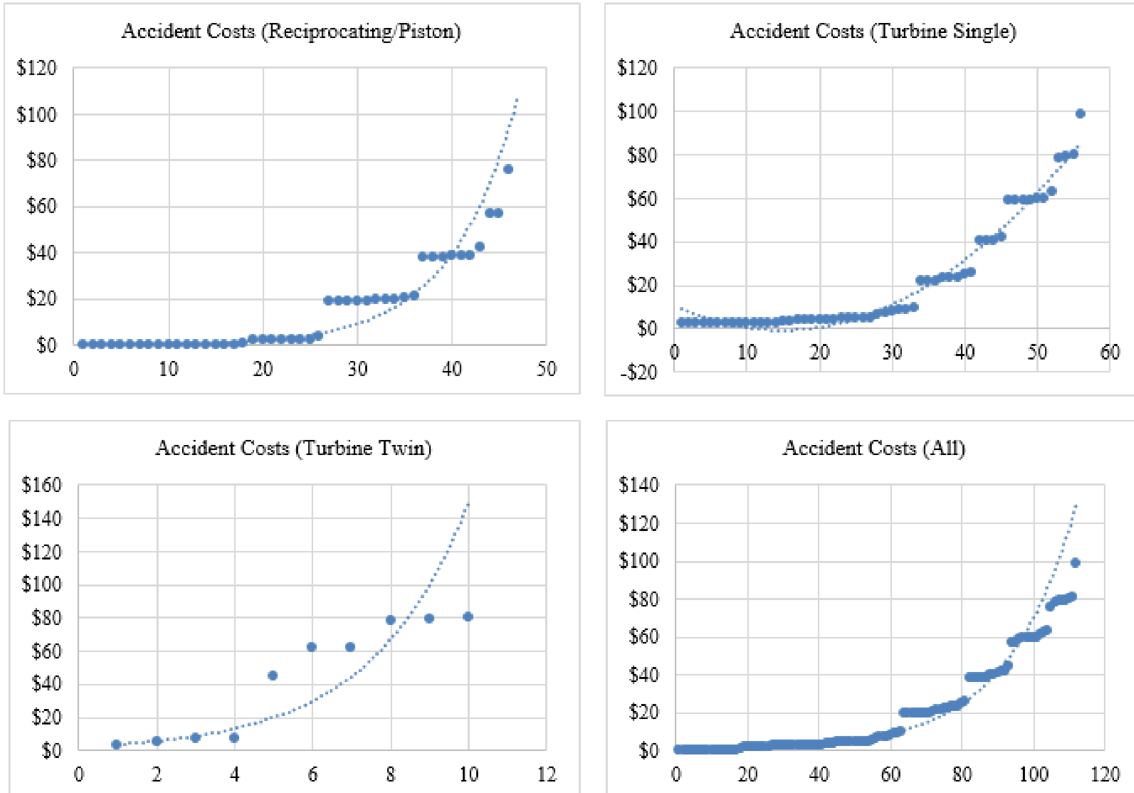

Figure 11. Rotorcraft accident costs, C_A, distribution in millions.

Technology costs. Technology adoption costs were estimated using data retrieved from the catalogs, advertisements, vendor quotes, or websites of the equipment manufacturers and vendors. Rotorcraft manufacturers were also considered to be vendors who retrofit the equipment in the fielded fleet and provide training as needed. In some instances, to maintain a competitive advantage within the market, aircraft manufacturers and vendors provided a combined value for equipment acquisition and installation (C_E + C_I). Additionally, the equipment and aircraft manufacturers have suggested that recent advancements in electronic equipment technology have made the components more reliable, thereby minimizing the hardware maintenance costs.

The equipment mean time between failures (MTBFs), provided by manufacturers in the specifications, ranged from 4,850 to 10,000 hours. The hardware maintenance costs claim was validated by applying the current recommended direct maintenance cost (DMC) methodology provided in the Helicopter Association International's Economic Committee's (2010) *Guide for the Presentation of Helicopter Operating Cost Estimates 2010.* With the equipment being repairable, the maintenance cost was approximately 15% of the average equipment cost of $14,692. Using the average MTBF of 7,425 hours, the DMC is $0.30 per flight hour (FH). If the failure resulted in equipment being scrapped, the replacement cost would be $2.08/FH. It was determined that the significant maintenance costs likely to be incurred are for the software updates and therefore were estimated for the life of the equipment.

No mandatory regulatory requirements for training on the new equipment were found. Pilots can use inexpensive ways to familiarize themselves with the equipment before using it as part of their recurrent and proficiency training. Familiarization could range from reading manuals, computer-based training, simulator time, in-hangar instruction, or flights, depending on complexity and costs (Mayhew, n.d.). Garmin offers the GTN 650/750 familiarization courses for $625 to $795, depending on the training location (Bergqvist, 2017). For the analysis, the cost of training materials and two training flights was estimated to be $850 based on the evaluated average helicopter rental rate. The total costs associated with the adoption of the CFIT-avoidance technology (C_T) were analyzed and summarized, as shown in Table 7. Installation costs assumed the aircraft is configured to accept the new equipment, and no major overhaul of systems is required. Due to its application being limited to military aircraft, the LOAS was not included in the equipment analysis.

Table 7

CFIT-avoidance Technology Adoption Costs

Equipment	$C_E + C_I$	C_M	C_T	C_{T2}
Radar Altimeters				
GRA™ 55 Radar Altimeter	$9,096	$0	$850	$9,946
GRA™ 5500 Radar Altimeter	$13,545	$0	$850	$14,395
RA-4000 Radar Altimeter	$18,878	$0	$850	$19,728
RA-4500 Radar Altimeter	$13,922	$0	$850	$14,772
King KRA 405B-15 Radar Altimeter	$16,699	$0	$850	$17,549
TAWS				
Sandel ST3400H-001 HeliTAWS	$16,422	$12,000	$850	$29,272
Sandel ST3400H-001N	$18,797	$10,200	$850	$29,847
GTN-750 GPS/NAV/COM/ MFD HTAWS	$14,681	$12,470	$850	$28,001
Honeywell Mark XXI	$21,765	$5,000	$850	$27,615
Moving Maps				
GDL-69A Sat. Weather Sys.	$4,369	$12,470	$850	$17,689
GTN 750 GPS/COM/NAV with MD200-306 Indicator	$14,832	$12,470	$850	$28,152
GTN 650 GPS/COM/NAV with MD200-306 Indicator	$11,696	$12,470	$850	$25,016
EX600 MFDs w/ Bendix/King RDR2000/2100	$13,715	$9,950	$850	$24,515
FD540 TS GPS/NAV/COM w/ Wifi, & FLTA/RTC, Blk	$17,276	$9,950	$850	$28,076

Note. C_E = Equipment acquisition costs, C_I = Equipment installation costs, C_M = Recurrent maintenance, C_T = Training costs, C_{T2} = Technology adoption costs. Costs evaluated in 2016 U.S. dollars.

Accident rate. To determine the number of accidents that can be potentially avoided through the adoption of CFIT-avoidance technology, the historical CFIT accident rate for the period of interest, January 1, 2005, and December 31, 2015, was determined. The rotorcraft fleet size and flight hours accumulated over the given period were retrieved from the FAA Aerospace Forecast Fiscal Year 2011-2031, Table 28

(FAA, 2017). The CFIT accident rates for each rotorcraft category and all rotorcraft were determined and are presented in Figure 12.

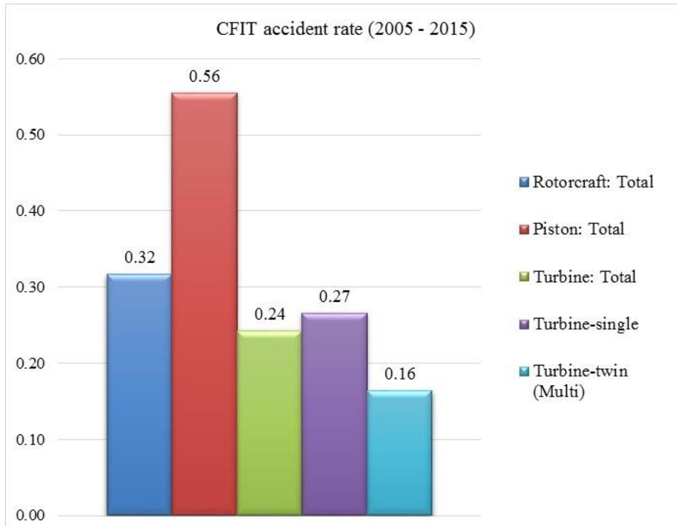

Figure 12. CFIT accident rate per 100,000 flight hours (2005 to 2015).

These accident rates, forecasted fleet size, and fleet hours, as detailed in the FAA Aerospace Forecast Fiscal Year 2016-2036, Table 29 (FAA, 2017), were used to project the number of CFIT related accidents that could potentially be incurred over the 10-year period 2017 through 2026. Table 8 provides a summary of the flight hours and accidents. Single and twin turbine hours were estimated using the historical fleet distribution where approximately76 percent of the turbine fleet hours were accumulated on single engines. For the ROI simulation, the number of accidents avoided was determined by applying the anticipated 50% to 80% reduction in the CFIT accident rate. This accident rate reduction was based on the 50% reduction achieved in fixed wing operations (FAA, 2011) and IHST reduction target for rotorcraft accidents of 80% (USJHST, 2010).

Table 8

Projected Flight Hours and Accidents (2017-2026)

	Flight Hours (10^5)	Accidents
Piston	83.66	46
Turbine- Single	236.93	64
Turbine - Twin	75.38	12

ROI Simulation

The goal of the Monte Carlo simulation was to estimate the potential ROI that can be achieved through the greater adoption of CFIT-avoidance technology. The Monte Carlo simulation, using the given bounds of variability expressed in the model, was used to compute the possible values of the ROI (Wang et al., 2012). The ROI was determined using several variables: (1) the safety costs (C_S), (2) the technology adoption costs (C_T), and (3) the number of accidents avoided based on the expected accident rate reduction (ΔR) between 50 and 80 percent. The accidents costs (C_A) values randomly generated from the defined range were multiplied with the number of accidents avoided to calculate the C_S values within the simulation model. The accident rate was considered to be uncontrollable as it could vary randomly over the 10-year period to get to the targeted 50 to 80% reduction. The C_A, as previously shown in Figure 11, exhibits an exponential distribution. The simulation results were calculated using the minimum to maximum values of the frequency distribution of the uncontrollable C_A and C_T variables, with the assumption that each value was reasonably expected to occur. For the simulation, the technology adoption costs (C_T) estimates were based on the assumed percentage of aircraft in the respective fleet that would have been retrofitted with the technology by the year 2026. For the simulation, a range of 25 to 75 percent of the fleet was considered with the understanding that some of the fielded aircraft may already have the technology, and, inversely, not all operators will choose to adopt the technology based on financial or operational considerations. This was reflected by the fact the equipment considered for adoption was not standard equipment on the rotorcraft but offered as an option kit or installed under supplemental type certificate by third party vendors. The cost and fleet values used in the simulation are shown in Table 9 and Table 10, respectively.

Table 9

Aircraft Accident Costs (C_A) and Technology Adoption (C_T) Simulation Value.

A/C Type	C_A			
	Mean	Min	Max	SD
Piston	$15,023,672	$220,120	$75,989,080	$19,218,693
Turbine - Single	$22,381,263	$2,392,200	$98,965,080	$26,221,629
Turbine - Twin	$43,060,528	$3,254,920	$86,605,040	$33,795,203
	C_T			
	$22,469	$9,946	$29,847	$6,610

Table 10

Projected Rotorcraft Fleet Flight Hours (2017- 2026) and Fleet Size (2026)

	Flight Hours (10^5)	Fleet 2026	25% of Fleet	50% of Fleet	75% of Fleet
Piston	83.66	4170	1043	2085	3128
Turbine - Single	236.93	7036	1759	3518	5277
Turbine - Twin	75.38	2149	537	1075	1612

Note. FAA forecast provides one value for the turbine fleet (9,185 aircraft for 2026). Single and twin turbine totals are estimated on historical ratios where singles are approximately 76% of the turbine fleet.

To calculate the estimated monetary costs and benefits operators should expect with the broader adoption of the CFIT-avoidance technology, the ROI formula, ROI = $[C_S – C_T] / C_T$, was applied. The ROI is a ratio of the difference between the accident costs avoided through accident reduction and the costs expected to be incurred to avoid them, considered the net benefits, and the same costs to be incurred. The expected costs were estimated as the technology adoption costs (C_T) likely to be incurred when the CFIT-avoidance equipment is installed in 25 to 75 percent of the fleet. The benefits were estimated as the safety costs (C_S) likely to be avoided with the reduction in the number of accidents. In the simulation model, the C_S values were calculated by multiplying the accident costs (C_A) by the number of accidents avoided. The number of accidents avoided (ΔR) were calculated by multiplying the current accident rate, projected flight hours for the period 2016 through 2027, and projected accident rate reduction percentage. The overall benefits were expressed as the ROI value for each scenario or iteration. As an example, the piston category current accident rate of 0.56 was multiplied with the randomly selected percentage reduction rate to calculate the number of accidents avoided (ΔR). This value was then multiplied with a randomly selected value of accident costs incurred for each accident (C_A) to calculate the overall rotorcraft safety costs (C_S) that would have been incurred for those accidents. In the simulation, a random value with the range of technology costs, C_T, was selected and multiplied with the estimated number of rotorcrafts within the fleet retrofitted with the CFIT-avoidance equipment. The ROI formula was coded in the last column to record the values for each iteration. A view of the simulation model setup with a sample of the ROI results for the piston category is shown in Table 11.

Table 11

ROI Monte Carlo Simulation Setup and Sample of Results

C_A	FHs[a]	Accident Rate	ΔR	C_S[b]	C_T[b]	ROI
$37,963,200	83.66	0.56	12	$450	$29	15
$28,460,547	83.66	0.56	20	$556	$76	6
$8,525,129	83.66	0.56	23	$195	$24	7
$32,732,306	83.66	0.56	19	$610	$72	7
$47,376,984	83.66	0.56	10	$467	$75	5
$1,137,113	83.66	0.56	21	$24	$23	0
$9,481,187	83.66	0.56	21	$198	$54	3
$61,823,925	83.66	0.56	11	$708	$29	24
$53,814,716	83.66	0.56	21	$1,115	$61	17
$69,708,281	83.66	0.56	14	$943	$50	18
$68,373,795	83.66	0.56	15	$1,048	$22	46
$34,752,143	83.66	0.56	12	$425	$60	6
$47,086,342	83.66	0.56	19	$897	$12	72
$64,001,304	83.66	0.56	11	$697	$46	14
$49,696,442	83.66	0.56	16	$811	$69	11
$17,456,103	83.66	0.56	18	$315	$43	6
$32,776,607	83.66	0.56	12	$400	$36	10
$65,512,358	83.66	0.56	16	$1,066	$62	16
$36,990,792	83.66	0.56	23	$843	$25	32
$6,985,366	83.66	0.56	21	$145	$54	2
$22,814,145	83.66	0.56	13	$306	$27	10
$10,019,442	83.66	0.56	12	$117	$61	1
$16,141,152	83.66	0.56	17	$270	$45	5

Note. [a]Flight hours (10^5), [b]Costs in Millions, ΔR=number of accidents avoided.

For the simulation to converge to a statistically significant result, 5,000 iterations of the ROI simulation were performed for each aircraft category. After the simulation was terminated, the ROI results were analyzed and scatter plots generated. Histograms with frequencies grouped in bins and box and whisker plots were also generated for easier visualization and interpretation of the distribution of the potential ROI that can be achieved. For histograms, the area under each bar or bin reflects the number of observations, while box plots, on the other hand, work with densities instead of frequencies or proportions with the area in the boxplot representing how dense the observations are within that interval. The same number of observations in the histogram are represented in a larger or smaller area in the boxplot (Bakker, Biehler & Konold, 2005). Boxplots are also used to identify five key measurements: the smallest value, the first or lower quartile Q_1, the median, the upper or third quartile Q_3 and the largest value, while also identifying extreme values and outliers in a data set (Abuzaid & Mohamed & Hussin, 2012). According to Hubert and Vandervieren (2008), boxplots provide information on the location, spread, skewness, and outliers of the data, and therefore the industry can get a good understanding of the potential ROI that can be achieved.

