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A Constructivist Grounded Theory Study of Airfield Lighting Maintenance Management Strategy

David A. Burgess
Embry-Riddle Aeronautical University, burgesd5@my.erau.edu

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David A. Burgess

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By

David A. Burgess

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 Digitally signed by Mark A Friend Date: 2022.09.15 08:37:19 -04'00'

Mark A. Friend, Ed.D.
Committee Chair

Ryan J. Wallace Digitally signed by Ryan J. Wallace Date: 2022.09.20 08:02:30 -04'00'

Ryan J. Wallace, Ed.D.
Committee Member

Kim Chambers Digitally signed by Kim Chambers Date: 2022.09.21 12:17:00 -04'00'

Kim Chambers, Ph.D.
Committee Member

Committee Member

Sarah Hubbard Digitally signed by Sarah Hubbard Date: 2022.09.19 20:12:53 -04'00'

Sarah M. Hubbard, Ph.D.
Committee Member (External)

Steven Hampton Digitally signed by Steven Hampton Date: 2022.09.21 13:42:43 -04'00'

Steven Hampton, Ed.D.
Associate Dean, School of Graduate Studies, College of Aviation

Alan Stolzer Digitally signed by Alan Stolzer Date: 2022.09.22 06:17:07 -04'00'

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

Lon Moeller Digitally signed by Lon Moeller Date: 2022.09.22 09:35:37 -04'00'

Lon Moeller, J.D.
Senior Vice President for Academic Affairs and Provost

June 23, 2022

Signature Page Date

Abstract

Researcher: David A. Burgess

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Asset management programs can keep senior airport managers informed of the performance and life-cycle costs of assets critical to airport operations. With this information, managers can adjust operations and maintenance to minimize costs without sacrificing service quality. However, program implementation is costly and time-consuming. In addition to management and information technology changes, the individual maintenance shops must also develop and incorporate new data collection processes into their everyday workflow. Knowledgeable and experienced maintenance managers must evaluate the data, consider alternatives, and find strategies to reduce costs without negative impact. Unfortunately, such managers are rare for highly specialized assets like airfield lighting systems and often gain most of their experience working at one airport.

This research investigated the maintenance strategies most often used for airfield lighting, examined which criteria affected strategy choices, and asked how managers make their selections. The researcher interviewed 23 participants from 15 airports, including facility managers, maintenance engineers, and supervisors. Interview

statements were first individually coded in detail and then grouped using focused codes to enable the continuous comparison of each organization's approach to addressing common problems. Ultimately, the analysis identified eight primary criteria that managers should consider when selecting a maintenance strategy.

The process used by U.S. commercial service airports for selecting a maintenance management strategy is modeled as a Multi-Criteria Decision-Making (MCDM) problem. The model includes a problem goal, the criteria affecting the decision, and all the possible alternatives. MCDM models can employ various quantitative decision support systems such as Simple Additive Weighting (SAW), which requires subject matter experts to assign weights to the performance of the multiple alternatives for each of the criteria. However, the research shows that airports consistently use an intuitive decision-making process that relies on the expertise and experience of their maintenance staff. Therefore, this research constructed a theory of airfield lighting maintenance strategy selection modeled as an MCDM problem using an intuitive decision support system.

Maintenance managers should consider each of the following criteria when considering their work strategy: access, environment, regulations, budget, design, condition, impetus, and staff. Data analysis also found nine alternative maintenance strategies divided into corrective and preventive types. Corrective maintenance involves action after an asset degradation or failure has occurred. Preventive maintenance is the action taken before problems to prevent degradation and failure. Research shows that maintenance managers consider corrective maintenance to be less costly. However, overuse of corrective maintenance results in higher risks of unexpected asset failure and higher costs over the long-term. In comparison, preventive maintenance may require

more daily effort but yields more reliable system performance and lower asset life-cycle costs. In practice, successful maintenance requires using both strategies.

Asset management practices require maintenance managers to measure and analyze their system performance, then regularly consider how they might change the maintenance program to minimize operating and maintenance costs without sacrificing performance. This research provides information helpful to maintenance managers with their strategy selection. Future research should investigate developing a quantitative decision-support system that maintenance managers could integrate into the current process and potentially deploy to maintenance organizations wanting supplemental guidance.

Keywords: airfield lighting, asset management, constructivist grounded theory, maintenance management strategy

Dedication

I am dedicating this dissertation to three beloved people who have meant and continue to mean so much to me. First and foremost, I dedicate to my father, Reverend Ronald Burgess, whose love, compassion, and wisdom I sorely miss but continue to inspire and guide me.

Next, I remember my loving wife, Nilufer, whose patience, encouragement, and un-wavering support enabled me to endure this seven-year effort.

Lastly, I make a dedication to my son, Anthony. His relentless pursuit and achievement of his goals over the last seven years drove me to work harder to reach mine.

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I give thanks to my committee chair Dr. Mark Friend, and committee members, Dr. Sarah Hubbard, Dr. Ryan Wallace, and Dr. Kim Chambers. Your encouragement and feedback have been invaluable. Additionally, I would like to thank the interviewees for taking the time to support academic research and share their experiences.

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Chapter I: Introduction

"The role of the modern airport manager has evolved from an operational coordinator to include business manager and economic or property developer" (Airport Cooperative Research Program [ACRP], 2019, p.32). As obtaining subsidies from local municipalities becomes more difficult, generating revenue and reducing expenses becomes more critical to the airport manager (ACRP, 2019). Based on the data reported to the Federal Aviation Administration (FAA) by U.S. commercial service airports, in 2018, the cost of repairs and maintenance constituted 13.2% of total operating expenses (FAA, 2021a). Restrictions on public funding for capital projects, reductions in fuel tax income due to the growth of low-cost carriers, and forecasted increases in passenger and cargo growth are all changes within the aviation industry driving U.S. airports to examine new strategies to maintain safety and customer service levels in the future (ACRP, 2012a). Federal and FAA grant assurances require airport managers to be as self-sufficient as possible (FAA, 2009; 49 U.S.C. § 47107(a)(13); & 49 U.S.C. § 47107(k)(3)).

The ACRP sponsored the development of a primer and guidebook to help airport managers implement asset management programs to improve operational efficiency and reduce costs (ACRP, 2012a). The guidance describes an asset management program developed by the Environmental Protection Agency (EPA) following practices described in Publicly Available Specification (PAS) 55, Asset Management, initially published in 2004 by the British Standards Institute and superseded in 2014 by International Standards Organization (ISO) 55000, Asset Management (ACRP, 2012a). PAS 55 defined asset management as follows:

> Systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks, and expenditures over their life cycles for the purposes of achieving its organizational strategic plan. (ACRP, 2012a, p. 8)

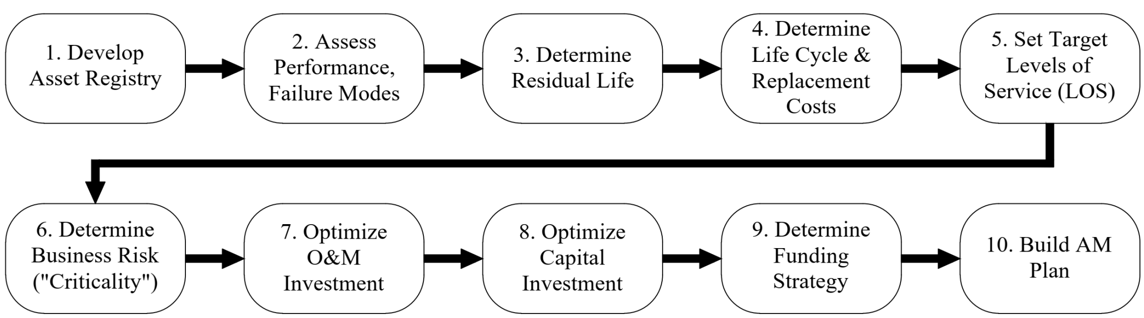
The implementation of asset management programs requires organizations to answer five core questions about the assets in their physical infrastructure:

1. What is the state of the assets?
2. What is the required level of service?
3. Which assets are critical to sustained performance?
4. What are the best operations, maintenance, and capital investment strategies?
5. What is the best funding strategy? (ACRP, 2012a, p. 49)

Figure 1 illustrates the ten-step process that airports undertake to answer these five questions.

Figure 1

Ten-Step Asset Management Process



Note. Adapted from "ACRP Report 69 Asset and infrastructure management for airports: primer and guidebook" (p. 10), by the Airport Cooperative Research Program, Washington, DC: Transportation Research Board. Copyright 2012 by National Academy of Sciences. Reprinted with permission.

In 2014, the International Standards Organization (ISO) formalized international standard practices for asset management programs into ISO 55000, ISO 55001, and ISO 55002 (ISO, 2014). ISO also developed a certification process for verifying that an organization has fully implemented recommended practices through the services of an independent auditor. As of this writing, no U.S. airport has completed ISO 55001 certification (ISO, 2021).[1] ISO 55000 supplies a more concise definition of asset management, "the coordinated activity of an organization to realize value from assets" (Institute of Asset Management [IAM], 2015, p.8). The rest of this document will refer to the goal of asset management using the more concise ISO definition of realizing the value from assets.

This research addresses one of the challenges to the implementation of asset management. Currently, available guidance describes how airport management can develop and integrate asset management programs into the organization. However, guidance for developing asset management practices at the shop level remains limited. For example, ACRP guidance requires managers to identify strategic changes for improvement (ACRP, 2012a). These requirements include:

- Full review of maintenance strategies for each asset group.
- Introduction of continuous condition monitoring equipment.
- Update maintenance contracts with respect to frequency and performance.
- Establish performance measures to monitor and manage the effectiveness of the program (ACRP 2012a, pp. 94-95)

[1] At Hartsfield-Jackson International Airport (ATL), ISO 55001 certification was obtained by Atlanta Airlines Terminal Corporation (AATC) which is a privately held company that operates and maintains the Central Passenger Terminal Complex at ATL (AATC, 2021).

Because of the many differences between asset systems and airport design, each maintenance manager must develop customized practices appropriate for local conditions. In addition, developing such programs requires managers with experience using various maintenance strategies. However, for airport-unique asset systems such as airfield lighting, many such managers gain their experience working at one airport. This research collects and analyzes various airfield lighting maintenance management practices at a wide range of U.S. commercial service airports. This study provided an opportunity to examine the differences between lighting systems and airports to develop a common theory of maintenance strategy selection suitable for application at all airports.

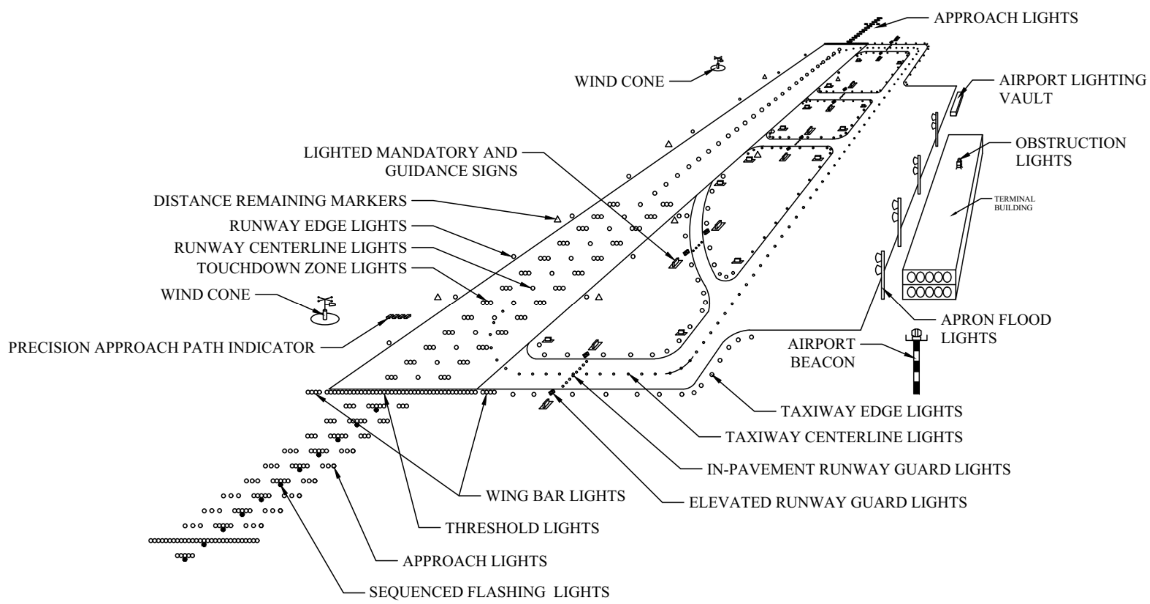
Airfield Lighting Systems

Runway and taxiway lighting outline the edges and sometimes the centerline to support safe aircraft movements during periods of darkness or restricted visibility (FAA 2021c). Other ground lighting systems such as guard lights, stop bars, and runway status lights supply automated or controlled signals to notify the pilots of aircraft when to stop or start moving (FAA, 2021b). Approach lighting systems supply the primary means for a pilot to transition from instrument flight to visual flight for landing (FAA, 2021b). Federal regulation 14 CFR § 139.311(c) requires runway, taxiway, approach, and obstruction lighting on airports as authorized by the FAA administrator. FAA AC 150/5210-22 *Airport Certification Manual* requires airports to develop and implement a lighting and signage plan specifically for the airport. FAA AC 150/5300-13A *Airport Design* describes which lighting systems are necessary according to the runway design. Annual Part 139 inspections by the FAA include examining all movement area lighting and signage at night, including maintenance records. Failure to properly operate and maintain airfield lighting risks the suspension of the airport operating certificate and potentially creates operational and safety hazards.