The ROI value in each iteration is a representation of the benefits likely to experienced when a given number of rotorcraft accidents are avoided with the adoption of the CFIT-avoidance technology. With the benefits and costs having the same monetary unit of measure, the resulting ROI value does not have a unit of measure. The ROI values in this study were interpreted as the accident costs in U.S. dollars that are likely to be avoided for every U.S. $1 invested in adopting the CFIT-avoidance technology. The results showed that a positive ROI would be achieved for each aircraft category except for the twin turbines, under certain conditions.

Piston category. The piston ROI scatter plot in Figure 13 shows that the adoption of the CFIT-avoidance technology provides a positive return on investment for the industry with values densely populated between zero and 40. As the ROI values go above 40, they become more scattered and become sparse above 60. This scattering was a result of the safety costs being relatively high, an indication of multiple deaths and complete loss of the airframe, with a relatively low investment on installing the CFIT-avoidance technology.

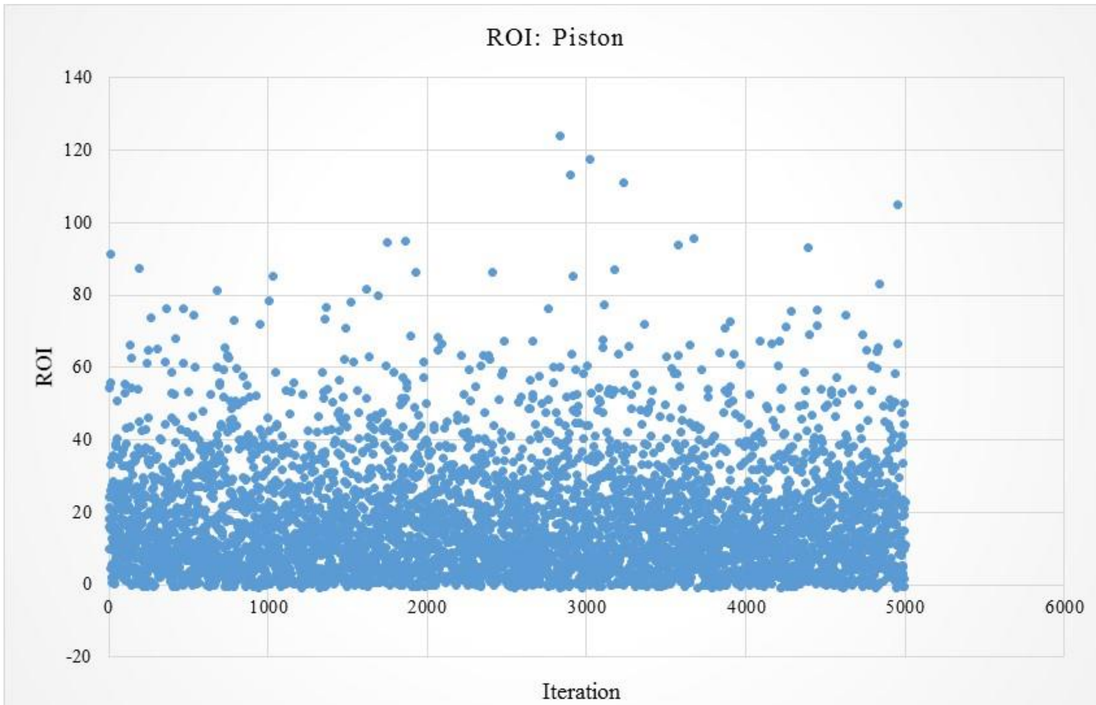

Figure 13. Piston ROI scatter plot.

The scatter plot in Figure 13 show that a positive ROI is likely to be achieved in most iterations but does not identify which ROI values are consistently observed. To facilitate this assessment, the histogram was generated. Results from multiple runs of the simulation indicated that the ROI values will consistently be grouped within a bin with an approximate of size 3, but the frequencies will vary. The frequency represents the number of times the simulation will result in an ROI value within that given bin. For this iteration, the values within the bins below 21 were found to have a frequency ranging from 371 to 574. Additionally, on all iterations, at least 53% of all ROI values were found to lie between zero and the median value of 14, as indicated with the red line and bin locations in Figure 14. The bin with values between 2 and 5 represents the range within which most of the estimated potential ROI values lie. The distribution was skewed right with a long tail of ROI values in the 123 to 126 bin which are considered to be outliers.

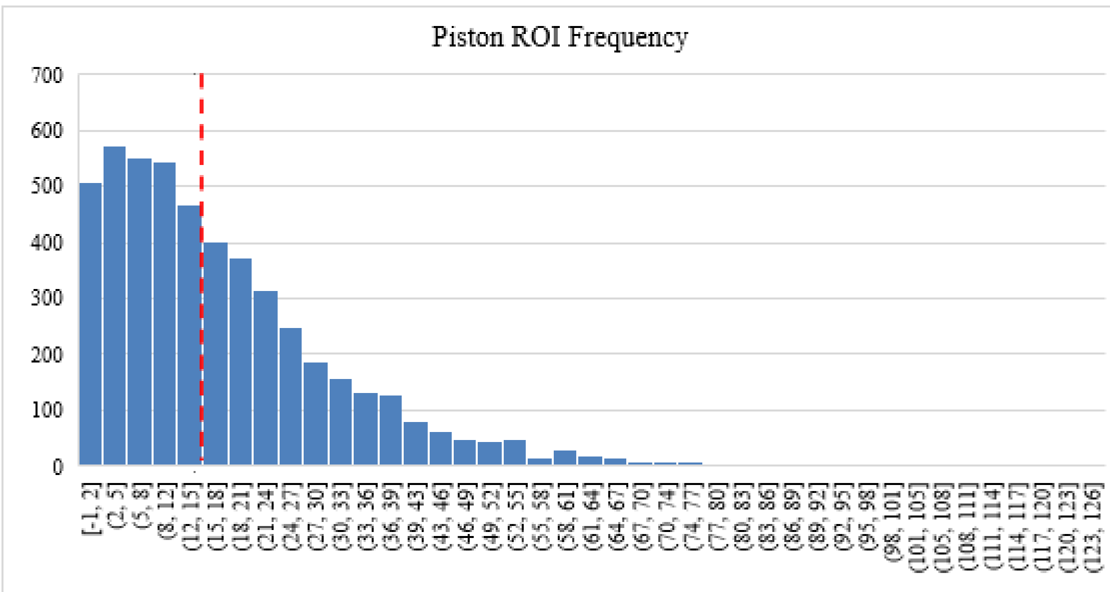

Figure 14. Piston ROI histogram.

Though scatter plots and histograms are valuable in displaying the distribution of the ROI values, it is important to understand which ROI values are most likely to be achieved in order to support decision making by the industry. To better understand the distribution of the ROI values, a boxplot was generated.

From the boxplot in Figure 15, the relatively narrower spread of values below the median, shown by the line within the box, than those above it, indicates that the data is skewed to the right and has a median value of 14. With a first quartile (Q1) value of 6 (indicated by the lower edge of the box) and third quartile (Q3) value of 24 (indicated by the upper edge of the box), the interquartile range (IQR) is 18. The IQR is defined as the range within which the middle 50 percent of the data will lie and is an indicator of the variability of the ROI values. Values above the upper and lower fences are considered to be outliers. To determine the location of the fence (whisker), the IQR is multiplied by the standard constant $k = 1.5$ (Frigge, Hoaglin, & Iglewicz, 1989) and marked from the first or third quartile, as applicable. With the data being skewed, values above 51 at the upper fence were determined to be outliers. It was observed that the resulting box plot was narrow in nature, an indication that the resulting ROI values would exhibit less spread and be closer to the median of 14. The high ROI values were achieved by having high safety costs that could be avoided with a reduction in the accident rate versus the costs of the technology.

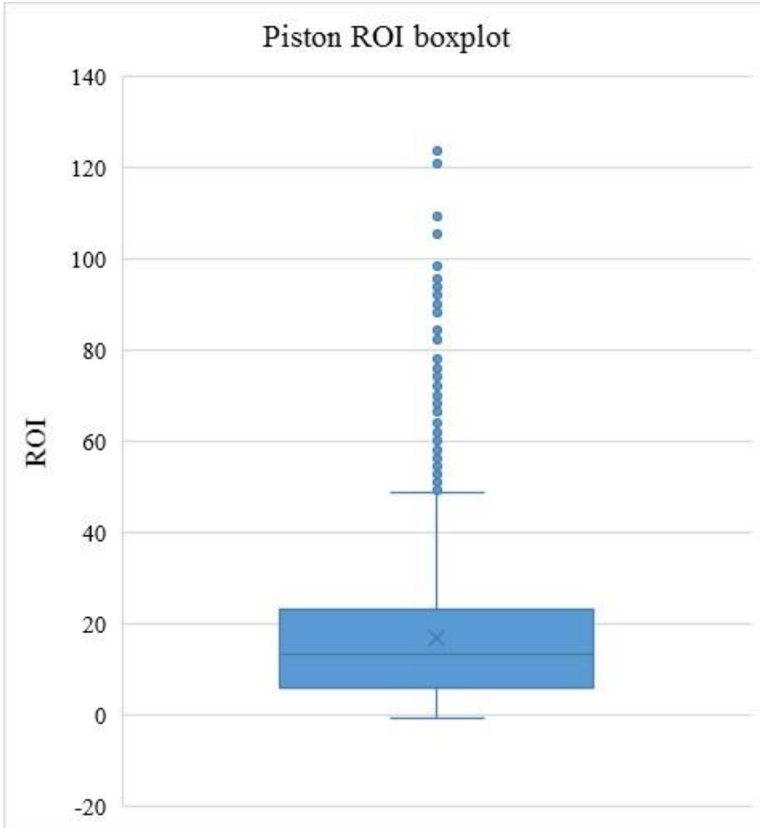

Figure 15. Piston category ROI boxplot.

Turbine-singles. The simulation was also performed for the turbine-single rotorcraft. A scatter plot of the results in Figure 16 shows that higher ROI values can be achieved than in the piston category, with values being densely populated between zero and 40. As the ROI increases, the values become sparser with few exceeding 80. The high ROI values reflect the high accident costs avoided relative to the technology adoption costs. The turbine singles are expected to have higher safety costs based on the seating capacity and value of the airframe.

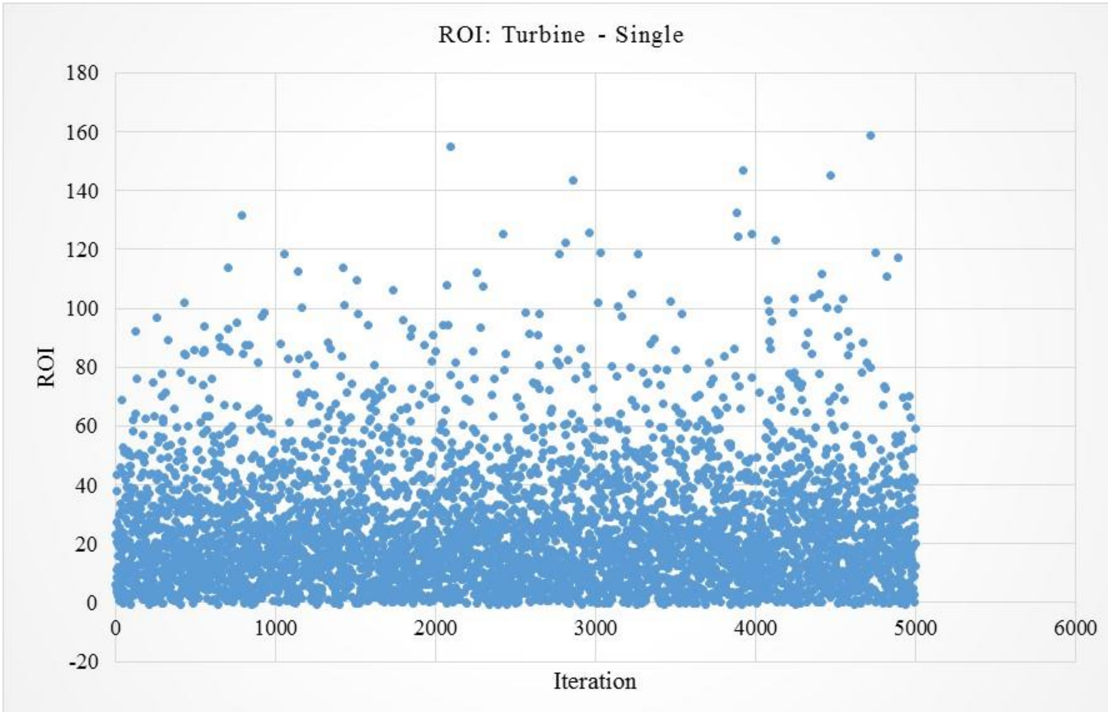

Figure 16. Turbine single ROI scatter plot.

A histogram of the results was generated with the values grouped into bins with an approximate size of 4. The bins with values below the median value of 19, indicated by the red line, were found to hold 53% of all ROI values, with each bin containing at least 500 values, as shown in Figure 17. In this simulation, the 8 to 12 bin represents the range within which most of the estimated potential ROI values lie, with 564. The distribution of the ROI values was skewed right with lower ROI values occurring at a higher frequency and a long tail of ROI values above 71 in bins with a frequency of less than 50. The potential ROI that could be achieved in this category is comparable to the piston rotorcraft category, as they had the higher number of accidents that could be avoided while the cost of the technology remains relatively the same.

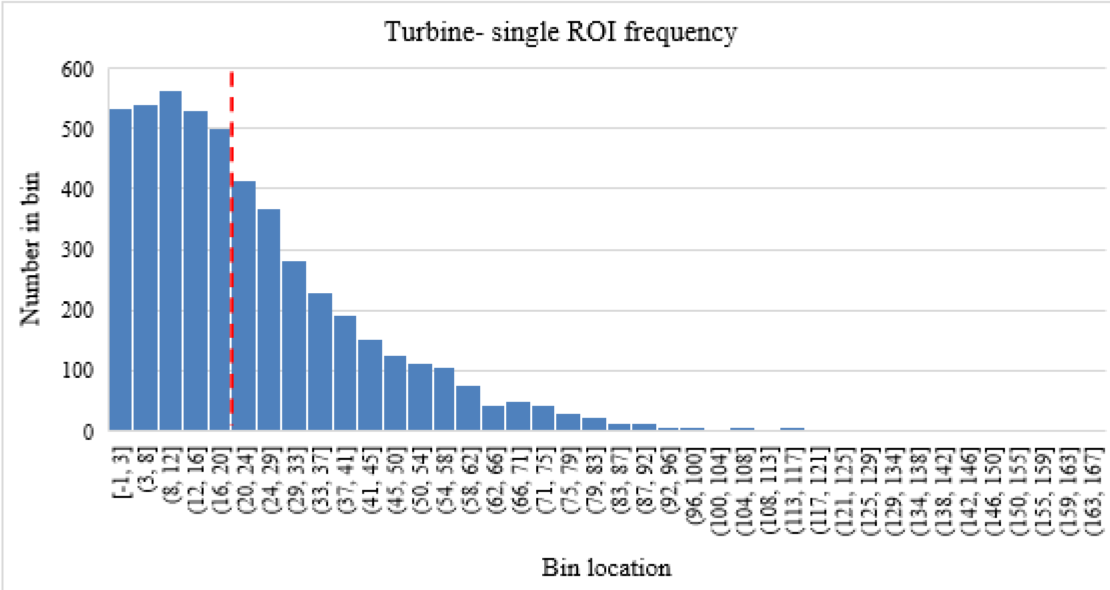

Figure 17. Turbine single ROI histogram.