Airfield lighting systems include various visual landing and ground movement aids, as illustrated in Figure 2. In addition, airfield lighting systems have a network of underground duct banks, junction structures, cables, sensors, and one or more structures with power and control equipment called the airfield lighting vault.

Figure 2

Diagram of Typical Above-Ground Components of a Category II/III Airfield Lighting System at a Single Runway Airport



Source: *Civil Aviation Bureau, Aeronautical Ground Lighting System* (Ministry of Land, Infrastructure, and Transport) (http://www.mlit.go.jp/koku/04_hoan/e/30.pdf). The figure was modified for clarity.

The most distinct technical feature of airfield lighting design is the *constant current* operating theory (FAA, 2018a). Constant current design sacrifices the safety features of most electrical systems to supply a more reliable power source. In other words, airfield lighting systems will continue to operate even under hazardous conditions that are not immediately apparent (FAA, 2014a). The potential for encountering these hazards is why airfield electricians require specialized training (FAA, 2014a). Airfield lighting systems typically operate between 2,000 and 3,000 volts using a constant current system (FAA, 2018a). Working with these systems requires training that is rare for facility electricians (FAA, 2014a). The staff performing airfield lighting maintenance must be a *qualified person,* defined as "one who has demonstrated skills and knowledge related to the construction and operation of electrical equipment and installations and has received safety training to identify and avoid the hazards involved" (FAA, 2014a; NFPA, 2021, art. 100).

At the systems level, airports may be able to share information for program implementation. For example, implementation step #2 requires the determination of asset performance and failure modes. Because of stringent FAA regulations, airfield lighting equipment is standard among airports (FAA, 2018a). Therefore, once an airport completes these analyses, they could share the information with others to avoid repeating the work. However, airports are also vastly different due to local environmental conditions.

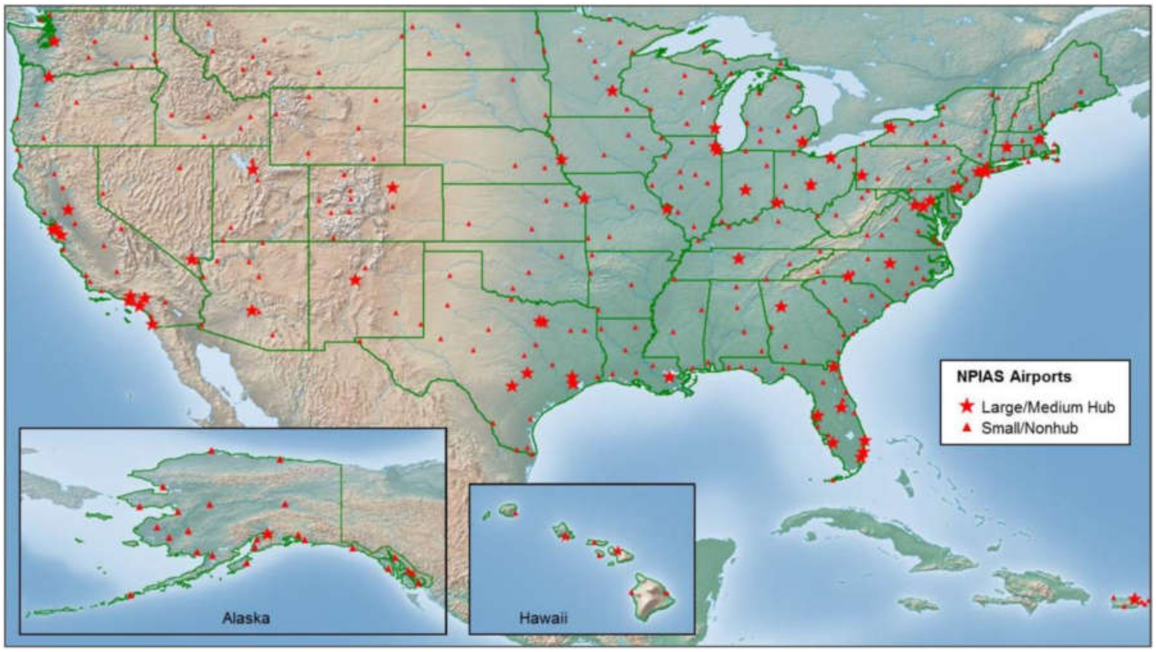
The Diversity of Airports

The analysis results show that a senior airfield lighting maintenance (ALM) manager with experience at small airports in hot and dry climates will find many differences in maintenance practices compared to large airports in cold and wet locations. Figure 3 illustrates the dispersed locations of U.S. primary commercial service airports.

Making important maintenance strategy decisions for an airport requires input from trained staff with experience at that airport or a similar one.

Figure 3

NPIAS Primary Airport Locations



Note. Taken from the Report to Congress National Plan of Integrated Airport Systems (NPIAS) 2017-2021, Figure 3, p. 4. The map illustrates the wide range of geographic locations of primary airports within the NPIAS. In the public domain.

The same FAA maintenance requirements apply to the single-runway Key West International Airport with 54,729 total annual operations in 2018 and the seven-runway Chicago O'Hare International Airport with 903,707 operations (FAA, 2014a; FAA, 2019a). Localized airfield lighting maintenance (ALM) programs adjust for these differences while following standard Part 139 operational and lighting system performance criteria (FAA, 2014a). Understanding the nature of the similarities and differences of ALM programs among airports requires understanding the system design and the unique maintenance hazards.

Statement of the Problem.

The lack of guidance for shop-level implementation of asset management programs presents a literature gap. Specifically, existing guidance and training programs focus on technical rather than management skills. Even though maintenance managers gain expertise through years of experience, those years are often obtained at a single airport, limiting exposure to multiple maintenance options. Asset management requires maintenance managers to compare alternatives to current practices to improve their programs. Conducting this comparison requires an understanding of a variety of proven maintenance practices.

Previous ACRP research describes airport organizations' implementation practices without providing specific guidance for modifying maintenance programs at the shop level (ACRP, 2012a). Another ACRP study research team interviewed lighting maintenance staff at several airports to better understand how their maintenance practices changed following upgrades to new LED technology (ACRP, 2015a). However, neither study provides sufficient guidance to managers to optimize their maintenance programs and minimize asset system life-cycle costs. The results of this study will help maintenance managers better understand the local factors that affect key decisions, such as the selection of the maintenance strategy to be used with each asset.

Purpose Statement

The research objective was to interview the airport maintenance management staff from various environmental and operational environments and document how each organization addresses the common challenges within airfield lighting maintenance. Using this data, the researcher learned fundamental factors influencing local maintenance decisions and identified the ALM practices common to all airports. The data analysis enabled the construction of a substantive theory of ALM management strategy selection developed from the practices described by the participants. Additionally, this theory can serve as the basis for developing a quantitative tool to augment the intuitive methods used for maintenance strategy selection decisions.

Significance of the Study

Creating a theory of airfield lighting maintenance strategy selection based on the input of a wide range of airport maintenance staff will provide a generalized understanding of the characteristics of airports affecting strategy selection. In addition, documenting the theory allows one to examine it to find improvements. One possible improvement is to develop a quantitative decision-making tool using expert input applied to the new theory and used to develop recommendations for maintenance managers. This model for theory construction and improvement could also be applied to other specialized asset systems, such as baggage handling or aircraft fuel distribution. Such a tool could recommend maintenance strategy alternatives and assist managers with finding optimal strategies.

The theory constructed from the data collection and analysis lists the primary factors affecting maintenance strategy selection and the commonly used strategies for airfield lighting. Maintenance managers can evaluate how these factors influence their local maintenance program, determine which factors are inside and outside their control, and then develop action plans to improve their programs. In addition, managers can use the research results to help justify program changes by showing how they impact factors that influence maintenance or by showing that other airports already use a similar alternative maintenance strategy.

Research Questions

The research questions for this study are as follows:

1. What factors affect the selection of airfield lighting maintenance strategy?
2. What airfield lighting maintenance strategies are currently used by U.S. commercial service airports?
3. What processes do airports use to select their airfield lighting maintenance strategies?
4. How do airports evaluate the success of their airfield lighting maintenance?

Delimitations

The target population for this research includes 380 US primary commercial service airports defined by 49 U.S.C. §47102(7) as a public airport in a State that the Secretary determines has at least 10,000 passenger boardings each year (FAA Authorization Act of 1994). The research assumes that a higher number of annual operations correlates with larger and more complex airfield lighting systems, more considerable wear on light fixtures, and more limited access for maintenance.

This study only addresses the airfield lighting equipment maintained by the airport staff. Radio navigation aids such as instrument landing systems and runway approach lighting systems are considered air navigation facilities usually owned, operated, and maintained by FAA personnel. The research excludes these systems because radio navigation aids are equipment outside the responsibilities of the airport maintenance staff.

The population of airports evaluated by this research does not include military-only airfields but does include joint-use airfields which would employ non-military staff to perform airfield maintenance. The U.S. military guidance documents are distinct from the FAA (Air Force Civil Engineer Center, 2018). The military conducts training in airfield lighting maintenance for staff for military airfields (Department of the Air Force, 2015). However, the research population includes joint-use airports. According to Appendix J-1 of the FAA Order 5190.6B *FAA Airport Compliance Manual*, the standard template for joint use agreements calls for the airport authority to maintain airfield lighting systems, not the military organization (FAA, 2009).

Limitations and Assumptions

The theory generated by using the research will describe the common current practice for selecting ALM management strategies used by U.S. primary commercial service airports. The theory will not explain how to find the best strategy. The current lack of common KPIs for airfield lighting maintenance management inhibits comparing performance between airports. The research results list the most common KPIs used by ALM management staff.

The telephone interview was the only data collection method used. Archival documents are also a data source often used in grounded theory research (Charmaz, 2014). The FAA requires that airfield lighting maintenance staff keep records documenting maintenance effectiveness (FAA 2014a). However, a lack of standardization complicates data comparison between airports. The interviewer documented the most common types of maintenance records currently maintained.

The researcher conducted semi-structured interviews with representatives from an initial sample of six airports, guided by the grounded theory research method and the *emerging theory* (Glaser & Strauss, 1967). The total sample size of airports selected depends on reaching data saturation (Aldiabat & Le Navenec, 2018). The researcher achieved data saturation after analyzing transcripts from interviews with 23 persons at 15 airports, including the initial six sample airports.

Summary

Asset management programs describe an approach that airport managers can use to improve maintenance management efficiency and reduce airport operating expenses. However, existing guidance requires airports to determine the program implementation requirements within each asset maintenance shop. The technical experts needed to develop these program details are within the airport maintenance staff; however, they may have limited exposure to alternative maintenance programs. By interviewing airfield lighting maintenance experts from a wide range of airports, a common theory of ALM strategy selection can be constructed and used to improve the understanding of criteria affecting critical decisions, alternative strategies, and key performance indicators.

Definitions of Terms

Airport/Aerodrome — An area of land or water used or intended for landing or takeoff of aircraft, including the appurtenant area used or intended for airport buildings, facilities, as well as rights-of-way together with the buildings and facilities (FAA,

	2019b, International Civil Aviation Organization [ICAO], 2018).
Airfield	For purposes of this study, the term is the same as the Airport Operations Area (AOA), which includes “paved or unpaved areas used or intended to be used for the unobstructed movement of aircraft, in addition to its associated runways, taxiways, or aprons. The term commonly refers to anything within the secured and fenced-in area of the airport” (FAA, 2015, p. B-2).
Asset	“An item, thing, or entity that has potential or actual value to an organization” (Institute of Asset Management, 2015, p. 8).
Asset Management	“The coordinated activity of an organization to realize value from assets” (Institute of Asset Management, 2015, p. 8).
Benchmark	“A standard measurement or reference that forms the basis for comparison. This performance level is recognized as the standard of excellence for a specific business process” (Gulati, 2021, p. 4).
CAT I (Category I)	An instrument approach operation with a minimum descent altitude (MDA), decision altitude (DA), or decision height (DH) not lower than 200 feet (60 m) and with either a visibility not less than ½ SM, or a Runway

	Visual Range (RVR) not less than 1800 feet (550 m) (FAA, 2018c, p. A1-1).
CAT II (Category II)	A precision instrument approach operation with a DH lower than 150 feet but not lower than 100 feet (30 m) and an RVR not less than 1000 feet (300 m) (FAA, 2018c, p. A1-1).
CAT III (Category III)	A precision instrument approach or approach and landing with a DH lower than 100 feet (30m), or no DH, or an RVR less than 1000 feet (300 m) (FAA, 2018c, p. A1-2).
Corrective Maintenance	"activities undertaken (or repair actions taken) as a result of observed or measured conditions of an asset after or before the functional failure. These repair actions will restore the asset to normal operating conditions" (Gulati, 2021, p. 73).
Infrastructure, Airside	"accommodates the movement of aircraft around the airport and includes such things as aircraft parking aprons, taxiways, airfield lights and signs, navigational and visual aids, and runways" (ACRP, 2015c, p. 7).
Infrastructure, Landside	"accommodates the movement of ground-based vehicles and passengers and includes such things as access roads, parking lots, garages, aviation- and non-aviation-related businesses, support buildings, and terminal buildings" (ACRP, 2015c, p. 7)

Key Performance Indicator	"quantitative or qualitative indicator of the quality of service, efficiency, productivity, or cost-effectiveness of an agency, program, or activity that enables a comparison to be made for management purposes of performance against a standard target or norm" (ACRP 2012a, p. 107).
Life-Cycle Cost	"sum of all recurring and one-time costs over the full lifespan or a specified period of an asset under consideration" (ACRP 2012a, p. 107).
Maintenance	"Keep in 'designed' or an acceptable condition. Keep from losing partial or full functional capabilities. Preserve, protect … includes tasks performed to prevent failures and tasks performed to restore the asset to its original condition" (Gulati, 2021, p. 70).
Maintenance Strategy	"a systematic approach to upkeep facilities and equipment … It involves identification, researching, and execution of many repair, replace, and inspect decisions and is concerned with formulating the best life plan for each unit …" (Velmurugan & Dhingra, 2015, p. 1626).
Multi-Criteria Decision-Making (MCDM)	"MCDM approach consists of a finite set of alternatives (e.g., maintenance strategies) among which a decision-maker has to select or rank, and a finite set of criteria (economic, social, environmental, etc.) weighted

	according to their importance. First, each alternative is evaluated with respect to each criterion using a suitable measure. Then, the evaluation ratings are aggregated to obtain a global evaluation for each alternative. Finally, the alternatives are prioritized from the best (optimal) to the worst" (Shafiee, 2015, p. p.379).
Preventive Maintenance	"activities involved in systematic, planned inspection and component replacement, at a fixed interval, regardless of the asset's condition at the time" (Gulati, 2021, p. 74).

List of Acronyms

AAA	Australian Airports Association
AAAE	American Association of Airport Executives
AC	Advisory Circular
ACE	Airport Certified Employee
ACM	Airport Certification Manual
ACRP	Airport Cooperative Research Program
AFL	Airfield Lighting
AHP	Analytic Hierarchy Process
AIP	Airport Improvement Program
ALM	Airfield Lighting Maintenance
ALS	Approach Lighting System
ALSF	Approach Lighting System with Sequenced Flashing Lights
ANP	Analytic Network Process

ARFF	Aircraft Rescue and Fire Fighting
ATADS	Air Traffic Activity System
ATCT	Air Traffic Control Tower
AVI	Automatic Vehicle Identification
BPI	Building Performance Indicator
CAT	Category
CAQDAS	Computer-Assisted Qualitative Data Analysis Software
CBM	Condition-Based Maintenance
CFR	Code of Federal Regulations
CGT	Constructivist Grounded Theory
CM	Condition Monitoring
CMMS	Computerized Maintenance Management System
CSCW	Computer-Supported Cooperative Work
DOE	Department of Education
EB	Engineering Brief
EFVS	Enhanced Flight Vision System
ELECTRE	Elimination and Choice Translating Reality
EPA	Environmental Protection Agency
EVS	Enhanced Vision System
FAA	Federal Aviation Administration
FMECA	Failure Mode, Effects, and Criticality Analysis
GAO	General Accounting Office
GIS	Geographical Information System

GP	Goal Programming
GPS	Global Positioning System
HCI	Human-Computer Interaction
HSESI	Health, Safety, and Environmentally Significant Item
HIRL	High Intensity Runway Lighting
IAM	Institute of Asset Management
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
IoT	Internet of Things
IPRF	Innovative Pavement Research Foundation
IRR	Inter-Rater Reliability
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LAHSO	Land and Hold Short Operations
LCC	Life-Cycle Cost
LED	Light Emitting Diode
LOS	Level of Service
MPI	Maintenance Performance Indicator
MCDM	Multi-Criteria Decision-Making
MSS	Maintenance Strategy Selection
NFPA	National Fire Protection Association
NOAA	National Oceanic and Atmospheric Administration
NOTAM	Notice to Airmen

NPIAS National Plan of Integrated Airport Systems

NVG Night Vision Goggles

PAPI Precision Approach Path Indicator

PdM Predictive Maintenance

PI Performance Indicators

PFC Passenger Facility Charge

PM Preventive Maintenance

PROMETHEE Preferred Ranking Organization Method for Enrichment of Evaluations

RCM Reliability-Centered Maintenance

RFID Radio Frequency Identification

RSA Runway Safety Area

RUL Remaining Useful Life

RTF Run-To-Failure

RVR Runway Visual Range

RWCL Runway Centerline Light

RWSL Runway Status Lighting System

SAW Simple Additive Weighting

SMGCS Surface Movement Guidance and Control System

SMS Safety Management System

TDZ Touchdown Zone

TOPSIS Technique for Order of Preference by the Similarity of Ideal Solution

TPM	Total Productive Maintenance
TQM	Total Quality Maintenance
VDGS	Visual Docking & Guidance System
VIKOR	Višekriterijumsko Kompromisno Rangiranje (Multi-Criteria Compromise Ranking)

Chapter II: Review of the Relevant Literature

Constructivist Ground Theory and the Literature Review

Traditional GT methodology does not support literature reviews before beginning research because immersing oneself in the literature could cause preconceived notions about an emerging theory (Glaser, 1967). While Glaser did not feel that researchers should approach their subject as a *tabula rasa*, he argued that the researcher's input would drop out as eccentric when using the appropriate research methods (Ramalho et al., 2015). However, various authors have contested the suggestion that the researcher's influence on the product could be successfully purged, particularly in qualitative research (Flick, 2014; Breuer et al., 2002; Goodman, 1978).

CGT methodology considers that the researcher's influence cannot be divorced from the results (Charmaz, 2014). The theory's groundedness "results from these researchers' commitment to analyze what they actually observe in the field or in their data" (Charmaz, 1990, p. 1162). In contrast to traditional grounded theory, the researcher does not discover a theory from the data but constructs a theory from the data (Ramalho et al., 2015). Thornberg (2012) recommends using an initial literature review as a source of inspiration or ideas while maintaining the *theoretical agnosticism* described by Henwood and Pidgeon (2003).

A review of the literature found research describing theories for selecting maintenance management strategies for various facility types but not strategies for airports or airfield lighting. Therefore, the literature review in this chapter examines current research related to airfield lighting and airport electrical maintenance staff and does not review other theories of maintenance strategy selection. This examination of current airfield lighting research guided the development of the research questions, the interview topics, and the interview questions. Additionally, this chapter includes a description of grounded theory research and why this methodology is most suitable to achieve the research goals.

After developing a theory for airfield lighting maintenance management strategy selection, the researcher examined studies of maintenance strategy selection in other industries to develop the theoretical framework and locate the constructed theory in the current literature. This second review is located at the beginning of chapter five.

Airfield Lighting Maintenance and Management Research

Airport Maintenance Management

Advisory Circular (AC) 150/5340-26C, *Maintenance of Airport Visual Aids* defines the purpose of the maintenance management system as "to ensure the maximum availability of any given system at a minimum cost in man-hours or funds" (FAA, 2014a, p. 23). The AC intends "to provide minimum maintenance procedures required for safe and efficient aircraft movement during takeoff, landing, and taxiing operation" (FAA, 2014a, p. 23). The AC supplies safety guidance, describes the requirements of a maintenance management program, lists recommended equipment, supplies recommended maintenance schedules, and lighting system troubleshooting procedures but does not discuss asset management programs. The AC describes the frequency of operations as one factor affecting maintenance strategy. Airports with a more substantial number of daily operations and also rely heavily on low visibility operations should maintain a more abundant supply of spare parts (FAA, 2014a).

The Transport Canada advisory circular for airfield lighting maintenance explicitly states that the maintenance procedures included in the document provide "an example of an acceptable means, but not the only means, of demonstrating compliance with regulations and standards" for maintenance (Transport Canada, 2015, p. 3). The Transport Canada advisory circular outlines a preventive maintenance program like the one described in the FAA advisory circular (AC). The program includes specific scheduled inspections and maintenance and describes procedures for performing specialized tasks.

The Australian Manual of Standards for Aerodromes (Australian Government, 2017) extensively describes the design and installation of airfield visual aids. However, the document only supplies maintenance performance objectives, and there is no discussion specifically about the maintenance program. The Australian Manual also includes requirements for maintaining the grounds around the visual aids to keep grass from blocking fixtures. The industry-run Australian Airports Association (AAA) published guidance by supplying a 120-page technical information supplement describing airfield lighting theory, equipment, safety, and practical examples of calculations and checklists (Steuten, 2016). In addition, a two-page chapter on serviceability stresses the importance of record-keeping, recommends numbering light fixtures, and recommends training.

Airport self-inspection programs are a statutory part of the operation of airports certified under 14 CFR Part 139 (FAA, 2014c). The FAA advisory circular for safety self-inspections specifically lists airfield lighting as one of the primary focus areas (FAA, 2014c). The advisory circular requires regular performance tests and condition inspections of signs, lighting, and visual navigation aids (FAA, 2014c). Conditions such as severe rain or snowstorms may require condition inspections of lighted signs and the Surface Movement Guidance and Control System (SMGCS). SMGCS provides “guidance to, and control or regulation of, all aircraft, ground vehicles, and personnel on the movement area of an aerodrome.” (FAA, 1996, pp. 3-4). The FAA recommends using an SMGCS when conducting air carrier operations where visibility is less than 1,200 feet Runway Visual Range (RVR) (FAA, 1996). Portions of the airfield lighting system are components of the SMGCS equipment (FAA, 1996).

The Innovative Pavement Research Foundation (IPRF) published an FAA-funded report supplementing the FAA advisory circular for designing and installing in-pavement lighting (IPRF, 2008). However, compliance with these industry recommendations is not mandatory, nor is the IPRF publication referenced in FAA lighting design or maintenance advisory circulars (FAA, 2014a, FAA 2018a). Insufficiently robust installation of in-pavement fixtures can result in degraded visual guidance resulting from aircraft wheel impacts on the fixture and reduce the life of the surrounding pavement (IPRF, 2008). Since repairing such damage is the responsibility of the airfield lighting and pavement maintenance staff, they can benefit from establishing practices to ensure that new installations follow industry best practices and not merely minimum FAA standards. ACRP guidance for asset management recommends considering the system lifecycle cost during the design stage (ACRP, 2012a); however, the FAA advisory circulars do not refer to the lifecycle cost considerations for designing or maintaining airport visual aids (FAA, 2014a; FAA, 2018a).

The ACRP sponsored a survey of 44 airports entitled ACRP Report 148, *LED Airfield Lighting System Operation and Maintenance* (ACRP, 2015a). In addition to the survey, the study also included case study interviews with 10 airports. The results of this report noted that the current maintenance documentation for Airfield Ground Lighting (AGL) fixtures outlines procedures for incandescent light fixtures, but 49% of airports have set up a different maintenance schedule for LED fixtures. The report also said individual airports rarely carry over established policies to other locations resulting in isolated solutions not scrutinized by the industry. This observation corroborates the earlier argument that the lessons learned by airfield lighting maintenance staff are rarely shared. The report provides best practices for airfield electrical maintenance staff at airports with LED fixtures and signs.