With the frequency with which the ROI values are likely to be achieved now known, a boxplot was generated. From the boxplot in Figure 18, it was observed that the relatively narrower spread of values below the median of 19 than those above it, indicates that the data is skewed to the right. With a first quartile (Q1) of 9 and third quartile (Q3) value of 33, the interquartile range (IQR) is 24. The IQR showed that the middle 50% of the turbine-single ROI values exhibited a larger spread than in the piston category, and therefore operators are more likely to achieve an ROI. Values above 68, or the upper fence, equal to Q3 plus 1.5 times the IQR were determined to be outliers. These are ROI values that are possible but unlikely to be achieved. The high range was a result of the cost of installing the technology being significantly lower than the accidents costs avoided for multiple fatalities in a single turbine rotorcraft. This boxplot, in the same manner as the piston category boxplot, was narrow, indicating that the ROI values would be densely populated around the median at 19 and close to the average ROI. The potential ROI values from the boxplot show that an accident rate reduction of 50% would put the industry in positive territory.

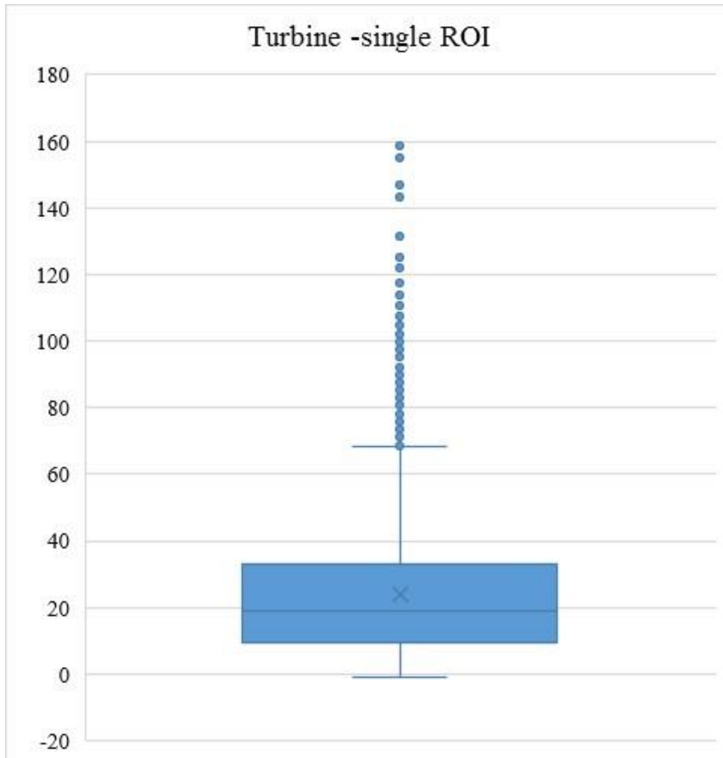

Figure 18. Turbine single ROI boxplot.

Turbine-twins. The simulation was performed for the third category, the turbine-twin, and the ROI values were used to generate the scatter plot shown in Figure 19. In a similar manner to the piston and turbine-single categories, the lower ROI values were densely populated and became sparse as the value increased. ROI values were dense below 5 but began to become sparse above 10, with very few values above 20. A closer look at the ROI values showed that the costs for retrofitting the CFIT-avoidance equipment into the rotorcraft (C_T) would be relatively high compared to the costs likely to be avoided with a reduction in the number of accidents. The turbine-twin category, by virtue of having the lowest number of accidents during the period of interest, would have lower costs to be avoided compared to the costs to retrofit most of the rotorcraft fleet.

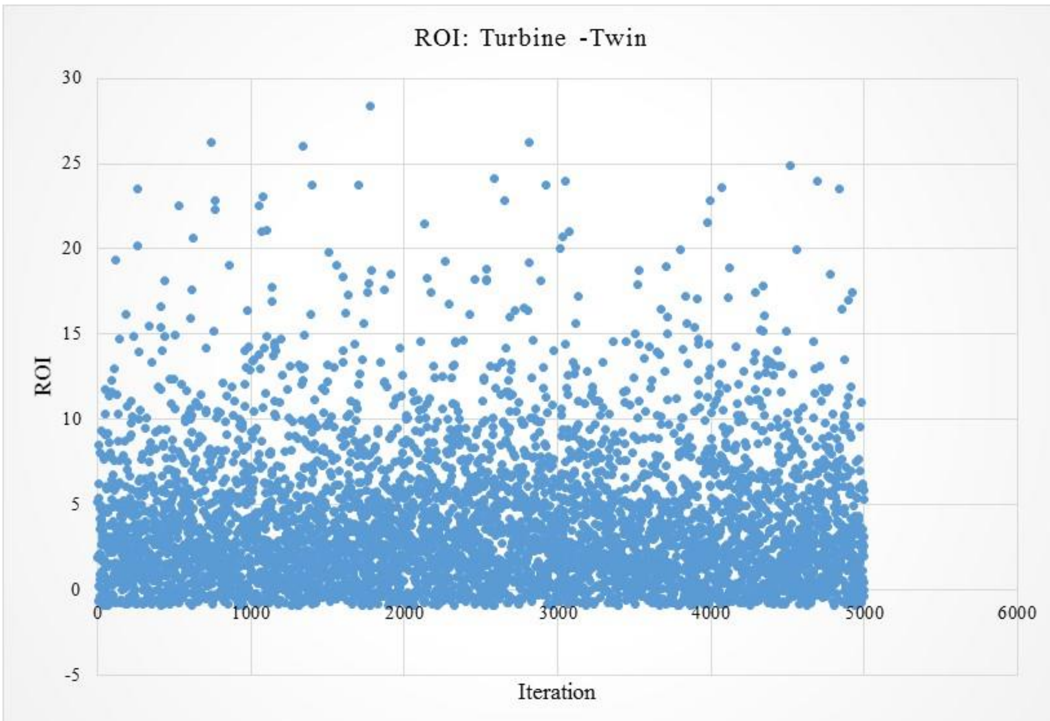

Figure 19. Turbine-twin ROI scatter plot.

To get a better understanding of the distribution, a histogram of the results was generated with the values grouped into bins, 1 in size. The bins with values below the median value of 3, indicated again by the red line, were found to hold over 55% of all ROI values with each bin containing at least 490 values, as shown in Figure 20. The frequencies in these bins ranged from 490 to 607. The 0 to 1 bin represents the range within which most of the estimated potential ROI values lie with 607. The histogram shows the data was skewed right with ROI values as high as 23 being realized at a very low frequency.

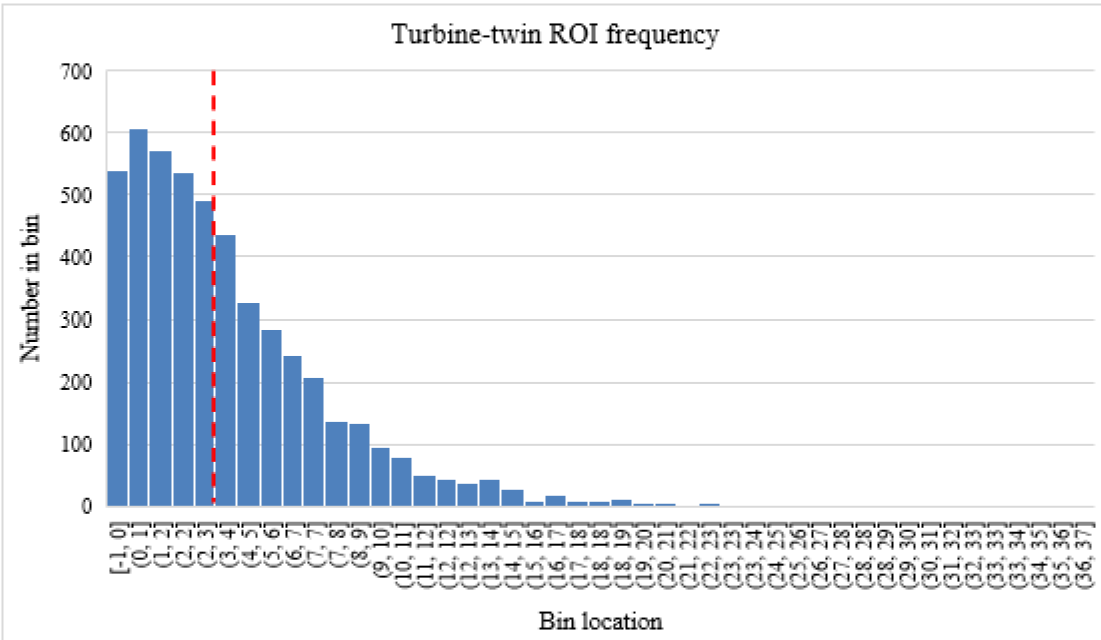

Figure 20. Turbine-twin ROI histogram.

To determine the ROI values that are more likely to be achieved, a boxplot was generated. The boxplot in Figure 21, like the previous boxplots, shows a relatively narrow spread of values below the median line than those above it, an indication that the data is also skewed to the right and had a median value of 3. The ROI value for the first quartile (Q1) was 1 and third quartile (Q3) was 6. The interquartile range (IQR) was therefore 5. With the data being skewed, values above 12 on the upper whisker, equal to IQR*1.5 plus Q3, were considered to be outliers. This was determined to be the category in which under certain scenarios a positive ROI is more likely not to be achieved as the

Q1 value (1) is close to zero. The lower fence (whisker) value of -1 is considered an outlier but indicates the possibility of higher losses still exists.

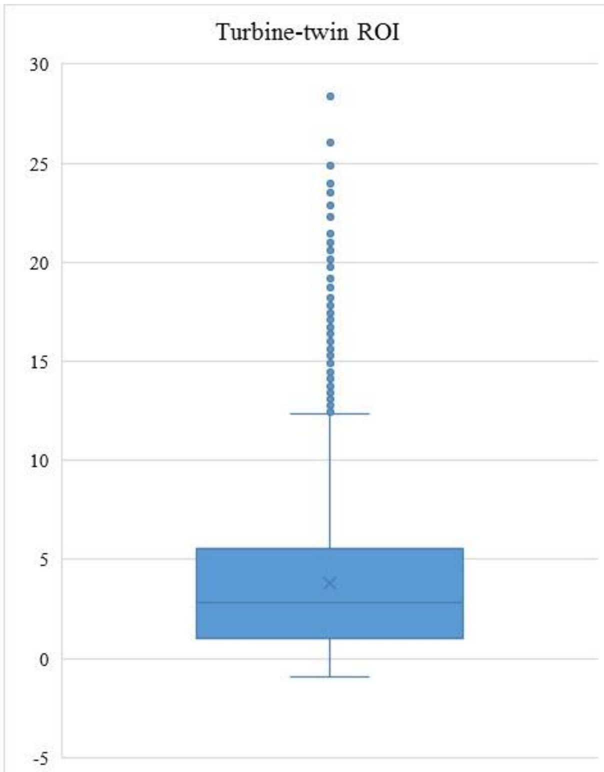

Figure 21. Turbine-twin ROI boxplot.

The results of the three ROI simulations showed positive ROI in most conditions. Consideration was therefore given to the ROI if the CFIT-avoidance technology was adopted broadly across all rotorcraft categories. This simulation did not factor in the reason for adoption, whether voluntary or due to the regulations introduced by the regulatory authorities. This simulation provided insight as to whether the industry would experience better returns if the adoption was targeted by all categories simultaneously.

The simulation was run, and the resulting ROI values were used to generate the scatter plot shown in Figure 22. The ROI values were densely populated below 20 and became increasingly sparse too.

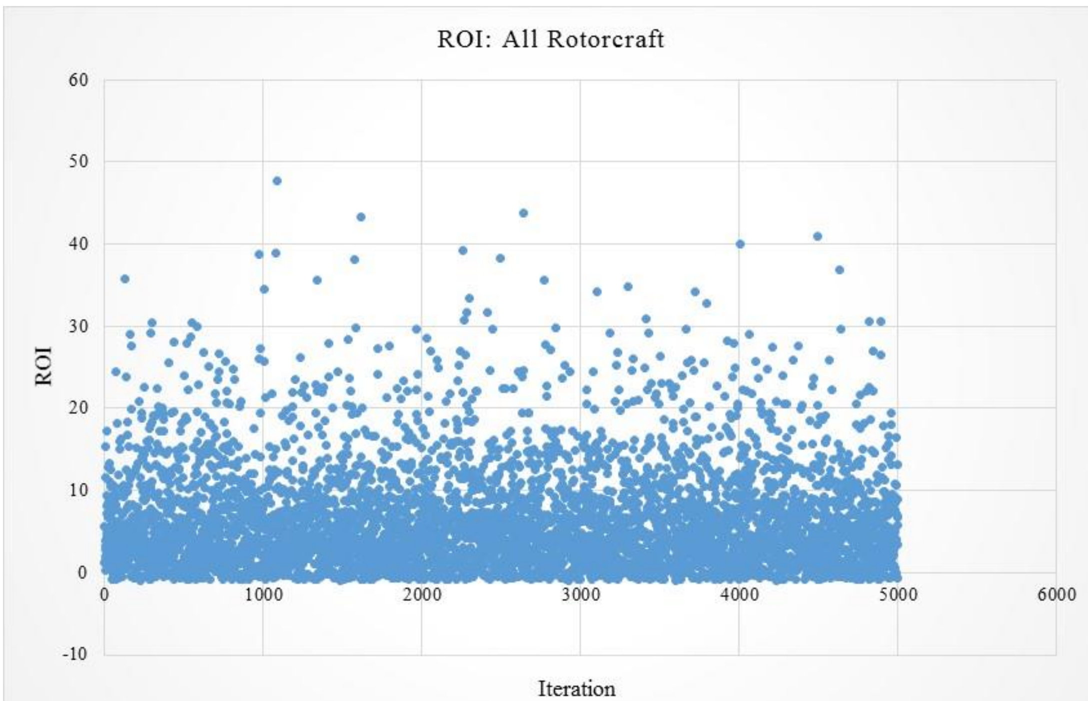

Figure 22. All rotorcraft ROI scatter plot.

A histogram of the results was generated and the values grouped into bins with a size of 1. The bins with values below the median value of 5, indicated again by the red line, held over 55% of all ROI values with each bin containing at least 490 values, as shown in Figure 23. The bin with values between 0 and 2 represents the range within which most of the potential ROI values lie with 602. The histogram shows the data was skewed to the right with ROI values as high as 47 being realized with a low frequency.

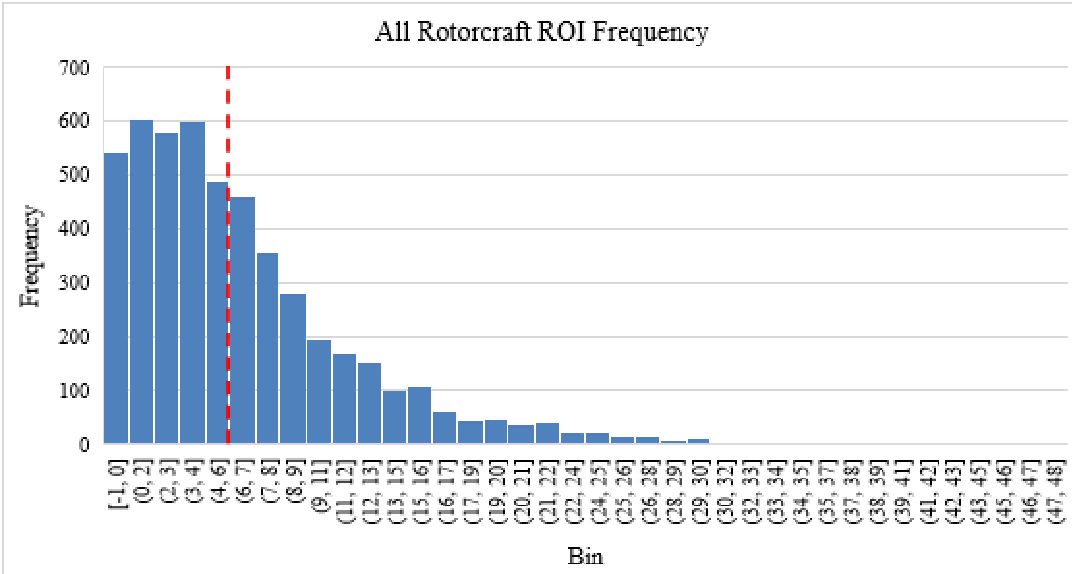

Figure 23. All rotorcraft ROI histogram.