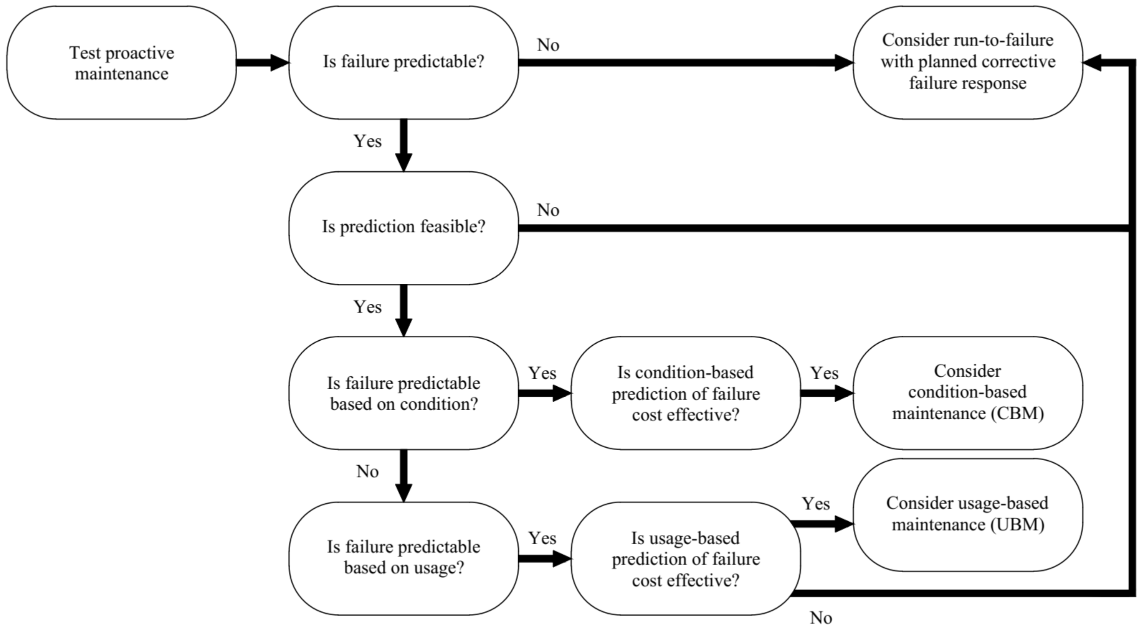
The ACRP published Report 69, *Asset and Infrastructure Management for Airports: Primer and Guidebook* (ACRP, 2012a), to help airports implement asset and infrastructure management programs. Evidence from other industries shows that asset management programs can help do more with less, help guide better investment decisions, align managers to everyday purposes, and improve flexibility (ACRP, 2012a). Part 1 of Report 69, the primer, describes reasons to implement an asset management strategy, how the program works, and how to implement a program (ACRP, 2012a). Part 2 of Report 69, the guidebook, supplies step-by-step instructions for developing an asset management plan, resourcing and staffing, and training the asset management organization (ACRP, 2012a). Program implementation according to ACRP guidance includes the 10-step process shown in Figure 1. The choice of the optimum maintenance strategy is part of the seventh step. The report describes the five actions listed below for finding the best maintenance strategy (ACRP, 2012a, p. 62).

- Using a spreadsheet analysis for business risk exposure from Step 6, name the critical assets by their high risk-exposure scores.
- For all critical assets, apply the decision process in Figure 4 to find the best maintenance strategies.
- Find the maintenance tactics associated with each strategy and estimate percentage impacts on the maintenance budget.
- Review maintenance programs and contract agreements to determine the impacts of changes to maintenance strategy.
- Add the projected maintenance cost to the asset management plan investment requirements.

Survey data collected as part of the ACRP research showed that six percent of respondents said they only performed reactive maintenance for airport maintenance. In comparison, “46 percent stated that their maintenance was somewhat proactive but mostly reactive” (ACRP, 2012a, p. 61).

Figure 4

Decision Diagram for Determining a Maintenance Strategy other than Preventive Maintenance



Note: Adapted from *ACRP Report 69 Asset and Infrastructure Management for Airports: Primer and Guidebook* (p. 62), by the Airport Cooperative Research Program, Washington, DC: Transportation Research Board. Copyright 2012 by National Academy of Sciences. Reprinted with permission.

Sheng et al. (2012) suggest that many light units in a typical airfield lighting system (approximately 440 for a Category I runway and approach lighting system) force the staff to perform reactive maintenance. The researchers stated that reliability analysis could help airports transition to a predictive maintenance program. Sheng et al. (2012) describe a typical airfield lighting system model using a fault tree illustrating how the individual component reliabilities contribute to the overall potential for system failure. Maintenance policy defines failure as non-compliance with standards for the minimum number of fixtures to be burning. The model assumes maintainers carry out no maintenance or repair over a 30-day period, which they admit is unlikely. Sheng et al. (2012) use this model to illustrate how to assess and use the reliability of the distinct subsystems of airfield lighting (e.g., approach lights, runway edge lights, runway centerline lights) to analyze business risk in the preparation of asset management programs. Sequenced flashers had the highest probability of failure in the model. Using a similar method, airport staff could more accurately determine the likelihood of failure of a given airfield lighting sub-system using the actual number of components in their subsystem and the estimated life specific to the manufacturer of that component. The likelihood of failure is a measure used to help find target levels of service and the business risk calculation (ACRP, 2012a). Interview questions included asking how airport maintenance staffs currently estimate the likelihood of failure of airfield lighting sub-systems at their airports.

In addition to advisory circulars, the FAA has supplied airfield lighting maintenance guidance using engineering briefs and alert notifications (FAA, 2014c; FAA, 2018b). For example, a certification alert (CertAlert) in 2014 followed an incident where “a departing air aircraft dislodged an in-pavement light fixture, causing significant damage to the aircraft” (FAA, 2014c, p. 1). In this case, the FAA issued the CertAlert as a reminder to airport lighting maintenance staff to ensure the correct installation of bolts for in-pavement light fixtures and to perform routine checks as already described by the FAA advisory circular for visual aids maintenance (FAA, 2014a). In addition, FAA Engineering Brief (EB) 83A supplied more mandatory guidance for using steel or coated carbon steel bolts for in-pavement light fixtures. For example, the visual aids maintenance advisory circular requires obtaining bolt torque criteria from the light fixture manufacturer (FAA, 2014a). EB 83A supplemented this requirement by providing procedures for calculating torque requirements based on the governing aircraft. In addition, the document recommends using electric or air-driven wrenches with dial-type torque settings by airfield lighting maintenance staff. These other guidance tools explain how to perform maintenance but do not address maintenance management.

Airport Electrician Workforce

In November of 2016, the ACRP published Project 06-04 *Identifying and Evaluating Airport Workforce Requirements* based on survey input from 746 airport stakeholders with the goal to:

> identify the specific industry trends, challenges, and future scenarios that present the greatest impact to the airport industry; document the current workforce capacity and anticipated requirements in those occupations most critical to the future of the industry; and evaluate the current airport education, training, and development landscape against these requirements. (ACRP, 2016a, p. 6)

ACRP Project 06-04 listed electricians as one of three occupations critical to airports and indicated an expectation that electricians will have the highest increase in employment across all industries from 2014-2024 (ACRP, 2016a). One hundred percent of airport respondents said, “there are significant costs/challenges when electricians make errors” (ACRP, 2016a, p. 45). However, respondents indicated roadblocks to filling airport electrician positions, including a small applicant pool; a highly specialized skillset; high competition across industries; risk of a vacancy; insufficient skill sets, knowledge, and interest in the labor market; and a lack of talent in existing airport employees (ACRP, 2016a). In addition, shortfalls exist in current programs for the training and education of airport electricians (ACRP, 2016a). The survey found that "most airport electricians and other maintenance personnel receive the majority of their training through non-aviation specific programs, and the research team did not identify training or education that focused specifically on developing electricians for airport careers" (ACRP, 2016a, pp. 94-95). Despite an estimated 14% increase in employment opportunities for electricians from 2014 to 2024, more than 60% of the US workforce was over the age of 45 in 2013, and "overall, a shortage of electricians is anticipated across industries, including airports" (ACRP, 2016a, p. 174).

Airfield Lighting Maintenance Training

Airport training and education programs are widely available in academic degree programs, technical training programs, leadership development programs, certification programs, and educational/industry partnerships (ACRP, 2016a). However, ACRP researchers could not find training or education programs specifically for developing airport electricians and engineers (ACRP, 2016a). Most airport electricians and engineers receive their training through non-aviation-specific programs and on the job (ACRP, 2016a). Some airport-specific airfield lighting training is available from industry organizations such as the American Association of Airport Executives (AAAE) Airport Certified Employee (ACE) program (AAAE, 2014; AAAE, 2016; AAAE, 2019) and directly from engineering and maintenance seminars taught by airfield lighting equipment manufacturers (Safegate, 2019a; Eaton, 2019).

Computerized Maintenance Management Systems (CMMS)

In 2018, the ACRP published a guide to help airport managers implement CMMS while integrating asset management programs and decision-making processes (ACRP, 2018). CMMS enhances the airport manager's ability to:

- "classify and group assets logically to achieve various levels tracking;
- define and measure levels of service (LOS);
- produce high quality, reliable data;
- track KPIs;
- and generate meaningful reports" (ACRP, 2018, p. 2).

Using this data, airport managers and executives can (a) improve business decisions involving the accurate timing of asset renewal or replacement, (b) create data-driven short and long-term budgets, (c) more accurately assess the total cost of ownership, (d) better understand asset condition and performance, and (e) more efficiently optimize the customer experience (ACRP, 2018).

Best practices for facility maintenance recommend doing no more than 25% of maintenance on a corrective/reactive basis. Nevertheless, airport managers report performing corrective maintenance as much as 75% of the time (ACRP, 2018). In addition, improved tracking of historical maintenance data allows airport maintenance staff to transition into a Reliability Centered Maintenance (RCM) program, which predicts failures and recommends proactive measures.

CMMS can help airports perform facility maintenance more efficiently by supplying a "single data repository for maintenance and asset management strategy implementation and reporting" (ACRP, 2018, p. 2). A survey of 25 airports asked which asset systems CMMS manages (ACRP, 2018). Electrical systems ranked highest. Runway lighting ranked fifth. Many airports integrate their CMMS with other automated systems (ACRP, 2018). Marks and Rietsema (2014) list six airside information management systems commonly in use by airport staff: gate management systems, aircraft fueling systems, Air Traffic Control (ATC) systems, weather monitoring systems, airfield lighting systems, and Automatic Vehicle Identification (AVI) systems. Airfield lighting control systems allow air traffic controllers and maintenance staff to control and monitor the individual areas of the lighting system. These systems can supply an automatic notification in fixture failure or other equipment problems (Marks & Rietsema, 2014). Airfield lighting is among the top five systems airports choose to integrate with CMMS (ACRP, 2018). The researchers performed five airport case studies, and runway lighting was one of the top six asset systems prioritized for integration with CMMS (ACRP, 2018).

Weather Impacts on Airfield Lighting Maintenance

In 1970, a team from the FAA visited nine airports to learn about existing snow removal practices to appreciate the factors that influence purchasing and deployment decisions and derive an approach for analysis of alternative systems (FAA, 1970). Clearing runway centerline lights was a complex problem at most airports. Researchers found that the risk of damage to runway centerline lighting and touchdown zone lights affected snowfall operations and equipment. In addition, the formation of ice around centerline lights, called *igloos*, was a severe problem at four airports because they created a hazard to airport operations. At all airports in the study, snow removal and ice control staff included the ALM staff.

Snow removal research by the FAA shows that light fixture damage is typical during snow removal operations (FAA, 1970; FAA, 2014a; ACRP, 2015b). In some cases, snow removal operations require the aid of airfield electricians (FAA, 1970; ACRP, 2015b). Alternatively, airfield electricians may follow the snow removal operations to rapidly repair damaged fixtures before friction testing (ACRP, 2016b). Each approach to employing electricians during snow removal operations may affect the lighting maintenance strategy. The FAA advisory circular for airfield lighting maintenance lists several added tasks needed because of snowfall:

- Conduct fixture damage checks immediately after snow removal operations.
- Install red flags next to fixtures to help them get noticed by snowplow operators.
- Remove snow from fixture lenses to avoid obscuration.
- Inspect cables installed in shallow pavement trenches, *saw kerfs,* to determine if the plow pulled out the cable (FAA, 2014b).

In addition, the buildup of ice and snow may freeze fixture bolts in place, requiring heating of the fixture and bolts before removal of the fixture is possible (FAA, 2014b). Therefore, airports with high average annual snowfall have different working conditions than airports with low average yearly snowfall. As a result, high and low-average airports are included in the initial research sample to find a broader range of maintenance management strategies.

The ACRP-published guidebook for winter operations explains that airports' maintenance staff should examine the cost-benefit of removing snow from in-pavement fixtures to support operations and the expenses necessary to protect the fixtures (ACRP, 2015b). Airports may be unable to use more effective steel snowplow blades in areas with in-pavement lights. The amount of damage to the airfield lighting and signage system may also be a performance indicator for the success of the snow removal operation as it can show the level of equipment operator situational awareness and training. Other options include using polyurethane blades or casters on the snow blade to elevate it above the light fixture. In-pavement lights invite compacted snow. Chemicals may be necessary to remove compacted snow from in-pavement light fixtures, but chemicals may also damage the fixture and underground electrical components.

Grounded Theory

Glaser and Strauss (1967, p.1) describe grounded theory research as the inductive "discovery of theory from data – systematically obtained and analyzed in social research." Grounded theory research contrasts with deductive research, which begins with *a priori* assumptions. Glaser and Strauss describe theoretical sampling as selecting samples based on the results of previously analyzed data. The researcher selects the initial sample based on a general perspective, subject, or problem area (Glaser & Strauss, 1967).