The boxplot in Figure 24, again shows a relatively narrower spread of values below the median than those above it, which indicates that the data is also skewed to the right with a median value of 5. The ROI value for Q1 was 2 and Q3, 9. The interquartile range (IQR) was therefore 7. With the data being skewed, values above 19 or 1.5*IQR+Q3 on the upper whisker were considered to be outliers. The average of the ROI value was 6 and a range of 49. The average and median ROI values were seen to be close, and the industry should therefore expect the likely outcome to be close to those values. As an outlier and unlikely outcome, a negative ROI can be achieved as indicated at the lower fence (whisker) value of -1. These value are driven by the high technology costs when the number of accidents, and therefore accident costs, avoided are low.

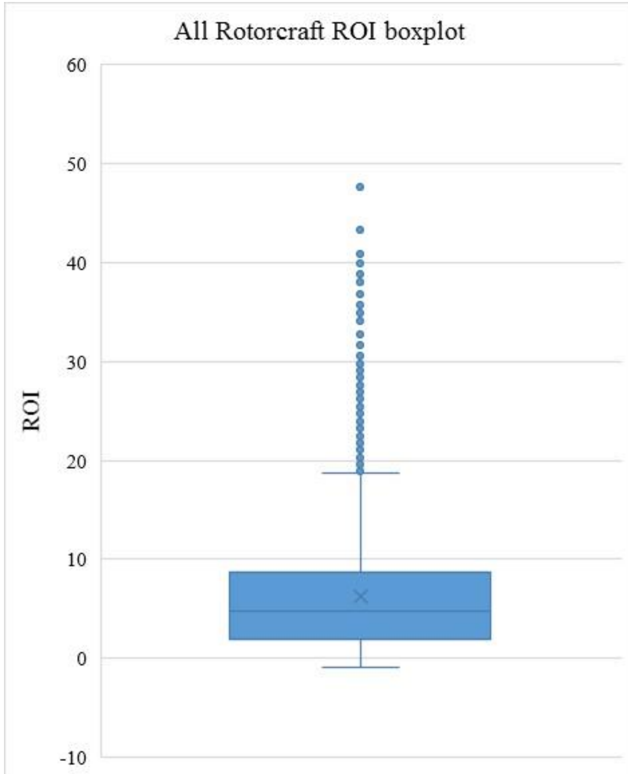

Figure 24. All rotorcraft ROI boxplot.

According to Tang (2006), the opinion of leaders and stakeholders and the existing socio-economic conditions will impact the adoption of new safety technology. Since the technology has to be integrated into the existing fleet (older rotorcraft) as well as the new rotorcraft where the equipment is not installed as standard equipment, the technology adoption costs are critical, especially for the piston category rotorcraft which are on the lower price range. In 2015, for example, a new R44 Beta II was priced at $456,000 and a R22 Beta II at $285,000 (HeliVaue$, Inc., 2015). To understand the margin available for the existing fleet, the technology adoption costs were increased tenfold to a minimum of $99,460 and maximum of $298,468, and the simulation with all rotorcraft considered was performed. A boxplot of the results, shown in Figure 25, was generated. The potential ROI values had a median of -0.4, a Q1 of -0.7, a Q3 of 0, and an IQR of 0.7. The ROI values were skewed to the right as evidenced by the wider spread of the values above the median. The average of the ROI value and the outliers, indicated by the lower and upper fences (whiskers), were 1.1 and -1 respectively. The results show that a positive ROI is unlikely to be achieved when the increased technology adoption costs constitute as much as 35% of a new lower capacity piston aircraft such as the R22.

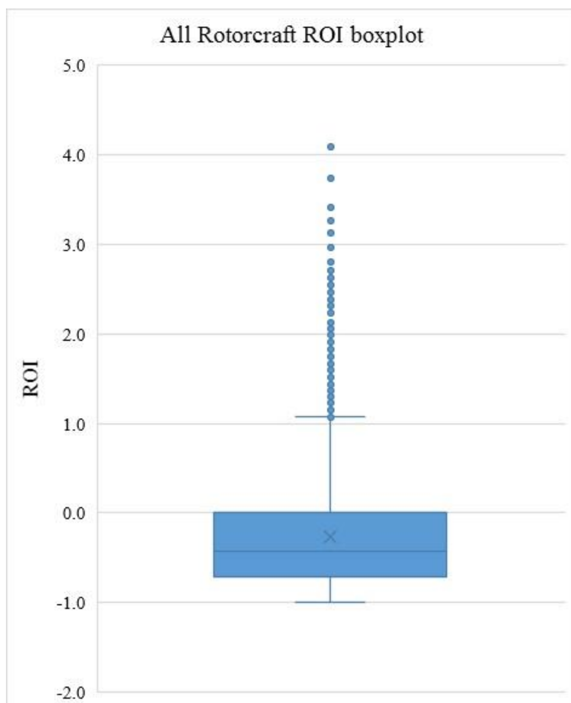

Figure 25. All rotorcraft ROI boxplot with increased technology adoption costs.

The results of the potential ROI values for all the rotorcraft categories were evaluated and were found to have high ranges (IQRs). A sensitivity analysis was considered but was not performed as all variables were not controllable. The accident costs (C_A) for each category were found to have significant variation due to the variance within each of its individual cost categories, of which none were controllable. The calculated safety costs (C_S) applied in the ROI formula were therefore an uncontrollable variable as well as the technology adoption costs (C_T). Since the two variables were uncontrollable, the resulting median and high IQR values for the simulation run were considered representative of the ROI value likely to be achieved by the industry or operators with the broader adoption of the CFIT-avoidance technology.

The most important finding from the ROI simulation for all three categories is the industry is more likely to achieve a positive ROI with negative ROI values being seen to be outliers on the boxplots. For a negative ROI or losses to be incurred, the cost of installing the CFIT-avoidance equipment in the fleet would be significantly higher than the accident costs avoided. The median ROI for the piston and turbine-single was significant at 14 and 19 respectively. The twin-turbine category, with a median ROI value of 3, was seen to have a lower margin for positive return. With regulatory changes having been introduced to address HAA safety, the number of twin turbine accidents could reduce by at least 40%, generating a ROI without making the additional push for the CIFT-avoidance technology adoption by all the operators. This possibility shows the focus for the industry should be on the piston and turbine-single categories for which a higher ROI will be achieved when the technology is voluntarily adopted in large numbers. The main driver of the ROI was the accident costs that could be avoided as direct costs, of which the loss of aircraft and fatality costs were the majority. The results showed that even when only the direct costs are considered, the industry is still likely to experience a positive ROI. When the indirect costs, which were estimated at a 1:1 ratio to the direct costs, are individually quantified in the future, the ROI is likely to reduce but is still a positive return when the CFIT-avoidance technology is broadly adopted. It was also observed that the ROI could be overstated, based on which direct to indirect costs ratio is selected. As discussed earlier, the direct to indirect costs ratio in previous research has varied from as low as 1-to- 4.9 in Willingness-to-Pay approach to as high as 1-to-30 for the International Safety Equipment Association, as recognized by Manuele (2011). By applying the 1:1 ratio suggested by Manuele (20110 and OSHA (2007), conservative values of the ROI were determined.

When all categories were considered, the potential ROI was positive largely due to the accident costs likely to be avoided in the piston and turbine-single categories. Consideration was given to the impact of higher technology adoption costs up to ten times the estimated technology adoption costs, and it was determined that the ROI was more likely to be negative. A repeat of the simulation with lower increases of the technology costs was used to determine that an increase by any factor greater than three would result in a negative ROI. It was determined that the rotorcraft industry can therefore anticipate a positive ROI on the broader adoption of the CFIT-avoidance technologies when the technology adoption costs are managed effectively.

CHAPTER V

DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

The current study estimated the potential ROI that could be achieved if the readily available CFIT-avoidance technology was to be more broadly adopted by the rotorcraft industry, resulting in a reduction in the number of accidents and costs that would be incurred. A review of previous research revealed an existing gap with respect to the estimation of the benefits for operators and the industry when safety solutions were implemented. Past research applied the cost benefit analysis with only the social or public benefits being evaluated. A simulation model applying the ROI formula expressed as ROI = $[C_S – C_T] / C_T$, was used. The ROI was defined as the ratio of the difference between the safety costs likely to be avoided with a reduction in accidents and the technology costs to be incurred to avoid them and the technology costs. The technology adoption costs (C_T) are to be incurred when the CFIT-avoidance equipment is installed in 25 to 75 percent of the fleet. The benefits were estimated as the safety costs (C_S) likely to be avoided with the reduction in the number of accidents. In the simulation model, the C_S were calculated by multiplying the accident costs (C_A) by the number of accidents avoided. The C_A were evaluated by estimating the different accident costs manifested in rotorcraft accidents. The number of accidents avoided were calculated by multiplying the current accident rate, projected flight hours over the 2016-2027 period, and projected accident rate reduction percentage. The study employed a mixed-methods research design conducted in two phases.

In the first phase, data was extracted from the NTSB aviation accident database using key search words associated with CFIT accidents. The accident reports associated with the records retained for analysis were also retrieved. The cause descriptions contained within the accident reports were analyzed to determine whether the accident was CFIT related and then classified into three *Accident Type* categories: (1) CFIT, (2) CFIT-obstacle, and (3) wire strike. The accident reports examined were those in the time period between January 1, 2005, and December 31, 2015. The extracted accident data were placed in a Microsoft Excel® file and used to calculate the accident costs, both direct and indirect, associated with the outcomes of each rotorcraft accident for the applicable rotorcraft categories: piston, turbine-single, and turbine-twin. The direct costs included: aircraft physical damage, loss of resale value, aircraft loss of use, death and injuries, and loss of staff. The indirect costs were estimated with a 1:1 ratio of the direct costs and were considered to cover: search and rescue, accident investigation, third party losses, loss of investment income, increased insurance, and loss of reputation. In the second phase, costs associated with the adoption of the CFIT-avoidance technology were calculated. The technology adoption costs included: acquisition, installation, maintenance, and training. With the costs defined, the simulation model was run and the results documented.

The objective of this chapter is to discuss the results of the study and how the ROI results may influence decision making in the future for the rotorcraft industry and the general aviation industry as a whole. The objective of the study was to provide an alternative method of evaluating the potential benefits of adopting existing and emerging technologies. Recommendations for future research are also discussed.

Discussion

To address the first research question, the costs likely to be incurred by rotorcraft operators were calculated in the Excel® spreadsheet with each cost variable identified in

Table 5 considered. An example of the results is provided in Appendix A. For every accident, the costs of fatality (C_F), injury (C_I), pilot replacement (C_P), aircraft damage (C_D), loss in resale value (C_R), and loss of use (C_L) were evaluated. The sum of these costs was the accident's direct costs, and the same value was assigned to the indirect costs (C_{IN}) as the direct and indirect costs were assumed to be incurred at the ratio of 1 to 1. The total accident costs (C_A) were primarily driven by the fatality in all categories: $6.95 million (piston), $9.06 million (turbine-single), and $18.8 million (turbine-twin), as shown in Table 6. Injury costs were the second highest contributor for the piston rotorcraft, loss of use costs for turbine-singles, and aircraft damage for turbine-twins. This observation showed that the size and design of the rotorcraft influences the costs due to survivability and value of the airframe. Rotorcraft leasing costs were also seen to be high for turbine-singles and twins. The key takeaway from the accident costs was that the adoption of the CFIT-avoidance technology has the potential to reduce fatalities and their associated costs, which in all rotorcraft categories, exceed the second highest cost contributor by a factor eight to 24 depending on the category.

For the second research question, the estimated costs and benefits the industry is likely to experience with the broader adoption of the CFIT-avoidance technology were estimated by applying the ROI formula, ROI = $[C_S – C_T] / C_T$, where the benefits were the estimated safety costs (C_S) likely to be avoided with the reduction in the number of accidents, and the costs were the estimated technology adoption costs (C_T) likely to be incurred when the CFIT-avoidance equipment is installed in 25 to 75 percent of the fleet. The C_S was calculated by multiplying the accident costs (C_A) by the number of accidents that would be avoided. The number of accidents avoided was calculated by multiplying the accident rate for the period between January 2005 and December 2015 with the projected flight hours for the ten-year period January 2017 between December 2026 and the randomly selected 50 to 80 percent reduction in the accident rate. The turbine-single category with a projection of 64 accidents, and an average C_A of $22.38 million was found to have the highest costs if the technology was not adopted broadly. Assuming each accident incurred the average C_A, the turbine-single fleet would accumulate $1.432 billion in costs, almost twice as much as the piston fleet with $729 million from a projected 46 accidents. The technology adoption costs, C_T, were calculated by summing the equipment acquisition, installation, maintenance, and training costs for each equipment that was considered. The total C_T was calculated by multiplying a randomly selected value within the range shown in Table 9 and multiplied by 25 to 75% of the number of rotorcraft in which the equipment would be installed. The ROI formula was used to perform 5,000 iterations and the results recorded. Table 11 shows that the C_S in most instances was relatively higher than the C_T resulting in high positive ROI values as shown in the boxplots and histograms in Chapter 4 and discussed herein.

To address the third research question, do the ROI results support the broader adoption of CFIT-avoidance technology beyond HAA operations, the simulation results for the three rotorcraft categories were reviewed. The results showed that the rotorcraft industry is more likely to experience a positive ROI than incurring losses and therefore support the broader adoption of CFIT-avoidance technology. The value of the ROI was influenced not only by the possible outcomes of the accident, but also the category of the rotorcraft, number of accidents likely to occur, and the potential costs of the CFIT-avoidance equipment. From Table 6, the average fatality cost for any of the three rotorcraft categories was over $6.98 million or at least 40% of the total accident costs. An increase in technology costs by a factor of three was found to result in a negative ROI.

Return on Investment. The projected ROI is a ratio of the rotorcraft accident costs that are likely to be avoided when CFIT-avoidance technology is adopted to the costs to be incurred when the fleet installs and utilizes the associated equipment. The equipment, that includes radar altimeters and HTAWS/EGPWS, are not always part of the standard configuration and are therefore provided as optional kits. The location and size of the bins or class intervals of the potential ROI values below the medians in Figures 13, 16, and 19 was an indicator that the rotorcraft industry was more likely to experience a positive outcome when the CFIT-avoidance technology is more broadly adopted. In each category, over 53% of ROI values lay between zero and their respective median values of 14 for the piston, 19 for turbine-singles, and 3 for twin-turbines. The likelihood of a positive ROI was also shown by the concentration of the potential ROI values around the median with IQR values of 18 for the piston, 24 for turbine-single, and 5 for the twin-turbine, which were higher than the median. The IQR represents the range in which 50% of the ROI values occur, in this case 2,500 for each rotorcraft category. Achieving a 25 percent or greater reduction in the CFIT accident rate for all rotorcraft would be a favorable outcome as the industry would experience a positive ROI with a median value of 5 and IQR of 7, as shown in Figure 24. This positive ROI for all rotorcraft would be limited by an increase in the technology adoption costs when inflated by a factor of more than three. When individual rotorcraft categories were analyzed, the ROI results boxplots in Figure 14, 17, and 20 showed that while the potential of a loss exists, it was still unlikely since the ROI values at or near the lower whisker are considered outliers. The twin-turbine category had the lowest margin for a positive ROI due to the high technology adoption costs that are likely to be incurred when retrofitting the fleet with CFIT-avoidance equipment to reduce an already low number of accidents.

The potential ROI values for the rotorcraft categories, individual or combined, were considered reasonable based on the results of Canada's Department of Transport (2011) analysis of the benefits of mandating an expanded adoption of TAWS equipment. With estimated costs of $59 million and benefits of $216 million, the estimated ROI, when the formula is applied, is 2.66. James and Avers (2012), in their research on human factors safety interventions, demonstrated that a large maintenance organization could achieve an ROI of 312% over six quarters by delivering fatigue training resulting in and effecting a reduction of equipment damage and injuries. Huang et al., (2009) based on 2006 injury data, estimated that for every dollar invested in safety for the U.S. private industry, a return of $4.41 could be achieved. High benefits-to-costs ratios were estimated for lane departure warning and roll stability control road transport safety systems for Class 7 and 8 trucks at 14.69 to 4.95 and 12.50 to 4.7 respectively (Department of Transport, 2013). Using the ROI formula applied in the study, the lane departure warning and roll stability control road transport safety systems provided an ROI of 1.97 and 1.66 respectively. With median ROI values of 14 for the piston, 19 for turbine-singles, 3 for twin-turbines, and 5 for all categories combined, the projected ROI values were considered to be reasonable.

Operators of single turbine rotorcraft are projected to experience the highest increase in the number of CFIT accidents, from 56 to 64, if the accident rate remains stagnant over the next 10 years through to 2026 (Table 8). This category will have the largest fleet at 7,036 rotorcrafts and, by maximizing the number of aircraft that have the

CFIT-avoidance equipment, the industry can generate the highest ROI with a median value of 19. This high ROI would be driven primarily by the occupant fatality (C_F) and injury costs (C_I), with an average of $9.06m and $0.5m likely to be avoided in a higher capacity rotorcraft. An IQR of 24 of the ROI shown in Figure 17 indicates that there is room for the technology adoption costs to grow before the industry experiences a negative ROI. It would therefore be reasonable for the industry to prioritize and accelerate the adoption of the CFIT-avoidance technology by the single turbine rotorcraft operators. The ROI results show that the accident rate, given in Figure 12, should not always be the primary deciding factor on which rotorcraft category should be prioritized for the broader adoption of CFIT-avoidance technology.

From an accident rate perspective, the piston category with the highest rate at 0.56 would have been the category to address. A comparison of the ROI showed that the piston category offers a lower return with a median ROI value of 14 compared to the single-turbine's 19. It was observed that the lost value of the rotorcraft given by aircraft damage (C_D) and the occupant fatality (C_F) played a significant role in the lower average accidents costs for piston aircraft at $15.86 million versus the single turbine at $22.4 million, as shown in Table 9. Single turbines, for example, the Bell 206 and Airbus 350, have a capacity of four to six occupants while piston rotorcraft such as Robinson R44s and Hughes 269 have a two to four occupant capacity (Aviation Week Network, 2016). Even with fewer accidents, the higher number of potential fatalities drives the accident costs and, conversely, the ROI when avoided. The ROI therefore can be considered a good indicator for the industry on where the investment would be best prioritized. For CFIT-avoidance technology, it is the single-turbine rotorcraft.

It was observed that with a low accident rate of 0.16, the cost of installing CFIT-avoidance technology on at least 25 percent of the twin engine rotorcraft fleet will not always result in a positive ROI, as shown in Figure 20. From the simulation results, in certain conditions, for example, a reduction of less than four accidents, the ROI can be less than zero (loss). With a Q1 ROI value of 1 (Figure 20), this category has a low band for generating a positive ROI. Table 8 shows that at the current accident rate, 12 of the projected fleet of 2,149 twin turbine rotorcraft through 2026 are likely to be involved in a CFIT accident. Therefore, the cost of installing the technology to reduce the number of CFIT accidents by only four or 33% cannot be justified by the low ROI. Eight of the 10 twin turbines recorded in the simulation spreadsheet were involved in CFIT accidents while being used for HAA operations at the time. The requirements introduced by the FAA with the Advisory Circular AC 135-14B Helicopter Air Ambulance Operations should suffice in the CFIT accident mitigation for this category of rotorcraft. The requirements for HAA operations that were addressed include TAWS equipment, pilot testing, alternate airports, and increased weather minimums (FAA, 2015). The change in HAA regulations is likely to generate a positive ROI on the twin-turbines prior to additonal investments by the non-HAA operators. The mandate is likely to reduce the accidents by over four, the minimum required for a positive ROI.

The potential ROI median and IQR values of 14 and 18 for the piston category and 19 and 24 for the single turbine rotorcraft, shown in Figures 14 and 17, should provide the industry with a sizeable risk margin even though each cost category of the indirect costs associated with the accidents could not be individually determined. The indirect costs were estimated by applying the 1:1 ratio of direct to indirect costs recommended in research by Manuele (2011) and OSHA (2007). These costs are associated with accident investigations, search and rescue, loss of investment, and loss of reputation, among others. A decrease in the direct to indirect costs ratio would decrease the ROI by the same magnitude, and therefore only a simultaneous large increase in technology costs would cause a significant reduction in the ROI to the critical point of turning negative.

The results of the potential ROI for each individual category as well as for all rotorcraft provide support for the broader adoption of the CFIT-avoidance technology. The data show that the equipment, mostly avionics, are reliable, and their maintenance costs (C_M) have a low impact on the technology adoption costs over the life of the aircraft (Table 7). The range of the technology costs, $C_{T,}$ from $9,946 to $29,468, will give the operators in any rotorcraft category options on the equipment to install based on their resources or operational needs and still generate a ROI. A ten-fold increase in the technology adoption costs resulted in a negative ROI, as shown in Figure 24, when all categories were considered. Further investigation showed that operators should limit the increase to no more than three times for a positive financial impact. Based on the ROI, the industry should determine whether the technology adoption should be prioritized based on category or FAR operations. The additional requirements put in place for the HAA and other Part 135 operators, though optional for Part 91 operations, should be encouraged for the segment.

Accidents. An analysis of the data extracted from the NTSB database was done, and 112 accident reports were retained for the study. As shown in Figure 6, 88 percent of the CFIT accidents occurred during VMC operations in which a pilot is required to be more attentive of the operational environment and to scan for possible obstacles. This observation is consistent with the Nall report finding that over 88 percent of both commercial and non-commercial rotorcraft accidents from 2014 through 2016 occurred in VMC (Air Safety Institute, 2017a; 2017b). Using the *Accident Type* category, it was observed that accidents involving wire-strikes were most prevalent at 48 percent, and almost all occurred frequently in VMC operations. Pilots were seen to have an initial awareness of the presence of the wires, and on losing sight of their location, the rotorcraft wound up in a collision. Those occurring in a VMC environment were a result of the pilot: (1) failing to maintain adequate clearance during low level operations, (2) experiencing loss of situation awareness in unfamiliar environment, (3) failing to identify and arrest the rotorcraft's descent, and (4) deciding to perform low level flight in low visibility conditions in mountainous areas, over water, and snow covered terrain. Accidents that involved collision with terrain were the second highest at 22% with 12 of them occurring in IMC flight. Inadvertent flight into IMC led to accidents as pilots were unable to re-establish a visual reference for their flight path thus emphasizing the need to adopt the CFIT-avoidance equipment broadly.

A review of the rotorcraft involved in the accidents revealed a need to break the light single category into two, the reciprocating (piston) and turboshaft (turbine) categories, in order to get a better understanding of the accident cost variations and ROI. The piston rotorcraft were mostly lower capacity aircraft and were involved in 50% of the accidents. As shown in Figure 7, the piston accident fleet consisted of Robinson R22s, R44s, Bell 47s, and Hughes 269C, among others. 34 of these rotorcrafts, or 60%, were Robinson R22 and R44s, underscoring the popularity of these aircraft for low altitude operations such as crop dusting, crop freezing prevention, cherry drying, and film production. Over 90% of rotorcraft CFIT accidents involve single engine aircraft which, more often than not, are certified for VMC flight for which pilots are expected to scan their environment for terrain and other obstacles. Ishihara (2005) had similarly observed that a high number of HEMS CFIT accidents occurred in VMC conditions. Twin engine rotorcraft were less likely to be involved in a CFIT accident. The HAI, AHS International, and GAMA teams in 2015 proposed the modification of Part 27 single-engine IFR certification as a means of addressing the high number of inadvertent flight into IMC and CFIT accidents (Sandel Avionics, 2012). The ROI results for the piston and single-turbine rotorcraft, which are mostly certified under Part 27, support the broader adoption of CFIT-avoidance technology.

In Figure 8, during the period of interest, it was observed that CFIT accidents were significantly higher over the first half, averaging 12 accidents per year. In the second half, the average dropped to nine accidents per year. The years 2008 and 2010 had the highest accidents with 14, and 2008 also had the highest number of twin engine accidents with 4. As the number of twin engine accidents reduced, the single turboshaft accidents spiked in 2010 to 11. Between 2010 and 2015, pistons and turboshaft singles were seen to reverse positions in number of accidents. This reversal could not be attributed to the variation in the rotorcraft utilization, as the fleet flight hours, as presented in the FAA Aerospace Forecast Fiscal Year 2011-2031, Table 28 (FAA, 2017), did not show a significant fluctuation during that period. The projected utilization between 2017 and 2026 (Table 8) reflects the same consistency, and without broader adoption of the technologies, the accident rate will only reflect the impact of the regulations being implemented for HAA and other Part 135 operations.

Accident costs. As expected in safety, accidents do come with the significant costs for an operator, organization, or industry. For the rotorcraft industry, CFIT-related accidents incur an average of nearly $22.38 million in related costs (C_A) for the turboshaft single category which had the highest occurrences. The piston category, which is more likely to consist of individual and small fleet operators performing aerial operations and personal travel (Figure 9), the C_A averages close to $15.86 million (Table 10). These operators are unlikely to have the bandwidth to bear such heavy losses. For flight instruction rotorcraft, the costs could be even higher if the student pilot is already a qualified pilot, as the current C_A costs only accounted for the loss of life but not the staff replacement costs. When the accident rates shown in Figure 11 are put into consideration, the turbine category is seen as the highest driver of costs due to utilization and fleet size (Table 10). These two rotorcraft categories represent the best opportunity for the industry to maximize its ROI by broadly adopting CFIT-avoidance technology.

Aircraft damage and injury costs were also significant for all rotorcraft categories but were relatively low when compared to fatality costs. The aircraft damage costs averaged between $104,079 and $1.42 million, while fatality costs averaged between $7.9 and $18.8 million for all categories (Table 6). The lower aircraft damage costs can be attributed to 77% of the accidents where rotorcraft experience significant damage and without being destroyed. The high average of fatality costs indicates that fatalities are the more likely outcome of CFIT accidents over injuries, and the NTSB has estimated that this is the outcome in 60 percent of these accidents (Sandel Avionics, 2012).

Technology costs. In order to generate a positive ROI, the results show that the CFIT-avoidance technology adoption costs, especially for the piston category operators, ranging from as low as $9,946 to as high $29,847 (Table 7) should remain relatively low when compared to the accident costs to be avoided. It should be noted that these costs could be much higher when different pieces of equipment are integrated into the same aircraft and if the integration is done by the equipment manufacturer, a vendor, or the rotorcraft OEM. The GTN 650/750 system with moving maps and HTAWS enabled, as an example, provides more capability at a higher cost. For piston category rotorcraft, the radar altimeters, with costs as low as $9.946 (Table 7), would provide the best value for operators, and having been already been mandated for Part 135 operations (FAA, 2014a; 2015), the possibility of even lower costs exists. The higher equipment maintenance costs, C_M, in Table 7, averaging around $12,000, were primarily driven by the software updates required over the life of the equipment. The repair or replacement costs were found to be relatively low as a result of the high average MTBF of the equipment at 7,425 flight hours. The ROI results show that the technology adoption costs ideally should not increase by more than a factor of three.

An increase in the C_T for the CFIT-avoidance technology for the piston and single turbine categories, even with a positive ROI, could rise to levels that would impact its rate of integration into the fleet. With the current adoption costs ranging from $9,946 to $29,847 (Table 7) being increased by a factor of 10, the analysis shows a positive ROI is unlikely to be achieved (Figure 24). The rise in the costs to a minimum of $99,460 could become unmanageable as it would represent 35% of the value of a new R22 or 22% of a new R44 in 2015. In simulations where the technology costs were continuously increased, it was observed that a positive ROI would not be achieved when the costs increased by more than a factor of three. As Tang (2006) suggested in his research, the adoption of new safety technology is influenced by the opinion of leaders and stakeholders, and rising or high costs could lead to a negative opinion.

Accident rate. The piston category of rotorcraft had the highest accident rate at 0.56 per 100,000 flight hours over the period of interest (Figure 11) followed by the single turbine at 0.27. In terms of individual accidents, single turbine was the highest with 56 against the piston's 46 (Table 8). Based on the operations identified in Figure 9, these accident rotorcrafts were mostly used for personal travel, farming activities, and low altitude observation operations. These operations are undertaken by individuals or small fleet operators. At the current accident rate, rotorcraft in the piston and single turbine category are projected to be involved in 46 and 64 accidents respectively, during the next ten-year period between 2017 and 2026, as shown in Table 8. This shows a marked increase in the possible single turbine accidents, while piston will remain relatively flat. Some accidents in the single turbine category, similar to the twin turbine, will be mitigated with the new requirement for Part 135 rotorcraft to have radio altimeters, but broader adoption of CFIT-avoidance equipment is still needed to drastically reduce the overall number of rotorcraft accidents. Twin-turbine rotorcraft accidents were seen to occur at a lower frequency, 0.16 per 100,000 flight hours (Figure 11) and will increase modestly over the same ten-year period to 12. With the number of piston and twin-turbine accidents remaining flat or increasing slightly, the industry would experience similar levels of losses as the previous 10-year period. The increase in single-turbine accidents by 8 and the potential to achieve a positive ROI with a median value of 18 supports the broader adoption of the CFIT-avoidance equipment.

Conclusions

This study was undertaken in order to propose and apply a method of estimating the potential ROI that can be achieved with the broader adoption of CFIT-avoidance equipment and to determine whether the results supported doing so. The methodology expanded on work previously done by Cavka & Cokorilo (2012) where they performed a CBA of aircraft safety based on the A320-200 aircraft. The rotorcraft industry or operators are more likely to experience a positive ROI in all rotorcraft categories. With a median value ranging from 3 for the twin-turbines on the lower end and 19 for turbine-singles on the higher end, the results indicate a positive ROI is more likely to be achieved. Key to the positive ROI is the management of the technology costs. With 50% of the ROI values for all rotorcraft being between two and nine, the results are consistent with the expected 2.66 ROI from the estimated costs and benefits of Canada's Department of Transport (2011) mandate of the adoption of TAWS equipment. The study therefore supports the broader adoption of the CFIT-avoidance technology.

The study applied cost categories identified in the ASTER research by the National Aerospace Laboratory (2001), and it was applicable to accidents involving airline aircraft. It was observed that there was limited information on rotorcraft accident costs, and for the study, it was necessary to add comments on how each category would be evaluated for inclusion into the analysis. For the evaluation of the ROI, it was also observed that some cost categories would have to be considered societal costs and excluded or covered under indirect costs since they could not be individually quantified. When commencing the study, it was concluded that the study would be a starting point for the evaluation of rotorcraft technology ROI, and future improvements though research would be required.

This research was performed in order to fill a research gap in the literature surrounding ROI for safety improvements. Although similar ROI research had been performed, it focused more on operations than aircraft equipment and technology. The Network Occupational Safety and Health Group's software, ROHSEI, is used for health, safety, and environmental ROI analysis. The FAA and Booze, Allen, Hamilton Consulting developed the ROI for human factors safety interventions (Johnson and Avers, 2012). Aviation related research on safety interventions was performed as cost-benefit analyses, and focus was on societal costs. This research has shown that the industry can use ROI to evaluate the costs and benefits of a safety intervention and make the decision on whether to invest in adopting it rather than waiting for a regulatory mandate.

Limitations of the Study

The study had limitations that could not be eliminated from the research design but were not considered to significantly impact the conclusions drawn from the results of the analysis. To estimate the technology adoption costs, the size of the fleet that would need to install the equipment should be known. It was difficult to accurately estimate the size of the fleet that had already installed the equipment. Regulatory authorities in some cases drive safety improvements by changing or introducing new rotorcraft certification and operation requirements to require the adoption of new technology. For example, the analysis of the accidents by FAR description (Figure 10) showed that 60% of CFIT related accidents over this period occurred during Part 91 general aviation operations. The new CFR Part 14 §135.160 radio altimeter for rotorcraft operations rule that came into effect in April 2017 would not affect all Part 91 operators, and only by their voluntary installation of the altimeters would their risk of CFIT accidents be minimized (FAA 2014a, 2014b; 2014c). With the introduction of the altimeter rule, only 11 of the

67 aircraft operating under Part 91 would have been required to install the equipment. Since the actual number of operators that could install the CFIT-avoidance equipment as part of the new regulations could not be estimated, a range of 25 to 75 percent of the fleet was used for the simulation. This ensures that the simulation results reflect the potential ROI values more likely to be achieved.