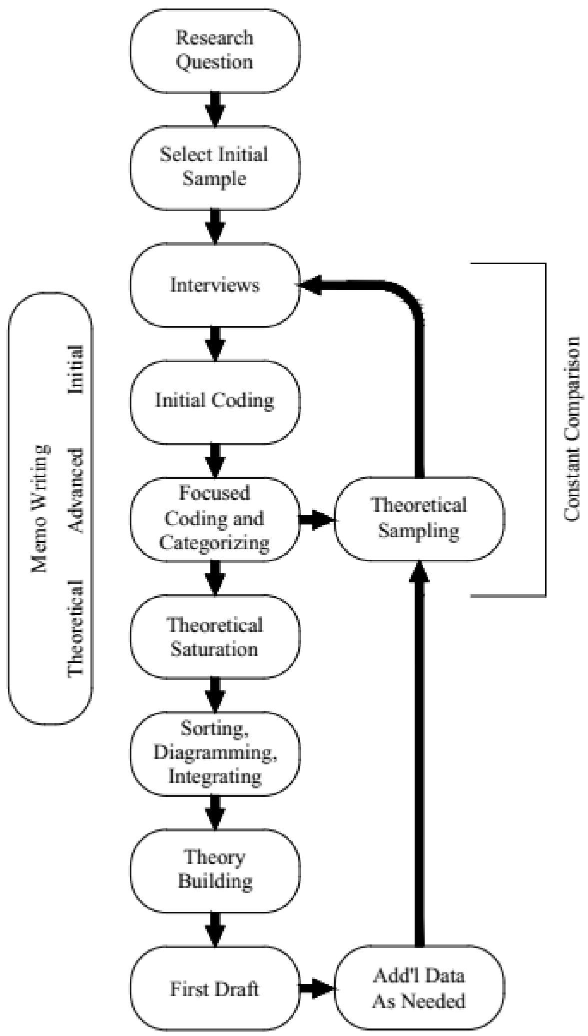
Locke (2001) wrote about grounded theory in management research after feeling that organization and management scholars cited a limited range of literature on grounded theory. Some researchers combined the practices of other qualitative analytic styles with grounded theory. Locke (2001) details the original grounded theory approach articulated by researchers for the past 30 years and describes the use of grounded theory in organization and management research for the past 30 years.

In her book on grounded theory, Goulding (2002) supplies a critical review of the grounded theory methodology. The method can fail to generate theory, particularly if the researcher does not establish clear research boundaries and ensure that the data collected focuses on the critical research questions (Goulding, 2002). Failure to do so may result in a wealth of unusable data for theory (Goulding, 2002). The researcher must also understand and apply theoretical sensitivity to avoid generating too many categories from which relationships become confused (Goulding, 2002). Strauss and Corbin (1990) introduced a structured coding process for the grounded theory method that emphasized conditions, context, action/interaction strategies, and consequences in later years. However, Glaser argued that applying these techniques overemphasizes mechanics at the expense of theoretical sensitivity (Goulding, 2002). Goulding (2002) describes multiple examples of researchers incorporating portions of the grounded theory method without a comprehensive approach, claiming to use grounded theory when using a different qualitative approach or incorporating quantitative measures such as random sampling or validity statistics. While nothing prohibits the use of mixed methods research, the purpose and procedures should be made clear (Goulding, 2002). This study uses a comprehensive research method based on Constructivist Grounded Theory (CGT) developed by Charmaz (2006) and does not employ a mixed-method approach.

Charmaz (2006) supplies a practical guide for constructing grounded theory. Figure 5 illustrates the research process. Building upon earlier work by Glaser and Strauss (1967), Charmaz (2006) supplies strategies and guidelines for executing grounded theory research based on her interpretation of the method. In addition, the book includes a summary of the evolution of grounded theory, explicitly noting how Strauss came to incorporate new research procedures that Glaser contended forced data and analysis into preconceived categories (Charmaz, 2006). Finally, Charmaz describes a research approach that includes basic grounded theory guidelines with modern methodological assumptions and practices (Charmaz, 2006).

Figure 5

The Grounded Theory Research Process



Note. Adapted from *Constructing grounded theory: a practical guide through qualitative analysis* (p. 11) by K. Charmaz, 2006 London, UK: Sage Publications. Copyright 2006 by Kathy Charmaz.

Aldiabat & Le Navenec (2018) examined the concept of data saturation in grounded theory to help novice researchers decide on the appropriate sample size. Hennick et al. (2016) differentiate between *code saturation* and *meaning saturation*. Researchers achieve code saturation when they have “heard it all” (Hennick et al., 2016, p. 605), but meaning saturation is needed to “understand it all” (Hennick et al., 2016, p. 605).

Alshenqeeti (2014) performed a literature review of interview methods, supplied a critical evaluation of interview research, and discussed ethical issues. The research highlights that interviews can supply a detailed account of individuals and events, allowing the analysis of constructs that are often not directly ‘observed.’ Also, the goal of the interview is to gain an interpretation of phenomena from the subject's perspective. The qualitative researcher performs an in-depth analysis of the meanings that subjects bring to the studied phenomena. Alshenqeeti (2014) describes four interview methods: structured, open-ended, semi-structured, and focus group. Structured interviews are predetermined questions with yes/no types of responses. Open-ended interviews supply more flexibility to the interviewer and the interviewee in the planning and execution of the interview than the structured type. Follow-up with interviewees may be needed to clarify specific issues. Semi-structured interviews start with a standard list of questions. This method allows the interviewer to probe the interviewee on their responses while staying within a set of boundaries. Focus groups are created from purposive rather than random groups. They can be challenging to implement and allow the researcher to quickly gather valuable data on complex topics. The intimacy of an interview sometimes becomes a quasi-therapeutic relationship that may result in the subject disclosing information they later regret. Therefore, the interviewer should tell the subject that their participation is voluntary and that the collected data should remain confidential.

McDonald et al. (2019) investigate the use and applicability of Inter-Rater Reliability (IRR) measures to assess the level of agreement between multiple coders in qualitative research. *Coding* refers to examining data and assigning descriptive text to that section. McDonald et al. (2019) develop guidelines for deciding when seeking agreement amongst multiple coders and using IRR measures in coding qualitative data are appropriate. They say, "Grounded theory rarely, if ever, requires IRR" (McDonald et al., 2019, p. 15). Assigning codes is merely an interim step in developing the theory, not a final result. Furthermore, agreement among multiple coders is rarely necessary when experts research within their specialty (McDonald et al., 2019).

Gaps in the Literature

The gap in the literature is the lack of theoretical guidance for airfield lighting maintenance management suitable to construct a maintenance program using asset management practices. Existing ACRP research addresses implementing airport-wide asset management and preventive maintenance programs (ACRP, 2012a; ACRP, 2015c). In addition, FAA advisory circulars and industry training courses help airfield electricians learn the technical skills necessary to safely and efficiently maintain and repair their systems. However, the specialized nature of airfield lighting maintenance and separation of airport organizations limit the ability of practical lessons to be shared among managers. A range of strategies and monitoring tools exist from which maintenance managers can design their programs. Little guidance exists to assist managers in making these decisions.

The literature currently has no research addressing maintenance management strategy selection for airfield lighting. The ACRP primer and guidebook on asset management lack the necessary details for maintenance managers to implement the program at the shop level. Implementation requires creating asset inventories, performing failure analysis studies, researching and possibly implementing new maintenance strategies, installing new sensors on assets, modifying existing maintenance practices to collect and analyze data, and training staff on asset management software.

The goal of asset management to minimize asset life-cycle costs without increasing risk or sacrificing performance can apply to all airports. However, more guidance is needed to explain how to apply these practices within ALM. Furthermore, the currently published implementation procedures are most likely beyond the resources of many medium, small, and non-hub airports. A better understanding of shop-level implementation requirements may generate lower-cost implementation ideas or ways to share costs between airports.

Summary

This literature review followed Charmaz's (2014) recommendations to generate sources of inspiration and ideas for conducting the research. The post-analysis literature review included in chapter five examines the Multi-Criteria Decision-Making method and the evolution of maintenance strategy selection methods to explore processes in other industries that may be comparable to airfield lighting maintenance management. The later comparison provides a theoretical framework and highlights potential areas for further theory development.

Chapter III: Methodology

This chapter describes the research method selection, reviews the population and samples, and explains the interview data collection process. Because the research involves collecting personal information, this chapter also reviews the ethical considerations and discusses the intensive interviewing method of data collection. This discussion is followed by a detailed description of the constructivist grounded theory data analysis approach used in this research. Finally, this chapter discusses traditional measures of research quality, reliability and validity, and the four quality evaluation criteria recommended by Charmaz (2014): credibility, originality, resonance, and usefulness.

Research Method Selection

Because of the lack of existing research on this topic, this study uses an exploratory, qualitative research approach called Constructivist Grounded Theory (CGT) with data collected using telephone interviews. Grounded theory supplies the opportunity to generate theory through qualitative research (Glaser & Strauss, 1967). CGT diverges from the original method by discarding notions of a neutral observer and value-free expert (Charmaz, 2014). Creswell (2014) states that a constructivist worldview, or paradigm, uses the following assumptions: (1) people construct meanings as they engage with the world they are interpreting, (2) people engage with their world to make sense of it based on their historical and social perspectives, and (3) the basic generation of meaning is always social and arises out of interaction with the community. Locke (2001) referred to *constructivism* as an interpretive paradigm distinguished from others by an interest in developing an understanding of the world through the interpretations of the experiences of those living in it. "Knowledge and learning are not 'out there' to be captured or discovered; rather, knowledge is socially embedded and constructed (Crotty, 2003; Schwandt, 2000; Thorpe, 2008)" (as cited in Grandy, 2018, p. 5).

Population/Sample

Population and Sampling Frame

The target research population was the 380 Primary Commercial Service airports in the 2019 NPIAS (FAA, 2019a), not including Non-Primary Commercial, Reliever, and General Aviation airports. Table 1 explains the various airport categories and shows which airports are considered Commercial Service, Reliever, and General Aviation. Table 2 lists the quantity of each type of airport in the NPIAS. Airports with at least 2,500 annual passenger boardings supplied more data-rich interviews due to more extensive staff and facilities. However, the research results should remain generalizable to all 3,321 NPIAS airports since operating requirements and technical skills are the same. Sample airports were selected from the target population using the sampling strategy described later.

Table 1

Categories of Airport Activities

Airport Classifications		Hub Type: Percentage of Annual Passenger Boardings	Common Name
Commercial Service: Publicly owned airports that have at least 2,500 passenger boardings each calendar year and receive scheduled passenger service §47102(7)	**Primary:** Have more than 10,000 passenger boardings each year §47102(16)	**Large:** 1% or more	**Large Hub**
		Medium: At least 0.25%, but less than 1%	**Medium Hub**
		Small: At least 0.05%, but less than 0.25%	**Small Hub**
		Nonhub: More than 10,000, but less than 0.05%	**Non-Hub Primary**
	Non-Primary	**Nonhub:** At least 2,500 and no more than 10,000	**Non-Primary Commercial Service**
Non-Primary (Except Commercial Service)		Not Applicable	**Reliever** §(47102(23)) **Generation Aviation** §(47102(8))

Note. Federal Aviation Administration (2019). Airport Categories, Retrieved March 9, 2019, from https://www.faa.gov/airports/planning_capacity/passenger_allcargo_stats /categories/. In the public domain.

Table 2

Number of Airports in the 2019 National Plan of Integrated Airport Systems (NPIAS)

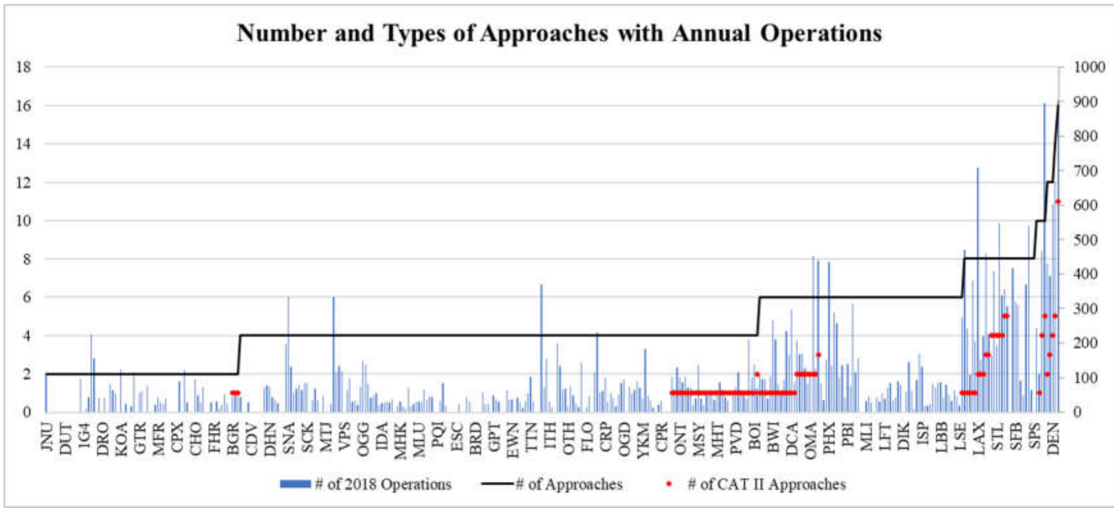
Airport Category	Number of Airports
Large Hub	30
Medium Hub	31
Small Hub	72
Primary Non-Hub	247
Total Population Size	380
Non-Primary Commercial Service	380
Reliever	261
General Aviation	2,554
Total 2019 NPIAS	3,321

Note. Federal Aviation Administration (2019). Appendix A: List of NPIAS Airports with 5-Year Forecast Activity and Development Estimate, Retrieved March 9, 2019, from https://www.faa.gov/airports/planning_capacity/npias/reports/media/NPIAS-Report-2019-2023-Appendix-A.pdf. In the public domain.