The estimation of the accident safety costs also posed a limitation. It was assumed that the costs of adopting the CFIT-avoidance technology could vary over time and were therefore limited to the time of extraction regardless of the source and method of extraction. As a key factor to a higher ROI, the C_T, which will vary from customer to customer, are based on the rotorcrafts' age, rotorcraft variants, avionics architecture, maintenance costs, and technology compatibility. It was assumed that the technology could be integrated into all aircraft in their current design or minor modifications would be required. The results showed that occupant fatality (C_F), occupant injury (C_I), loss of use costs (C_L), and aircraft damage (C_D) costs were the main drivers of the ROI values, and a moderate fluctuation in the C_T would not significantly alter the results. The available data could not support the estimation of the magnitude of the variation of the C_T based on the current or future fleet. With this limitation in mind, the costs were escalated to identify a range through which an increase was acceptable before the ROI turned negative. For every ROI analysis, the researcher will be limited by the available data on technology costs, especially when multiple types of equipment are considered.

The decision to use a ratio of direct to indirect costs of 1:1 in a similar manner to previous research done by Manuele (2011) and OSHA (2007) research to estimate the indirect costs could limit the understanding of how the individual cost categories influence the ROI. The lack of data on the average costs for search and rescue, accident investigations, loss of investment with increased insurance costs, third party damage, and loss of reputation led to the assumption that direct costs were the major drivers. Additionally, the loss of baggage category was considered not to be applicable due to the limited amount of luggage passengers in rotorcrafts are likely to carry which also limits the scope of the cost categories. In future studies, the researcher should quantify the costs associated with cargo that may not necessarily be considered baggage such as offshore supplies, skiing equipment, medical supplies on HAA aircraft, and power line inspection equipment, all of which are not considered part of the airframe. Quantifying these costs will improve the quality of the ROI analysis results.

Another limitation of the study was the inability to factor out the impact of other safety initiatives on CFIT accident reduction. The accident reports did not explicitly state that the installation of CFIT-avoidance could have prevented the accident, and it was therefore not possible to estimate what percentage of accidents could be avoided over the next ten years purely as a result of installing the equipment. Additionally, the study was limited to the technologies that were recommended by the NLR (2014). The use of other equipment such as tail rotor cameras to prevent tail rotor strikes was not factored in. For the study, it was therefore assumed that the recommended equipment would be more likely to help prevent the accident. The results from the study therefore do not offer insight into other potential factors that may affect the ROI from an operations perspective.

Recommendations

This study was intended to provide a method of estimating the potential ROI that could be achieved with the broader adoption of CFIT-avoidance technology and evaluating the same. The study applied accident cost categories originally defined for large fixed wing or airline category aircraft in the ASTER project report (NLR, 2001) which acknowledged that the existing methodologies did not allow for effective cost-benefit assessment. The report determined that the most significant determinants of accident costs arising from aircraft accidents and incidents were aircraft damage, deaths and injuries suffered by occupants, and loss of reputation. The findings from this study on accident costs were consistent with those of the NLR report with occupant deaths and injuries and aircraft damage being the main determinants, but rotorcraft leasing costs were seen to be a more significant contributor than loss of reputation for rotorcrafts. This suggests that the methodology herein can be applied as a starting point for understanding the financial implications in terms of ROI for new or existing safety technology. The methodology should be validated by evaluating the ROI of other initiatives such as safety management systems, human factors, and automation.

In this study, there were three major implications. First, it was determined early in the study that there was a need to split the rotorcraft into three categories to get a better understanding of the ROI results. These categories were: piston, turbine-single, and turbine-twin. When compared to the study done by Cavka & Cokorilo (2012) for airline aircraft, only two categories, narrow or wide-body, were required. Using three categories for this study was not only influenced by the aircraft capacity but also a combination of potential certification and operational requirements. For the piston and turbine-single rotorcraft, some of the technology would likely be considered optional kits while on turbine-twins they could be offered as part of the standard configuration. Second, it was observed that the evaluation of certain accident cost categories will be needed. Not all the cost categories were applicable to rotorcraft accidents and had to be excluded with applicable explanations. As an example, airport closure costs were excluded as most CFIT accidents do not occur near airports, while site contamination and clearance were considered societal costs. Additionally, the indirect costs such as third party damage, loss of reputation, and cost of accident investigation were estimated using the direct costs. This study suggests that further research into the rotorcraft accident cost categories and their applicable values is required to fully understand the ROI likely to be achieved for safety interventions as they are introduced. Third, the study showed that for the industry, a key factor to a higher ROI was ensuring that the technology adoption costs, C_T, remain low. The C_T will vary from customer to customer and for the industry as a whole based on the rotorcraft fleet's age, variants, avionics architecture, ease of installation, maintenance costs, and technology compatibility. The analysis assumed that the technology could be integrated into all aircraft in their current design or with minor modifications required. Of importance will be the industry's ability to ensure that the technology adoption costs for all operators remains relatively low and within reach of individual or small fleet operators by developing low cost variants, training methods, and maintenance options.

A review of the ROI results shows that the industry should adopt the CFIT-avoidance technology more broadly for piston and turbine-single category rotorcraft. Operators may not need to spend additional resources to reduce the number of CFIT accidents for the twin-turbine category. There may be a need to use alternative methods such as improved safety risk management (SRM) training for crew to further reduce the CFIT accidents. Of the 10 twin turbine accidents, 8 were involved in HAA operations at the time of the accident. The adoption of the new HAA regulations (FAA, 2014a) should provide a CFIT accident reduction. For any further reduction beyond HAA operations, SRM training could address the operational pitfalls or behavioral traps that the FAA has identified as accident inducing such as continuing VFR into instrument conditions, Get-There-Itis, and loss of positional/situational awareness (FAA, 2008; FAA, 2009b). With twin-turbines likely to experience an ROI with a median value of 2 and IQR of 5 plus the impact of the HAA regulations, it is recommended that operators will be better served by investing in SRM training for their crew.

Contribution to the literature. This study, which briefly introduced the background of how the costs and benefits of aviation safety initiatives have been previously evaluated, has made several significant contributions to the literature where gaps exist. In previous research, the CBA methodology, in which the government or public perspective is considered, was applied. The ROI methodology applied herein goes beyond what has been done with CBAs for various aviation safety initiatives. It evaluates the costs and benefits for the industry from an investors' or operators' perspective. The methodology expands on previous research performed by Cavka & Cokorilo (2012), where they performed a CBA of aircraft safety based on the A320-200 aircraft. The ROI considers the costs that operators are likely to avoid when a reduction in CFIT accidents is achieved. The study contributes to rotorcraft research by proposing a method of estimating rotorcraft accident or safety costs not previously done and provides a theoretical framework on which future ROI evaluations can be done. The study provides an understanding of the cost categories that drive rotorcraft accident costs: deaths and injuries suffered by occupants, aircraft damage, and leasing costs. This was in contrast to one of the expected drivers for airline aircraft, loss of reputation.

The study also provides a basis on which refinements to the methodology can be made using current resources such as the Aircraft BlueBook®, HeliValue$, Inc.

Helicopter Blue Book, rotorcraft OEMS, regulators, and safety equipment vendors. The study identifies that indirect costs are difficult to estimate since the data is not publicly available or it's difficult for the OEMS and regulators to quantify as they may not always be involved in all incident and accident investigations. The average cost of accident investigations for the regulators or OEMs were not quantifiable, but the study used the direct to indirect costs ratio of 1:1 as a starting point for future research. This study calls for the examination of similar costs to facilitate future ROI analysis. Additionally, the use of this methodology as described can provide results that can complement the findings of a CBA done by the government or industry to support the implementation of given safety initiatives, for example, the Canadian Department of Transport's decision to amend the aviation regulations to facilitate the wider adoption of TAWS (Department of Transport, 2011).

Another contribution to the literature is that this study utilizes the rotorcraft categories to provide insight into the potential ROI. Some previous safety studies have used the type of operations according to the Federal Air Regulations description or by industry affected. For example, observations on CFIT accidents in the HEMS/HAA industry by Ishihara (2005) and Part 27 rotorcraft by the HAI, AHS, and GAMA (Sandel Avionics, 2012). The findings of the study contribute to the literature by showing that the ROI for a given rotorcraft category may be impacted by the regulations that have been or are likely to be mandated. It demonstrates that the relationship between the ROI and mandated regulations for safety initiatives needs to be understood not only by operational segment but also by rotorcraft category. In this case, the new HAA regulations with respect to TAWS may potentially reduce the number of accidents, and investing in CFIT-avoidance technology beyond HAA operations for twin-turbines may result in a negative ROI.

Practical implications. The study provides recommendations which will improve the estimation of the ROI for current and future safety initiatives. The recommendations are based on the findings of the study which adopted the cost categories identified in the ASTER project report (NLR,2001). The recommendations address gaps identified within the analysis.

Improving the methodology. The current study applied accident cost categories originally defined for large fixed wing or airline category aircraft in the ASTER project report (NLR, 2001). Cavka & Cokorilo (2012) applied the same categories for a cost-benefit assessment on A320 accidents. The NLR report acknowledged that the existing methodologies did not allow for effective cost-benefit assessment, and therefore the methodology used in this study should be improved for future studies. Improvements should be made by determining the applicability of the different cost categories as direct or indirect costs and the values that should be used. The cost categories may include:

a) Airline costs for delay: For rotorcraft operations where timing is critical such as HAA, scheduled flights or on-demand taxi, it should be determined whether the cost impact of delays is high enough to warrant its inclusion in future ROI analyses. The delay costs include the reallocation of another aircraft to cover the trip, the management of customers before alternate aircraft is provided, etc.

b) Loss of baggage: This cost for this study was considered negligible. Consideration should be given for non-aircraft equipment that is lost such as medical bags and supplies for HAA, cargo for off-shore ops, and chemical spray for agricultural applications. The costs incurred in such losses can be categorized with loss of baggage for a more accurate model.

c) Search and rescue costs: These costs whether incurred by the operator, OEMs, or the local emergency services should be quantified for future research. This study showed that a large percentage of CFIT accidents occurred in VMC and near land, but for other studies where the majority of the operations may be offshore or in remote locations, it would be useful to know the SAR costs.

d) Airline immediate response: When a catastrophic accident occurs, a rotorcraft operator assists the immediate families, colleagues, and the members of society where the accident occurred to deal with the aftermath. Additionally, the operator handles some of the communication of critical information on how the post-accident events are being handled to the same individuals and members of the media. This immediate response comes with additional costs. These should be evaluated by rotorcraft category for the industry.

e) Costs of accident investigation: Rotorcraft OEMS, operators, and regulators are usually involved in incident and accident investigations. The degree of their involvement is based on the outcomes. For example, OEMs expertise may be required to understand the rotorcraft's design and failure modes of a given system. When the occurrence is a minor accident, the FAA or NTSB may choose to delegate the investigation to the OEM or industry experts. For the ROI, the industry should evaluate the average costs to the OEM or operators to support the investigations for each rotorcraft category.

f) Loss of reputation: This includes the loss of investment income costs. Accidents can result in the loss of reputation for the airframe or engine manufacturer or the operator. When customers view either party as having an unsafe product or operations, customers will not engage with them. OEMs should evaluate the financial impact of accidents to their reputation.

Technology adoption costs. One of the recommendations for the industry was to ensure that the technology adoption costs, C_T, remain relatively low to increase the likelihood of a positive ROI. The results of the study showed that the C_T should not increase by a factor of more than three. Previous research shows that the adoption of technology will be driven by some of the exogenous factors identified by Venkatesh, Thong, and Xu (2012) and Tang (2006) such as the price value, operators' needs, ease of integration and use, expected performance of the equipment, and whether other users recommend the use of the equipment or social influence. The industry or operators will need to evaluate the different technologies against their operations, the rotorcraft, the pilots' proficiency, financial resources, and the level of capabilities they would desire and adopt which will not increase costs significantly for any category or all rotorcraft. Based on this factor, the industry should explore ways of reducing or maintaining the technology costs as low as possible as it will be a key factor for operators.

Recommendations for Future Research

This research provided a framework for estimating the potential ROI that could be achieved with the broader adoption of CFIT-avoidance technologies. Future research should study the accuracy of the model by using safety data for implemented safety technologies or solutions. For example, the adoption of CFIT-avoidance technology for fixed wing aircraft or the introduction of a safety management system or quality assurance maintenance program could be studied and the ROI evaluated. The results from the estimated and actual ROI achieved will provide a better understanding of how the methodology can be improved. Additionally, the methodology should be improved to support the study of a specific category of aircraft. For the study, the methodology was adopted from Cavka and Cokorilo's (2012) study of airline aircraft to reflect rotorcraft accident costs. Future research can focus on quantifying the accident costs associated with not only general aviation aircraft but both manned and unmanned. This will allow operators, especially fleet operators, to make a quick assessment on the financial impact of adopting new or emerging technologies broadly and also evaluate the impact of regulations introduced by regulators based on their CBA assessment.

The industry should make improvements on the ROI estimation method applied herein by defining or proposing better processes of estimating rotorcraft accident costs. In this study, consideration was given to the replacement costs of pilots, but a more definitive model would require the consideration of other personnel such as law enforcement officers, flight nurses, news producers, and firefighters, among others, who may be lost in the accidents. In addition to the staff replacement costs that would be incurred by the organization, significant amounts of resources will be invested in getting the new personnel to the same level of experience. Though these individuals may not be in aviation roles, the industry will bear the costs involved in replacing them in their respective organizations, and the services they provide are likely to become more expensive. Other costs to the rotorcraft industry such as the organizations' immediate response to the accidents, costs of supporting accident investigations led by the NTSB or FAA, increased cost of insurance due the recurrence of the same type of accidents, and loss of reputation will need to be defined or estimated. Helicopter accidents, like all aviation accidents, can have a negative impact to a community especially if the industry is the primary economic activity. The overall economic impact should also be estimated. Some of these costs in the study were estimated as indirect costs in a 1:1 ratio to direct costs based on research previously performed by Manuele (2011) and OSHA (2007). Having more accurate cost estimates will improve the industry's understanding of the financial impact of adopting different technologies and will drive better decision making and strategic approach to technology development.

The rotorcraft industry should adopt the proposed ROI estimation methodology and apply it to other safety initiatives. In the same manner that a CBA was performed for accident safety costs for airline aircraft (Cavka & Cokorilo, 2012), airport security (Stewart & Mueller, 2013), aviation security (Stewart & Mueller, 2014), and U.K. offshore helicopter industry (Mitchell, 2006), an ROI can be performed for each safety initiative to help the industry understand the impact the financial resources proactively invested in safety would have. Safety investments would therefore be driven by the industry rather than regulations which may take a longer time to be adopted or implemented. In May 2017, during the HeliOffshore Conference, Andrea Cicero, the then Managing Director of Babcock Mission Critical Services, acknowledged that demonstrating a ROI has been historically challenging due to the need for comprehensive safety and financial data (Cicero, 2017). Though this methodology provides a starting point for estimating the ROI, future research should be used to refine data on the various safety or accident costs, both direct and indirect, and to make it more accessible to the rest of the industry for analysis. For example, understanding the costs associated with accident investigations for both the airframe OEMs, operators, and the regulatory authorities would give a more accurate ROI estimate.

REFERENCES

Abuzaid, A. H., I. B. Mohamed, and A. G. Hussin. 2011. Boxplot for circular variables. *Computational. Statistics, 27*, 381–392. doi: 10.1007/s00180-011-0261-5

AOPA Air Safety Institute (2017a). *26th Joseph T. Nall report.* Retrieved from https://www.aopa.org/-/media/files/aopa/home/training-and-safety/nall-report/26thnallreport2017.pdf

AOPA Air Safety Institute (2017b). *2015-2016 GA accident scorecard.* Retrieved from https://www.aopa.org/-/media/files/aopa/home/training-and-safety/nall-report/20152016accidentscorecard.pdf

Anderson, C. L. (2013). *The effects of aircraft certification rules on general aviation accidents* (Doctoral dissertation). Retrieved from ProQuest Dissertations and Theses database. (UMI No. 3609356)

Andersson, H. (2007). Willingness to pay for road safety and estimates of the risk of death: Evidence from a Swedish contingent valuation study. *Accident Analysis and Prevention*, *39*, 853–865.