Figure 6 illustrates the range of airport sizes and complexity in the population by showing the number of approaches, the CAT II approaches, and the annual operations at each airport in the research population. For clarity, the Table does not show all airport codes. However, the data demonstrates that most airports within the population have four or six runway approaches with a small percentage of CAT II approaches. Airports with more than six approaches and over 350,000 annual operations represent a small portion of the population. Therefore, the challenges encountered at the largest airports may not be typical of those found at most airports. Similarly, the solutions used by airports with several hundred thousand annual operations may not be practical at airports with fewer than 200,000 annual operations because of fewer resources and different constraints.

Figure 6

Number and Types of Approaches with Annual Operations



Note. Created from the list of U.S. commercial service airports, analysis of ATAS data, and the Airport Facility Directory. The left vertical axis labels are for the number of approaches. The right vertical axis labels are the number of operations in thousands.

Theoretical Sampling and Data Saturation

Sampling using the grounded theory method is a two-step process beginning with an initial sample followed by multiple theoretical samples. The following paragraphs describe each sampling method, summarize their processes, and explain achieving data saturation.

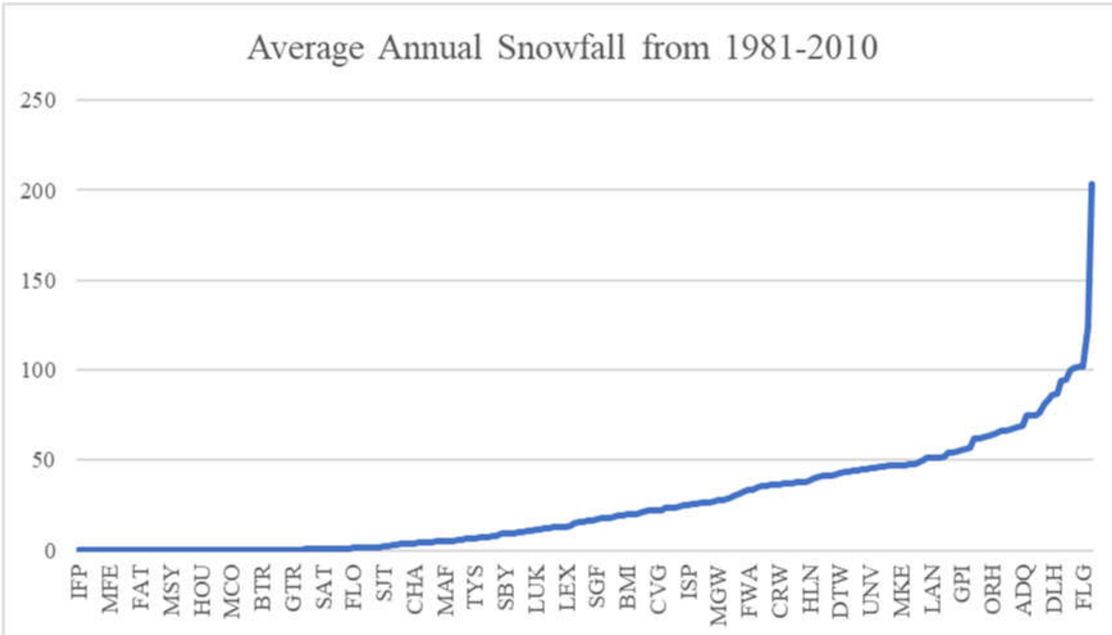
Initial Sample. Grounded Theory requires basing the initial sampling decisions on a general perspective and subject area (Glaser & Strauss, 1967). Sampling began with a partial framework of *local* concepts selected by the researcher to get a foothold in the data collection. To select the initial sample, the researcher hypothesized that the selection of maintenance strategy depends on the size of the airport lighting system and the amount of snowfall. Based on the researcher's experience, snowfall complicates maintenance by increasing cleaning requirements due to snow removal chemicals, increasing knockdowns from snow removal equipment, and increasing usage because of frequent low visibility operations. A risk exists that the initial concepts might eventually be found irrelevant when a researcher is not already familiar with the field. However, these concepts became part of the core categories of *access* and *environment*. Additionally, these selection criteria only applied to the initial samples and not the later theoretical samples.

The researcher divided the research population into two groups for the initial sample based on the average annual snowfall over 30 years recorded in the National Oceanic and Atmospheric Administration (NOAA) in the 1981-2010 U.S. Climate Normals, illustrated in Figure 7. Only 234 of the 380 airports within the population sample reported snowfall data to the NOAA database.

To assess the impact of snow on maintenance, one of the two groups included airports with zero average snowfall (39 airports). The second group had airports with the most annual average snowfall, but not less than 60 inches (28 airports). The second group was large enough to provide a range of airports with various operations, large enough to obtain a responding airport from each level of operations, but small enough to ensure the selection of airports with the highest snow levels. The selection of groups at extremes of the snowfall averages highlighted the differences in practices due to snowfall. Following the initial data analysis, the researcher used theoretical samples to investigate differences over the entire research population further.

Figure 7

Average Annual Snowfall at U.S. Primary Commercial Service Airports based on NOAA 1981-2010 U.S. Climate Normals

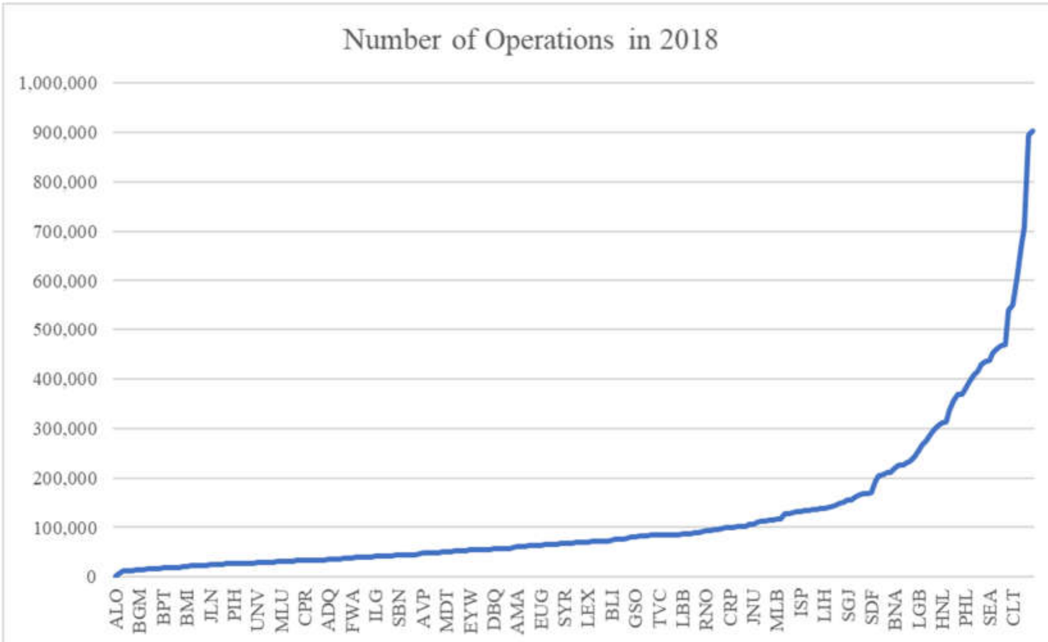


Note. The vertical axis is the average annual inches of snow over 30 years. The horizontal axis includes the 234 airports with data in the NOAA database and reported 2018 operations to Air Traffic Activity System (ATADS). The horizontal axis only shows some airport identifiers due to chart space limitations.

The two snowfall sample groups each included three subgroups based on the annual airport operations in 2018. The number of annual operations at each airport served as a proxy for the size of the airport lighting system. Higher operations were assumed to require more runways, taxiways, airfield lighting circuits, sophisticated system designs, and access restrictions. Data for the number of annual airport operations for commercial service airports in 2018 was taken from the FAA ATADS (FAA, 2019a) and is illustrated in Figure 8.

Figure 8

Number of Airport Operations at U.S. Primary Commercial Service Airports in 2018



Note. The vertical axis is the number of operations in 2018 reported in ATADS. The horizontal axis includes the 234 airports with 2018 data in ATADS and reported 1981-2010 snowfall data to NOAA. The horizontal axis only shows some airport identifiers due to chart space limitations.

The researcher then selected three samples representing the range of the annual operations of airports within the research population. Unfortunately, specific airports could not be chosen for the sample because there was no guarantee that the airport staff would agree to participate in the research. Therefore, the researcher divided the population into groups and tried to secure interviews from one airport in each group.

The FAA separates primary airports into four categories based on their percentage of total U.S. annual enplanements: large, medium, small, and non-hub. However, because the size of the airfield lighting system is related to the number and size of the runways, the number of annual operations is a better proxy for the lighting system than the number of enplanements. Also, sampling based on hub size would bias the sample selection toward larger airports. Large hubs comprise only 7.9% of the population, and medium hubs include only 8.1%. Using four samples, one from each hub, would result in half of the samples being from the top 16% of airports. As a result, the basis for sampling was not hub size.

The researcher selected three sample groups because of the left-skewed data presented in Figure 8. Roughly two-thirds of the curve is a gradual and constant increase in operations, and the final busiest third has a significantly higher number of operations. Therefore, sample selection included three from the zero-snowfall group and three from the high snowfall group for six initial samples.

Interview requests began with airports with the highest annual operations and worked through the group until securing an interview. Secondly, requests began with the lowest number of operations airports and continued with higher ones until securing an interview. Finally, the third sample began with requests to airports nearest the median number of operations within the snowfall group. Requests continued to alternately lower and higher operations airports until an organization agreed to an interview.

The researcher personally asked for interviews with staff at airports. For confidentiality, this report does not include the airport names. The group with the highest number of operations included two airports with greater than 130,000 operations. The low group had two airports with less than 40,000 operations. The mid-range group included two airports with operations between 40,000 and 130,000 operations.

Theoretical Samples. Charmaz (2014) defines theoretical sampling as a method the researcher uses to select samples that will explicate the properties of their developing categories. Theoretical sampling does not use random sampling of selected populations or samples representative distributions of a particular population. Glaser & Strauss (1967) provide the following definition:

> Theoretical sampling is the process of data collection for generating theory whereby the analyst jointly collects, codes, and analyzes his data and decides what data to collect next and where to find them in order to develop his theory as it emerges. (p. 45)

The researcher coded and analyzed the initial sample interview transcripts using the process described later in the Data Analysis section. The first six interviews generated 97 pages of transcripts, 1,133 initial (line-by-line) codes, and 50 focused codes. The transcripts and codes were provided to an airfield lighting subject matter expert with doctoral-level qualitative research experience to conduct a peer review of the initial and focused coding. The analysis began to uncover the relevant characteristics of airport organizations and other factors impacting their maintenance decisions. The researcher used the factors identified during the initial analysis as guiding criteria to select additional sample airports.

For example, the analysis uncovered that the size and complexity of the airport lighting systems are more directly related to the number and type of runway approaches rather than the number of annual operations. The research population was sorted by the number of runway approaches, the approach category, and those airports permitted by the FAA to operate under low visibility conditions. Finally, a new purposeful sample was selected based on high and low levels of these criteria.

Sample sizes differed for each iteration of theoretical sampling because each iteration investigated different emerging concepts. After determining which categories need further exploration, the researcher identified a long list of airports most likely to have the appropriate information. Next, the researcher placed phone calls and e-mails to senior airport facility managers to solicit interviews. Typically, a small number of airports from the list agreed to conduct interviews. For example, 15 suitable airports were identified to provide data to explicate the environment category further. However, representatives from only five airports on this list agreed to conduct interviews. In this case, the five interviews sufficiently addressed all information shortfalls and thoroughly defined the environment category. In practical application, the sample size of an iteration of theoretical sampling is known only after the category under investigation is fully explicated. Therefore, the researcher continues sampling until satisfied with the category definitions.

Common themes emerged as the researcher completed more interviews and analyses. Data analysis identified additional information to explain the emerging categories more thoroughly and select the theoretical samples to locate the required information. For example, the researcher determined that various weather and geological conditions influence decisions and created an *environment* category. Also, several of the airports had begun the implementation of asset management programs and associated computer systems. In most cases, these systems did not significantly change the decision-making processes but facilitated record keeping and work order tracking of large workloads. The additional analysis helped differentiate factors unique to certain airports.