Andersson, H., & Treich, N. (2011). The value of a statistical life. In de Palma, A., Lindsey, R., Quinet., & Vickerman, R. *A handbook of transport economics* (p. 396-424). Cheltenham, UK: Edward Elgar.

Appelbaum, E., & Milkman, R. (2006). *Achieving a workable balance: New Jersey's employers' experiences managing employee leaves and turnover*. New Jersey: Center for Women and Work, Rutgers University.

Aviation Week Network (2016). *Aircraft bluebook.* Overland Park, KS: Penton.

Bakker, A., Biehler, R., & Konold, C. (2005). Should young students learn about box plots? In G. Burrill & M. Camden (Eds.), *Curricular development in statistics education: International Association for Statistical Education (IASE) roundtable, Lund, Sweden, 28 June-3 July 2004* (pp. 163-173). Voorburg, The Netherlands: International Statistical Institute.

Banks, J., Reichard, K., Crow, E., & Nickell, K. (2005). How engineers can conduct cost-benefit analysis for PHM systems. *Proceedings of the IEEE Aerospace Conference.* Big Sky, MT: IEEE.

Beringer, D. B. & Drechsler, G. (2013). Head-mounted displays for civil helicopter navigation and obstacle avoidance: Is what you see what you don't get, or is seeing not believing? *Proceedings of the 57th Annual Meeting of the Human Factors and Ergonomics Society*. San Diego, CA: Sage Publications.

Bers, K., Schulz, K. R., & Armbuster, W. (2005). Laser radar system for obstacle avoidance. *Proceedings from the International Society of Optical Engineering.* Warsaw, Poland. http://dx.doi.org/10.1117/12.626082

Bergqvist, P. (2017, January 12). *Systems-specific courses are offered at Garmin's headquarters, remotely and online*. Flying. Retrieved from http://www.flyingmag.com/garmin-offers-training-programs-for-glass-avionics

Blom, H. A. P., Stroeve, S. H., de Jong, H. H., & National Aerospace Laboratory, NLR (2006). *Safety risk assessment by Monte Carlo simulation of complex safety critical operations.* (NLR Document NLR-TP-2006-684). Amsterdam, Netherlands: NLR.

Boushey, H. & Glynn, S.J. (2012). There are significant business costs to replacing employees. Retrieved from https://www.americanprogress.org/issues/

economy/reports/2012/11/16/44464/there-are-significant-business-costs-to-replacing-employees/

Čavka, I. & Čokorilo, O. (2012). Cost-benefit assessment of aircraft safety. *International Journal for Traffic and Transport Engineering*, *2*(4), 359 – 371. DOI:htpp://dx.doi.org/10.7708/ijtte.2012.2(4).06

Charles-Owaba, O. E., &Adebiyi, K. A. (2006). The development of manufacturing safety programme simulator. *Journal of Modeling in Management, 1*(3), 270-290. doi:10.1108/17465660610715249

Chang, M., Sandborn, P., Pecht, M., Yung, W. K. C., & Wang, W. (2015). A return on investment analysis of applying health monitoring to LED lighting systems. *Microelectronics Reliability*, *55,* 527-537. http://dx.doi.org/10.1016/j.microrel. 2015.01.009

Cicero, A. (2017). *Focus on value: Return on investment.* Retrieved from http://helioffshore.org/wp-content/uploads/2017/05/Day1_02_Focus-on-Value.pdf

Civil Aviation Safety Authority (2010). *Cost benefit analysis procedures manual, Version 1.1: November 2010*. (CASADOC 257). Canberra, Australia: Civil Aviation Safety Authority.

Čokorilo, O., Gvozdenović, S., Vasov, L., & Mirosavljević, P. (2010). Costs of unsafety in aviation. *Technological and economic development of economy: Baltic Journal on Sustainability*, *16*(2), 188-201.

Connor, G. (2014, June). Sandel, Garmin, and Honeywell develop new HTAWS to warn pilots about wires, cables and power lines. *Professional Pilot*, 48-52.

Defence iQ (2016, October). Military helicopter market, international challenges. *Defence iQ*, 17-22.

Department of Transport (2011). *Regulation amending the Canadian aviation regulations (Parts I. VI and VII).* (Canada Gazette Part 1, Vol. 145, No. 49, pp. 3673-80.). Ottawa, Canada: Publishing and Depository Services. http://www. gazette.gc.ca/rp-pr/p1/2011/2011-12-03/pdf/g1-14549.pdf

Department of Transport (2012). *Status report: Assessment of compatibility of planned LightSquared ancillary terrestrial component transmissions in the 1526-1536MHz band with certified aviation GPS receivers*. (Redacted version cleared for public release). Retrieved from https://www.ntia.doc.gov/files/ntia/ publications/faa_report_public_release_25_jan_2012_final.pdf

Department of Transport (2013). *Onboard safety systems effectiveness evaluation*. (Report DTMC 75-09-C-00021). Washington, DC: DOT. http://ntl.bts.gov/lib/51000/51200/51256/12-012_OBSS_Report.pdf

Duncan, M. & Frank, M. (2007, August). Helicopter market forecast sees major equipment change. *World Oil*, pp. 147-150.

European Commission (2009). *Part III: Annexes to impact assessment guidelines*. Retrieved from http://ec.europa.eu/smart-regulation/impact/ commission_guidelines/docs/iag_2009_annex_en.pdf

European Organisation for the Safety of Air Navigation (2015). *Standard inputs for EUROCONTROL cost-benefit analyses*. Retrieved from https://www.eurocontrol.int/sites/default/files/publication/files/standard-input-for-eurocontrol-cost-benefit-analyses-2015.pdf

Fabius, R., Thayer, R. D., Konicki, D. L., Yarborough, C. M., Peterson, K. W., Isaac, F., Loeppke, R. R., Eisenburg, B. S., & Dreger, M. (2013). The link between workforce health and safety and the health of the bottom line: Tracking market performance of companies that nurture a "culture of health”. *Journal of Occupational and Environmental Medicine*, *55*(9), 993-1000. doi:10.1097/JOM.0b013e3182a6bb75

Fadali, E., Griswold, T., Packham, J., & Harris, T. R. (2011). *Feasibility of helicopter emergency medical services in Humboldt County*. (UCED 2010/11-XX). Reno, Nevada: University of Nevada, Reno.

Federal Aviation Administration (1998). *Economic analysis of investment and regulatory decision - - Revised guide* (FAA-APO-98-4). Washington, DC: Government Publishing Office.

Federal Aviation Administration (2003). *General aviation controlled flight into terrain awareness* (FAA Advisory Circular 61-134). Retrieved from http://www.faa.gov/documentLibrary/media/Advisory Circular/ac61-134.pdf

Federal Aviation Administration (2007). *ATO En Route services: Surveillance and broadcast services benefits basis of estimates*. Retrieved from http://www.gama.aero/files/FAA-2007-29305-0285_-_Cost_Benefit.pdf

Federal Aviation Administration (2008). *Aviation instructor’s handbook.* Washington, D.C.: Government Printing Office.

Federal Aviation Administration (2009a). *Testimony - statement of John Allen, director of flight standards*. Retrieved from https://www.faa.gov/news/testimony/news_story.cfm?newsId=10497

Federal Aviation Administration (2009b). *Risk management handbook*. Washington, D.C.: Government Printing Office.

Federal Aviation Administration. (2011). *Airmen transition to experimental or unfamiliar aircraft* (Federal Aviation Administration Advisory Circular No. 90-109). U.S. Department of Transportation, Federal Aviation Administration. Washington, DC: U.S. Government Printing Office

Federal Aviation Administration (2014a). *Helicopter air ambulance, commercial helicopter, and Part 91 helicopter operations*. (RIN 2120-AJ53). Washington, DC: Government Publishing Office.

Federal Aviation Administration (2014b). *Certification of normal category aircraft*. (FAA Advisory Circular 27-1B). Washington, DC: Government Publishing Office.

Federal Aviation Administration (2014c). *Certification of transport category aircraft*. (FAA Advisory Circular 29-2C). Washington, DC: Government Publishing Office.

Federal Aviation Administration (2014d). *Fact sheet – FAA initiatives to improve helicopter air ambulance safety*. Retrieved from http://www.faa.gov/news/fact_sheets/ news_story.cfm?newsId=15794

Federal Aviation Administration (2015). *AC 135-14B helicopter air ambulance operations.* Retrieved from https://www.faa.gov/documentLibrary/media/ Advisory_Circular/AC_135-14B.pdf

Federal Aviation Administration (2016). *Policy and guidance, benefit-cost analysis, economic values for valuation of FAA investment and regulatory decisions.*

Section 2: Treatment of the values of life and injury in economic analysis. Retrieved from https://www.faa.gov/regulations_policies/policy_guidance/benefit_cost/media/econ-value-section-2-tx-values.pdf

Federal Aviation Administration (2017). *FAA aerospace forecasts, FY 2011-2031 and FY 2016-2036*. Retrieved from https://www.faa.gov/data_research/aviation/aerospace_forecasts/

Feldman, K., Jazouli, T., & Sandborn, P. (2009). A methodology for determining the return on investment associated with prognostics and health management. *Reliability, 58*, 305-316.

Fernández-Muñiz, B., Montes-Peón, J. M., Vázquez-Ordás, C. J. (2009). Relation between occupational safety management and firm performance. *Safety Science*, *47*, 980-991.

Flight Safety Foundation (2012, September). Safety ROI, the surest route to profitability is an evolving investment in safety. *AeroSafety World.* Retrieved from http://flightsafety.org/aerosafety-world-magazine/sept-2012/safety-roi

Friend, M. (2011). Top management support. In A. J. Stolzer, C. D., Halford, & J. J. Goglia, (Eds.), *Implementing safety management systems in aviation* (1st ed., p. 89). Burlington, VT: Ashgate Publishing.

Frigge, M., Hoaglin, D., & Iglewicz, B. (1989). Some implementations of the boxplot. *The American Statistician*, *43*(1), 50-54. doi:10.2307/2685173

Garmin Ltd. (2016a). *GTN™ 750*. Retrieved from https://buy.garmin.com/en-US/US/in-the-air/avionics-safety/gps-nav-comm/gtn-750/prod67886.html

Garmin Ltd. (2016b). *Garmin helicopter solutions*. Retrieved from http://sites.garmin.com/en-US/helicopters/

General Aviation Joint Steering Committee. (2012). *Loss of control group approach and landing*. Retrieved from http://www.avweb.com/pdf/ faaaopaaoareport.pdf

Guzman, A., & Asgari, B. (2014). *A cost-benefit analysis of investing in safety and risk engineering: The case of oil & gas transportation services by pipelines.* Paper presented at Portland International Center for Management of Engineering and Management (PICMET) '14 Conference. Portland, Oregon.

Helicopter Association International, American Helicopter Society International, General Aviation Manufacturers Association, & Aircraft Electronics Association (2015). *14 CFR 27 single-engine IFR certification proposal* [White Paper]. Retrieved from https://www.aea.net/pdf/Part_27_SE_IFR_White_Paper_6-19-15b.pdf

Helicopter Association International Economic Committee (2010). *Guide for the presentation of helicopter operating cost estimates 2010.* Retrieved from https://www.rotor.org/portals/1/membership/Guide%20for%20the%20Presentation%20of%20Helicopter%20Operating%20Cost%20Estimates.pdf

HeliValue$, Inc. (2015). *The official helicopter Blue Book*. Wauconda, IL: HeliValue$.

Helmreich, R. L. (2000). On error management: Lessons from aviation. *BMJ: British Medical Journal*, *320*(7237), 781–785.

Henry, M., Schmitz, S., Kelbaugh, K., & Revenko, N. (2013). *A Monte Caro simulation for evaluating airborne collision risk in intersecting runways*. McLean, VA: MITRE Corporation.

Henry, M., Schmitz, S., Revenko, N., & Kelbaugh, K. (2013). A Monte Carlo simulation for evaluating airborne collision risk in intersecting runways. *Proceedings from AIAA Modeling and Simulation Technologies (MST) Conference*. Boston, Massachusetts: AIAA.

Huang, Y. H., Leamon, T. B., Courtney, T. K., DeArmond, S., Chen, P. Y., & Blair, M. F. (2009). Financial decision makers' views on safety. What SH&E professionals should know. *Professional Safety*, *54*(04).

International Helicopter Safety Team (2016). *IHST after 10 years: A worldwide reduction in helicopter accidents*. Retrieved from http://www.ihst.org/Default.aspx?tabid=1507&mid=2918&newsid2918=64021&language=en-US

Ishihara, Y. (2005). *Controlled flight into terrain (CFIT) accidents in helicopter EMS and offshore operations.* Paper presented at the International Helicopter Safety Symposium, Montreal, QC, Canada.

Jervis, S. & Collins, T. R. (2001). Measuring safety's return on investment. *Professional Safety*, *46*(9), 18-23.

Johnson, O. (2016). *Airbus helicopter begins H160 commercialization*. Retrieved from https://www.verticalmag.com/news/airbus-helicopters-begins-h160-commercialization/

Johnson, W. B. & Avers, K. (2012). *Return on investment tool for assessing safety interventions*. Paper presented at the Shell Aviation Safety Seminar: Human Factors-Safety's Vital Ingredient. The Hague, Netherlands. Retrieved from https://www.faa.gov/about/initiatives/maintenance_hf/fatigue/publications/media/2012-10_return_on_investment_examples.pdf

Jones, K. M. (2002). *The use of moving map technology to prevent wire strikes in helicopter flight* (Masters thesis). Retrieved from San Jose State University ScholarWorks. (UMI No. 1411614)

Kraemer, K. A. (2002). *TAWS for rotorcraft*. Retrieved from http://www.aviationtoday.com/av/issue/feature/A-TAWS-for-Rotorcraft_12610.html

Krlev, G., Munscher, R., & Mulbert, K. (2013). *Social return on investment (SROI): State-of-the-art and perspectives. A meta-analysis of practice in social return on investment (SROI) studies published 20002-2012*. Retrieved from http://archiv.ub.uni-heidelberg.de/volltextserver/18758/1/CSI_SROI_Meta_Analysis_2013.pdf

Landau, S., Weisbrod, G., & Alstadt, B. (2010). Applying benefit-cost analysis for airport improvements: Challenges in a multimodal world. *Transport Research Board: Journal of the Transport Research Board*, 2177, 1-7. doi:10.3141/2177-01

Lee, M. J. (2012). *A quasi-experimental approach to estimating the value of reducing risk* (Doctoral dissertation). Retrieved from ProQuest Dissertations and Theses database. (UMI No. 3538285)

Lercel, D., Steckel, R., Mondello, S., Carr, E. & Patankar, M. (2011). *Aviation safety management systems return on investment study*. Retrieved from http://parks.slu.edu/research/centers-labs-facilities/CASR/research-papers/aviation-safety-management-systems-roi-study

Linhard, J. B. (2005). Understanding the return on health, safety, and environmental investments. *Journal of Safety Research*, *36*(3), 257-260.

Manuele, F. A. (2011). Accident costs: Rethinking ratios of indirect to direct costs. *Professional Safety*, *56*(1), 39-47.

Marais, K., & Weigel, A. L. (2006, March). *Encouraging and ensuring successful technology transition in civil aviation*. In 25th Digital Avionics System Conference. Portland, OR.

Mayhew, N. (n.d.). *Training fact sheet – recurrent training: "Are you current and proficient?"*. Retrieved from http://www.ihst.org/portals/54/insights/Training_Recurrent.pdf

Mitchell, S.J. Le M (2006). The economics of safety: A case study of the U.K. off shore helicopter industry (Doctoral Dissertation). Cranfield University, U.K.