Data collection, analysis, and theoretical sampling concluded upon achieving data saturation.

In collecting data using the interview process, Charmaz (2014) noted four concerns affecting which data to seek and how to collect it: *theoretical plausibility*, *direction*, *centrality*, and *adequacy*. Grounded theorists place higher importance on the theoretical plausibility of statements made by interviewees than their accuracy. Collecting large amounts of data and comparing the results helps mitigate concerns that a single interviewee makes an exaggerated or misleading statement. As interviews continued, certain statements were significant and provided a theoretical direction that helped shape later interviews. As central concepts emerged, the researcher used these ideas to identify later sample airports and create more targeted questions. Interviewing continued until the investigation of the core concepts provided sufficient data to describe each category adequately.

Data Saturation. Glaser and Strauss (1967, p. 61) state that "saturation means that no additional data are being found whereby the sociologist can develop properties of the category." According to Charmaz (2014), saturation occurs when the researcher has defined, checked, and explained relationships between categories and the range of variation within and between categories, not by completing a specific number of interviews. The researcher developed outlines for six categories after interviews with nine airports. As interviews continued to investigate these six categories further, two more categories emerged from the growing data set. The impact of well-trained and motivated staff on decision-making became clearer and led to developing the *impetus* and *staff* categories. The data collection and analysis achieved saturation following the full explication of eight theoretical categories affecting maintenance strategy selection decisions.

Sample Size. Grounded theorists agree that the appropriate number of samples is the quantity necessary to represent the theoretical concepts adequately (Mason, 2010). Mason (2010) examined 174 grounded theory studies conducted by PhD students and found the number of interviews used ranged from 4 to 87, with a mean of 32 and a standard deviation of 16.6. Charmaz (2014, p. 108) states that “a very small sample can provide an in-depth interview study of lasting significance.” Additionally, the number of necessary samples may be affected by pursuing a controversial topic, anticipating or discovering surprising or provocative findings, and constructing complex conceptual analyses (Charmaz, 2014). Thomson’s (2011) analysis of 100 grounded theory studies found that the number of interviews necessary to reach theoretical saturation can be affected by the scope of the research question, the sensitivity of the phenomena, and the researcher's ability. Furthermore, the sample size is affected by the information richness of the data, the variety of participants, the broadness of the research question and the phenomenon, the data collection method, and the sampling strategy (Moser & Korstjens, 2018). In this study, the simplicity of the research questions and the homogeneity of airfield lighting systems contributed to the ability to achieve saturation with fewer interviews.

Sample Characteristics

The entire research sample included 23 interviewees from 15 airports. Participants receive anonymity, so this section provides only a few identifying details. The jobs of interviewees included nine electricians, four maintenance engineers, four facility technicians, and four maintenance managers. Electricians hold a current or previous journeyman's license and perform ALM tasks regularly. Facility technicians were responsible for airfield lighting maintenance but never formally trained as electricians. The maintenance engineers interviewed provide technical or managerial guidance to the ALM staff. Finally, the maintenance managers are those held responsible for airfield lighting maintenance but do not personally perform the work regularly.

When comparing Figure 8, which represents the total research population, to Figure 9, which represents the research sample, the weighting of the sample toward airports with larger numbers of operations is apparent. This intentional skew in the theoretical sampling occurred because the researcher found that maintenance challenges and programs at small and non-hub airports tend to be similar and therefore interviewed more medium and large-hub airports to gather more diverse data. In addition, interviews with staff at airports with higher operational levels provided the opportunity to investigate advanced maintenance programs, including complex management solutions such as asset management programs or the establishment of a maintenance engineering department.

Figure 9

Number of Designated Runways vs. Operations for the Total Research Sample

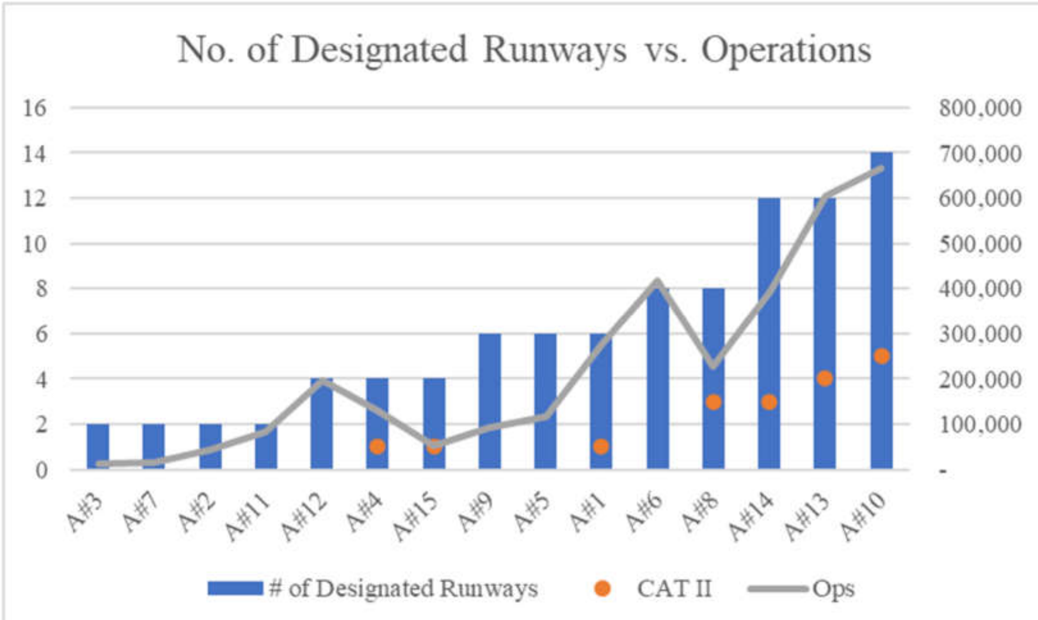
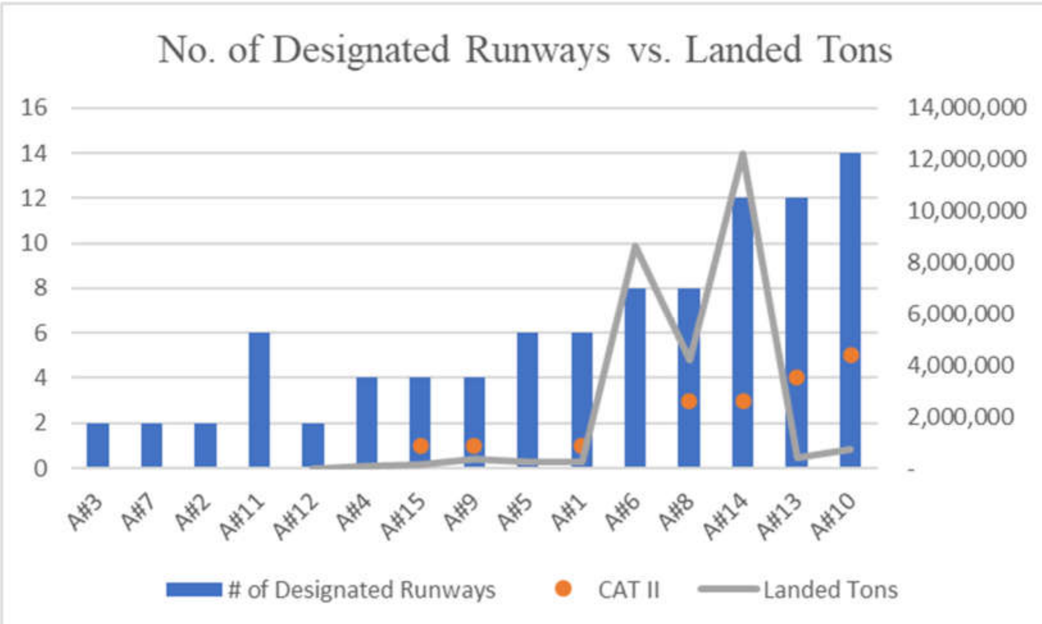


Figure 10 compares landed tons and the number of runway approaches at the sample airports. This table simply shows that research interviews included airports with high cargo operations. Interviews indicated that airports with cargo-intensive operations might have different maintenance challenges. For example, the runway may be more accessible during the day because more cargo flight operations occur at night. Furthermore, cargo aircraft pilots use Enhanced Flight Vision Systems (EFVS) more commonly than passenger aircraft pilots. The FAA determined that LED runway lighting is more difficult to see when using EFVS (FAA, 2011). As a result, airport management may elect to keep existing incandescent lighting on runways used primarily for cargo operations instead of upgrading them to more reliable LED systems.

Figure 10

Number of Designated Runways vs. Landed Tons for the Total Research Sample



Data Collection Process

Data collection followed the standard Grounded Theory process, including an iterative process of sampling, interviews, and data analysis until achieving data saturation. The initial sample of six interviews was analyzed and used to create theoretical categories for further analysis. A peer reviewer reviewed the codebook to ensure the researcher assigned codes consistently. Other interviews focused on further understanding and describing the emerging theoretical categories and generated new ones. Upon conclusion of the data analysis, the researcher developed eight theoretical categories that affect ALM strategy selection decisions in several ways and to varying extents.

Design and Procedures

This study is exploratory and explanatory research using a constructivist grounded theory method to create a substantive theory describing the selection of management strategies for airfield lighting maintenance. The researcher identified 15 airports and 23 interviewees that met the initial and theoretical sampling criteria. Next, the researcher identified potential interview candidates by searching airport website staff lists, industry conference attendee lists, industry organization membership lists, and received referrals from other interviewees. The researcher contacted the airport director when the facility manager or electrical maintenance manager was unavailable and made initial contact using an e-mail that briefly explained the request and included a description of the research.

With this information, the airport contact decided on the most qualified person or persons available. Upon finding a potential interviewee, the researcher/interviewer sent the candidate a brief description of the study, the informed consent form (see Appendix B), and a list of interview questions (see Appendix C). Primary interview topics were directly related to the research questions and included:

- identifying maintenance strategies in use
- asking how maintenance performance is measured
- asking how major maintenance decisions are made
- identifying the primary factors that affect the airport staff’s approach to maintenance

The researcher then scheduled interviews with each participant at a mutually agreed time. The discussion began by asking about the interviewee's work experience, local maintenance organization, and facilities. The interviewer then asked pre-established open-ended questions within each topic area. Each interviewee was encouraged to interpret questions as they found proper and answer questions as thoroughly as possible. The purpose of open-ended questions was to foster unrestricted and original ideas and perspectives from each interviewee. In addition, the interview included more questions within the topic area to obtain further information about or clarify specific items of interest arising during the interview. Each interview was recorded and transcribed by the researcher. Call durations ranged from 45-90 minutes to allow the interviewee to address the interview topic completely. The researcher imported the completed interview transcripts into NVivo software for initial and focused coding.

Apparatus and Materials

Because a detailed interview analysis required a transcript, the interviewer used a third-party phone application called TapeACall Pro to record the phone call. An iPad served as a backup recording device. After the call, the audio file was e-mailed to the researcher and downloaded to a dedicated research flash drive. Upon successfully downloading the audio file, the researcher deleted the backup files. When beginning the transcription, the researcher uploaded the audio files to NVivo software and manually created the transcripts using the software's audio playback feature and a separate word processer. Otter.ai transcription software performed the initial transcription for the final six interviews to rapidly create the transcriptions. However, the interviewer closely reviewed each transcript while listening to the audio file because the software had difficulty with the technical jargon. Whenever the transcription appeared incorrect, the researcher corrected the transcript. After completion, the transcripts were copied to the research flash drive for backup storage. After successful transcription, the researcher deleted the audio files from the TapeACall Pro application, the research e-mail folder, and the research flash drive. Also, relevant information from e-mail conversations was documented in memos or general notes and stored on the research flash drive. E-mail conversations data files were copied to the research flash drive for deletion upon completing the dissertation. Finally, the researcher imported the transcripts and coded them within the NVivo software.

Sources of the Data

Airport Lighting Maintenance Managers. The primary data sources were those responsible for the management of airfield lighting maintenance or an understanding of the maintenance program. These sources varied depending on the airport organization and available personnel but included senior electricians, facility management directors, operations managers, maintenance engineers, and airport directors. At the beginning of the interview, participants described their experience working with airfield lighting and with their current airport. The sample questions in Appendix C illustrate the primary topics and questions asked by the interviewer. However, the open-ended nature of the interview format allowed the interviewer to ask other questions to investigate specific details and areas of interest further.

Interviews took place from October 1, 2020, through April 24, 2021. Data analysis began after coding the initial six interviews in December 2020. The preliminary analysis results determined which airports to sample next based on their ability to supply data to help explain the emerging theoretical categories.