National Aerospace Laboratory, NLR (2001). *Aviation safety targets for effective regulation, a consolidated report*. Retrieved from http://www.transport-research.info/sites/default/files/project/documents/20100310_120301_24152_Aster%20Consolidated%20Final%20Report.pdf

National Aerospace Laboratory, NLR (2014). *The potential technologies to mitigate helicopter accident factors – An EHEST study*. (NLR Document NLR-TP-2014-311). Amsterdam, Netherlands: NLR.

NTSB. (2009). *Safety recommendation, A-09-87 through -96*. Washington, DC: Government Printing Office. Retrieved from http://www.ntsb.gov/safety/safety-recs/recletters/A09_87_96.pdf

NTSB. (2013). *NTSB strategic plan, fiscal years 2013 through 2016*. NTSB, Washington, DC. Retrieved from: http://www.ntsb.gov/about/strategic_plan/table_of_contents.html

NTSB. (2015). *Most wanted. Transportation safety improvements*. Retrieved from http://www.ntsb.gov/safety/mwl/Documents/MWL_2015_Factsheet_03.pdf

NTSB (2017). Aviation accident database & synopses. [Data file]. Retrieved from https://www.ntsb.gov/_layouts/ntsb.aviation/index.aspx

OSHA (2007). *Safety &health management systems eTool, costs of accidents*. Retrieved from https://www.osha.gov/SLTC/etools/safetyhealth/mod1_costs.html

Porter, M. E., & Kramer, M. R. (2206). Strategy and society: The link between competitive advantage and corporate social responsibility. *Harvard Business Review*, (84), 78-92.

Rosenkrans (2011*). Financial SMS: Excel worksheets help airline safety officers to predict return-on-investment while proposing risk mitigations*. Retrieved from http://www.faa.gov/about/initiatives/maintenance_hf/library/documents/media/roi/roi_from_fsf.pdf

Sandel Avionics (2012). *Avoid controlled flight into terrain, obstacles, and wires.* Retrieved from http://www.sandel.com/doc_download/144-cfit-white-paper

Schmidt, J., Schmorrow, D., & Figlock, R. (2000). Forecasting return on investment (ROI) for naval aviation maintenance safety initiatives. *Proceedings of the 2000 Advances in Aviation Safety Conference.* Dayton Beach, Florida: Society of Automotive Engineers Inc.

Scuffham, P., Chalmers, D., O'Hare, D., & Wilson, E. (2002). Direct and indirect cost of general aviation crashes. *Aviation, Space, and Environmental Medicine, 73*(9), 851-858.

Skydel, S. (2011). Collision avoidance: Measuring the benefits of onboard safety systems. *Fleet Equipment*, *37*(8), 30-32.

Stanford University, Department of Civil Engineering (1981). *Improving construction safety performance: The user's role*. (Technical Report No. 260). Palo Alto, CA.

Stevenson, G., Verdun, H. R., Stern, P. & Koechner, W. (1994). Helicopter laser radar for obstacle avoidance. *Proceedings of AHS International Forum 50*: Washington, D.C.

Stewart, M. G., & Mueller, J. (2013). Terrorism risks and cost-benefit analysis of aviation security. *Risk Analysis, 33(5)*, 893-908. doi:10.1111/j.1539-6924.2012.01905.x

Stewart, M. G., & Mueller, J. (2014). Cost-benefit analysis of airport security: Are airports too safe? *Journal of Air Transport Management*, *35*, 19-28. http://dx.doi.org/10.1016/j.jairtraman.2013.11.003

Stone, P. W. (2005). Return on Investment Models. *Applied Nursing Research, 18* (1005), 186-189.

Stolzer, A. J., Halford, C. D., & Goglia, J. J. (2008). *Safety management systems in aviation.* Burlington, VT: Ashgate.

Tang, H. K. (2006). Adoption of navigation technologies: Five historical and contemporary cases. *Technological Forecasting & Social Change*, *73*(7), 845-859.

Taylor, J. C. (2000). A new model for measuring return on investment (ROI) for safety programs in aviation: An example from airline maintenance resource management (MRM). *Proceedings of the 2000 Advances in Aviation Safety Conference.* Dayton Beach, Florida: Society of Automotive Engineers Inc.

Tsang, P. S., & Vidulich, M. A. (2003). *Principles and practice of aviation psychology*. Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

U.S. Bureau of Labor Statistics (2016). *Overview of BLS wage data by area and occupation* [Data file]. Retrieved from http://www.bls.gov/oes/current/oes_nat.htm#53-0000

U.S. Department of Agriculture Forest Service (2017). *Helicopter services hourly flight rates, fuel consumption, and weight reduction chart effective July 16, 2017 for contracts awarded 2013-2017.* Retrieved from https://www.fs.fed.us/fire/contracting/helicopters_cwn/flt_chrt_awarded_2013-2017.pdf

U.S. Department of Transport (2015). *Guidance on treatment of the economic value of statistical life (VSL) in Depart of Transportation analyses - 2015 adjustment.* Retrieved from https://www.transportation.gov/sites/dot.gov/files/docs/VSL2015_0.pdf

U.S. Joint Helicopter Safety Analysis Team (2010). *Calendar year 2006 report*. Retrieved from http://www.ihst.org/portals/54/jhsat/safety_reports/CY2006_USJHSAT_Report_09132010.pdf

U.S. Joint Helicopter Safety Analysis Team (2011). *The compendium report: The U.S. JHSAT baseline of helicopter accident analysis*. Retrieved from http://www.ihst.org/portals/54/US_JSHAT_Compendium_Report1.pdf

Vasign, B., Fleming, K., & Tacker, T. (2008). *Introduction to air transport economics*. Burlington, VT: Ashgate Publishing.

Veltri, A., Pagell, M., Behm, M., & Das, A. (2007). A data-based evaluation of the relationship between occupational safety and operating performance. *Journal of SH&E Research, 4*(1), 3-22.

Venkatesh, V., Thong, J., & Xin, X. (2012). Consumer acceptance and use of information technology: Extending the unified theory of acceptance and use of technology. *MIS Quarterly*, 36(1), 157–178.

Viscusi, W. K. (2005). *The value of life*. Retrieved from http://www.law.harvard.edu/programs/olin_center/

Wang, N., Chang, Y., & El-Sheikh, A. A. (2012). Monte Carlo simulation to life cycle cost management. *Structure and Infrastructure Engineering, 8*(8), 739-746. doi:http://dx.doi.org/10.1080/15732479.2010.481304

Westerlind, K. (2004). *Evaluating return on information technology investment*. (Unpublished master's thesis). Gothenburg University, Sweden.

Whealan-George, K. A. (2013). Economic modeling to improve estimates of the benefits of safety management systems. *Collegiate Aviation Review, 31*(1). Retrieved from http://commons.erau.edu/ww-economics-social-sciences/

Yang, Y., Liu, P., & Xu, X. (2016). Estimation of social value of statistical life using willingness-to-pay method in Nanjing, China. *Accident Analysis and Prevention, 95*, 308–316.

APPENDIX A

Accident Cost Categories Results Sample

EventId	Investigation	AccidentNumber	EventDate	InjurySeverity	AircraftDamage	AircraftCategory	RegistrationN	Make	Model
20050623X00845	Accident	CHI05CA147	05/19/2005	Non-Fatal	2	Helicopter	N8505F	Bell	47G
20050601X00695	Accident	LAX05LA187	05/25/2005	Non-Fatal	1	Helicopter	N110DT	Bell	47G-4A
20060922X01375	Accident	CHI06CA242	08/23/2006	Non-Fatal	2	Helicopter	N2251W	Bell	47G-5
20070809X01160	Accident	DFW07CA156	07/11/2007	Non-Fatal	2	Helicopter	N7878	Bell	47G-2A
20080722X01096	Accident	DEN08FA122	07/15/2008	Fatal(2)	1	Helicopter	N469E	HUGHES	269B
20080826X01322	Accident	CHI08CA238	08/05/2008	Non-Fatal	2	Helicopter	N57UP	ROBINSON HELICOPTER	R22 BETA
20090324X52648	Accident	WPR09CA163	03/24/2009	Non-Fatal	2	Helicopter	N139RJ	ROBINSON HELICOPTER	R22 BETA
20090607X15237	Accident	CEN09CA339	06/05/2009	Non-Fatal	2	Helicopter	N8420E	BELL	47G-2
20100705X12909	Accident	ERA10LA348	07/05/2010	Fatal(1)	2	Helicopter	N857PM	ROBINSON HELICOPTER	R44
20120612X20331	Accident	WPR12LA259	06/12/2012	Fatal(2)	2	Helicopter	N282MC	ROBINSON HELICOPTER	R44 II
20130804X12723	Accident	WPR13CA354	06/25/2013	Fatal(2)	2	Helicopter	N74666	ROBINSON HELICOPTER	R44 II
20140531X12419	Accident	WPR14CA216	05/31/2014	Fatal(2)	2	Helicopter	N7122E	ROBINSON HELICOPTER	R22 BETA
20140804X11431	Accident	CEN14CA403	07/31/2014	Fatal(2)	2	Helicopter	N7194H	ROBINSON HELICOPTER	R44
20140812X50722	Accident	CEN14LA423	08/12/2014	Fatal(2)	2	Helicopter	N7089J	BELL	47G 5
20140813X51839	Accident	CEN14CA426	08/13/2014	Fatal(2)	2	Helicopter	N8343P	ROBINSON HELICOPTER	R44
20140908X10448	Accident	CEN14LA487	09/06/2014	Fatal(2)	2	Helicopter	N699TQ	ROBINSON HELICOPTER	R44 II
20050927X01538	Accident	LAX05FA311	09/20/2005	Fatal(1)	2	Helicopter	N957SH	ROBINSON HELICOPTER	R22 BETA
20060627X00832	Accident	ATL06CA073	05/02/2006	Non-Fatal	2	Helicopter	N288RH	ROBINSON HELICOPTER	R44 Raven II
20071119X01805	Accident	NYC08FA026	11/05/2007	Fatal(3)	1	Helicopter	N8356C	ROBINSON HELICOPTER	R44
20090724X05537	Accident	ERA09FA417	07/23/2009	Fatal(4)	2	Helicopter	N7189W	ROBINSON HELICOPTER	R44
20150811X15940	Accident	CEN15CA348	08/07/2015	Fatal(2)	1	Helicopter	N20KD	ROBINSON HELICOPTER	R44
20151006X02643	Accident	GAA16CA006	10/05/2015	Fatal(2)	2	Helicopter	N174CD	ROBINSON HELICOPTER	R44 II
20060306X00268	Accident	LAX06LA123	02/25/2006	Fatal(1)	1	Helicopter	N61466	Schweizer	269C-1
20080710X01015	Accident	LAX08LA213	07/04/2008	Fatal(2)	1	Helicopter	N2011A	SCHWEIZER	269 C-1
20090611X91250	Accident	WPR09FA284	06/11/2009	Fatal(1)	2	Helicopter	N149SH	ROBINSON HELICOPTER	R22 BETA
20051108X01805	Accident	DFW05CA235	09/10/2005	Non-Fatal	2	Helicopter	N862Z	Bell	47G
20051019X01693	Accident	LAX06LA006	10/14/2005	Fatal(2)	2	Helicopter	N7196J	ROBINSON HELICOPTER	R22 BETA
20060419X00461	Accident	DFW06FA102	04/13/2006	Fatal(2)	1		N123CK	ROBINSON HELICOPTER	R44 II
20080201X00130	Accident	LAX08FA052	01/25/2008	Fatal(1)	1	Helicopter	N705JJ	ROBINSON HELICOPTER	R22 BETA
20080815X01250	Accident	CHI08CA177	07/04/2008	Non-Fatal	2	Helicopter	N31138	ROBINSON HELICOPTER	R44 II
20081019X15543	Accident	ERA09FA022	10/16/2008	Fatal(1)	2	Helicopter	N943MH	ROBINSON HELICOPTER	R22
20090713X81043	Accident	WPR09CA339	07/13/2009	Non-Fatal	2	Helicopter	N244HP	ROBINSON HELICOPTER	R44
20100407X12526	Accident	WPR10CA193	10/29/2009	Non-Fatal	2	Helicopter	N144RF	ROBINSON HELICOPTER	R44
20100525X54249	Accident	CEN10CA268	05/24/2010	Non-Fatal	3	Helicopter	N927SH	ROBINSON HELICOPTER	R22 BETA

APPENDIX A

Accident Cost Categories Results Sample (Part B)

C_D	C_R	C_L	C_F	C_I	C_P	C_{IN}	C_{DIRECT}	C_A
$65,600	$4,100	$510,000	$0	$28,200	$0	$607,900	$607,900	$1,215,800
$88,000	$0	$510,000	$0	$987,000	$0	$1,585,000	$1,585,000	$3,170,000
$73,600	$4,600	$510,000	$0	$0	$0	$588,200	$588,200	$1,176,400
$67,200	$4,200	$510,000	$0	$28,200	$0	$609,600	$609,600	$1,219,200
$44,000	$0	$510,000	$18,800,000	$0	$179,040	$19,533,040	$19,533,040	$39,066,080
$64,000	$4,000	$510,000	$0	$0	$0	$578,000	$578,000	$1,156,000
$64,000	$4,000	$510,000	$0	$987,000	$0	$1,565,000	$1,565,000	$3,130,000
$64,000	$4,000	$510,000	$0	$987,000	$0	$1,565,000	$1,565,000	$3,130,000
$92,800	$5,800	$510,000	$9,400,000	$0	$179,040	$10,187,640	$10,187,640	$20,375,280
$156,000	$9,750	$510,000	$9,400,000	$987,000	$179,040	$11,241,790	$11,241,790	$22,483,580
$156,000	$9,750	$510,000	$0	$0	$0	$675,750	$675,750	$1,351,500
$88,000	$5,500	$510,000	$0	$0	$0	$603,500	$603,500	$1,207,000
$84,800	$5,300	$510,000	$0	$28,200	$0	$628,300	$628,300	$1,256,600
$76,800	$4,800	$510,000	$9,400,000	$0	$179,040	$10,170,640	$10,170,640	$20,341,280
$88,000	$5,500	$510,000	$0	$0	$0	$603,500	$603,500	$1,207,000
$144,000	$9,000	$510,000	$9,400,000	$0	$179,040	$10,242,040	$10,242,040	$20,484,080
$108,000	$6,750	$510,000	$9,400,000	$0	$179,040	$10,203,790	$10,203,790	$20,407,580
$144,000	$9,000	$510,000	$0	$0	$0	$663,000	$663,000	$1,326,000
$110,000	$0	$510,000	$28,200,000	$0	$179,040	$28,999,040	$28,999,040	$57,998,080
$84,800	$5,300	$510,000	$37,600,000	$0	$179,040	$38,379,140	$38,379,140	$76,758,280
$116,000	$0	$510,000	$0	$28,200	$0	$654,200	$654,200	$1,308,400
$364,800	$22,800	$510,000	$0	$0	$0	$897,600	$897,600	$1,795,200
$50,000	$0	$510,000	$9,400,000	$987,000	$0	$10,947,000	$10,947,000	$21,894,000
$50,000	$0	$510,000	$18,800,000	$0	$358,080	$19,718,080	$19,718,080	$39,436,160
$116,000	$7,250	$510,000	$9,400,000	$0	$179,040	$10,212,290	$10,212,290	$20,424,580
$67,200	$4,200	$510,000	$0	$1,974,000	$0	$2,555,400	$2,555,400	$5,110,800
$92,000	$5,750	$510,000	$18,800,000	$0	$358,080	$19,765,830	$19,765,830	$39,531,660
$165,000	$0	$510,000	$18,800,000	$1,974,000	$0	$21,449,000	$21,449,000	$42,898,000
$145,000	$0	$510,000	$9,400,000	$0	$179,040	$10,234,040	$10,234,040	$20,468,080
$180,000	$11,250	$510,000	$0	$0	$0	$701,250	$701,250	$1,402,500
$68,000	$4,250	$510,000	$9,400,000	$0	$179,040	$10,161,290	$10,161,290	$20,322,580
$88,000	$5,500	$510,000	$0	$0	$0	$603,500	$603,500	$1,207,000
$100,800	$6,300	$510,000	$0	$0	$0	$617,100	$617,100	$1,234,200
$20,250	$6,750	$510,000	$0	$987,000	$0	$1,524,000	$1,524,000	$3,048,000