Telephone Interview Transcripts. All interviews included recordings and transcriptions. Using transcribed interviews for data analysis helped reduce researcher bias by summarizing the conversation. However, the requirement to transcribe the discussion resulted in two potential candidates deciding not to participate. In addition, staff at two large airports required approval from senior management and security staff before conducting the interviews. Interviewees were eventually able to obtain permission in these two instances. However, phone calls for follow-up questions were not recorded. The researcher used follow-up discussions with interviewees to improve the coding of unclear portions of the transcription and to supply additional information when the researcher was preparing memos.

Ethical Consideration

Interviewees were provided the informed consent form in Appendix B for review and signature. They were reminded that a recording and a transcript would be made and used for data analysis. The Institutional Review Board (IRB) approved the exempt category for the research because the interaction only included interview procedures. The investigator annotated the transcription to hide the identity of the human subjects. In addition, disclosing the interviewee's responses outside the research would not reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, educational advancement, or reputation.

Confidentiality

The researcher maintained confidentiality by storing personally identifiable material on a secure flash drive. This material included the interviewee list, contact information, interview audio files, and interview transcripts. Files containing personally identifiable information were moved to secure storage or deleted when storage was unnecessary.

The interviewer used the third-party software TapeACall Pro to create recordings. The audio file was e-mailed to a personal account upon completing the interview and then downloaded to a dedicated research data flash drive. After verifying the quality of the recording, the researcher deleted the audio file on the TapeACall database, the associated e-mail, and the backup iPad recording. Next, the researcher manually transcribed the audio recordings to a Microsoft Word document stored on the research data flash drive, using NVivo and Otter.ai software described earlier. Confidentiality practices included converting identifiable information to pseudonyms. In addition, interviewee-specific data such as names, pseudonyms, job titles, work experience, and airport statistics were stored in an Excel spreadsheet on the secure flash drive. The secure storage also contained all statistical information about the research population and the sample airports collected in Excel spreadsheets.

Anonymity

Personally identifiable information was not used in this manuscript. Instead, direct quotes cited within this report use pseudonyms. In addition, the document does not mention individual interviewee airports.

Measurement Instrument

The *intensive interviewing* method used as the measurement instrument during data collection is the typical practice for research using the Constructivist Grounded Theory method (Charmaz, 2014). Key characteristics of intensive interviewing are:

- selection of research participants with first-hand experience

- in-depth exploration of participants' experiences and situations
- reliance on open-ended questions
- the objective of obtaining detailed responses
- emphasis on understanding the research participants' perspective, meanings, and experience
- the practice of follow-up on unanticipated areas of inquiry, hints, and implicit views and accounts of actions (Charmaz, 2014, p. 56)

The intensive interviewing format creates an interactive space to allow ideas to emerge. The format elicits a broader range of responses compared to quantitative methods. Interviewees can express concerns, justifications, and reflections within their responses. Sometimes, the need to explain their answer may force the interviewee to reappraise their opinion. The format allows for extended discourses that supply an opportunity for the interviewer to understand the interviewee's perspective.

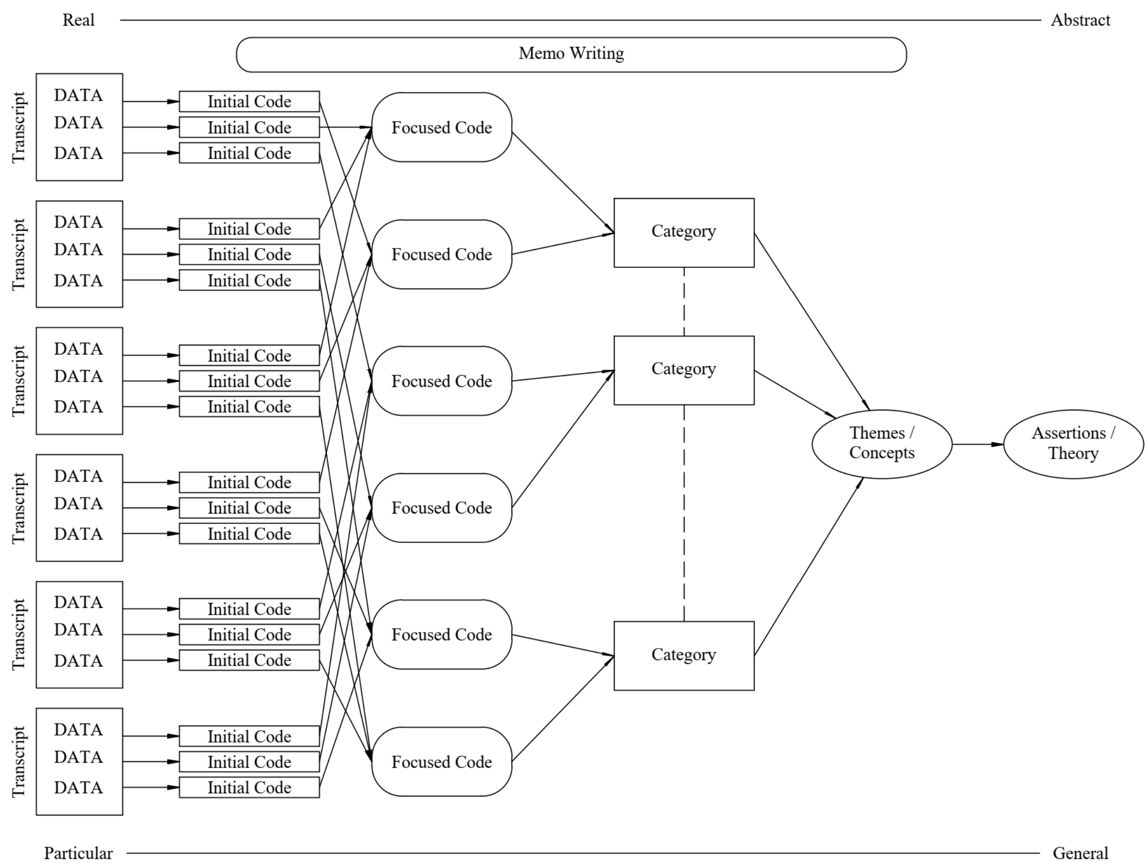
Appendix C includes the interview protocol used for the research showing six phases in each interview. The initial background phase included open-ended, straightforward questions to relax the participant and collect basic information. The subsequent four phases collected the data required to answer the four research questions. The four phases allowed the open discussion of the research question as a topic rather than explicitly asking the question. The interviewer used the questions listed in the protocol to spur conversation and ensure each participant thoroughly addressed the topic. However, the specific questions asked would vary depending on the answers provided by the participant. For example, during the earlier interviews, participants would regularly describe new maintenance strategies that required additional specific questions so that the interviewer obtained a complete understanding. The final phase of the interview allowed the participant to elaborate on responses to previous questions and offer new ideas about maintenance that were not discussed.

Data Analysis Approach

The data analysis approach described in this study follows Constructivist Grounded Theory (CGT), as defined by Charmaz (2014) and illustrated in Figure 11. CGT "adopts the inductive, comparative, emergent, and open-ended approach of Glaser and Strauss's original statement" (Charmaz, 2014, p. 12). However, CGT rejects foundational objectivist assumptions of an objective external reality, the discovery of data, the emergence of conceptualizations from the data, the view that data representation is unproblematic, and the neutrality of the observer (Charmaz, 2014). Instead, CGT assumes the existence of multiple realities; the mutual construction of data through interaction; that the researcher constructs categories; that data representation is problematic, relativistic, situational, and partial; and that the observer's values, priorities, positions, and actions affect their views (Charmaz, 2014). The differences illustrate how CGT is distinctive from classic grounded theory: the analysis acknowledges subjectivity throughout, constructed data begins the analytic direction, the research process is flexible, and participant views are integral to the investigation (Charmaz, 2014).

Figure 11

Grounded Theory Data Analysis Process



Note. Adapted from "The Coding Manual for Qualitative Researchers" (p. 14), by J. Saldaña, 2016. Thousand Oaks, CA: Sage. Copyright 2016 by Johnny Saldaña.

Initial codes were derived using a line-by-line examination of the interview transcripts. Focused codes were selected based on the analysis of initial codes and emerging ideas. The CGT method encourages the drafting of memos to summarize specific concepts and ideas found throughout the interview and analysis process. Focused codes that best represent concepts became categories. Categories are the first conceptual elements of the emerging theory. Data saturation occurred when the researcher named and developed all significant categories and their properties. Using sorting, diagramming, and integrating methods, theoretical concepts and themes were derived from the category memos and other memos to develop a theory to explain how maintenance management strategies are selected and influenced by the significant factors involved.

Coding

Locke (2001) explains that the term *code* refers to a label used for data retrieving. Specifically, coding is the process of naming and comparing data incidents. Researchers attempt to conceptualize and develop abstract meaning from the incidents described in the interview transcript when naming the incidents (Locke, 2001). Data incidents are grouped when related and examined to formulate conceptual categories.

Initial Coding. The first step in data analysis was coding the interview data in transcript form. “Coding means categorizing segments of data with a short name that simultaneously summarizes and accounts for each piece of data” (Charmaz, 2006, p. 43). Babbie (2013) describes two coding approaches: manifest content and latent content. Manifest content codes are clear and concrete, such as words from the interview, whereas latent content coding selects codes based on the underlying meaning of the communication (Babbie, 2013). This data analysis used both manifest and latent coding. The researcher used manifest content-coding when interviewees discussed specific, standard equipment or technologies such as mobile photometric measurement trailers or computerized maintenance management systems. Latent content-coding was used for less clear concepts, such as the essential maintenance practices or the quality of on-the-job training.

Focused Coding. Focused codes were selected by studying and comparing the initial codes and identifying the most significant or frequent. “Focused coding requires decisions about which initial codes make the most analytic sense to categorize your data incisively and completely” (Charmaz, 2006, p. 138).

Peer Analysis. One method of increasing reliability included a peer review of the initial and focused coding of the first samples. The peer reviewer assessed the reasonableness and consistency of the researcher’s assignment of initial (line-by-line) codes to interviewee statements and the assignment of focused codes to groups of initial codes. To carry out this task, the reviewer needed comprehensive knowledge of airfield lighting systems and their maintenance challenges because the open-ended interview questions led to discussions covering various topics. Given these knowledge requirements, the reviewer needed extensive experience working with airfield lighting systems at different airports. One senior electrical engineer with fifteen years of experience in airfield lighting design and experience with doctoral-level qualitative research agreed to perform the peer review. The reviewer recommended rewriting codes more clearly and improving their organization.

The peer reviewer examined the initial and focused codes developed by the primary researcher but did not generate a second set of codes for comparison. Some qualitative researchers use multiple coders to independently evaluate the same material and then evaluate the consistency between the coders using Inter-Rater Reliability (IRR) testing as a tool for reliability testing. However, no foundational grounded theory texts recommend using IRR (Grinter, 2010). “For the grounded theorist, codes are merely an interim process that support the development of theory, not a final result that requires testing" (McDonald et al., 2019, p. 15). Additionally, McDonald, Schoenebeck & Forte (2019) argue that coder agreement "is rarely appropriate when a single researcher with unique expertise and experience in conducting the research."

Memoing

While collecting and coding data, the researcher wrote short memos capturing emerging ideas about the interview data and codes. "Memos give you a space and place for making comparisons between data and data, data and codes, codes of data and other codes, codes and category, and category and concept and for articulating conjectures about these comparisons" (Charmaz, 2014, p. 163). The researcher used the memos as the first drafts of the data analysis. Tentative relationships, or conceptual properties, are summarized by written memos and substantiate the theoretical framework.

For example, one memo summarized FAA regulations for the airfield lighting equipment and maintenance requirements for the various runway approaches. This analysis helped determine that only a few large hub airports use advanced airfield lighting systems such as Surface Movement and Guidance Control Systems (SMGCS). This discovery dispelled an earlier assumption that interviews with large hub airports would provide the most valuable data because their staff performed more maintenance than medium or small hub airports. Furthermore, the maintenance requirements at these large hub airports were not typical of most airports in the research sample.

A second memo described how maintainers could impact the life cycle cost of airfield lighting assets. Asset management programs are a coordinated effort of an organization to minimize asset life cycle costs. Using the interview transcripts, the researcher recorded how airfield lighting maintenance staff impacted initial, operating, maintenance, disposal, and residual costs. In this case, the experiences at large hub airports are more comparable to the medium, small, and non-hub airports, with the primary difference being the scale of their economic impact.

Categorization

Codes that best represented what was happening in the data were elevated to tentative or conceptual *categories*. "Categories explicate ideas, events, or processes in your data" (Charmaz, 2014, p. 189). Glaser and Strauss (1967, p. 37) define a category as a "conceptual element in a theory." Charmaz (2014) recommends that categories be as conceptual as possible while staying consistent with the temporal, social, and situational conditions of their production. In addition, categories should explain the process and inferences made by the category (Charmaz, 2014).

The researcher created category memos to define properties more completely as the categories were named. Appendix D includes an example of the *condition* category memo. These memos defined the category; explicated the properties; specified conditions under which the category arises, is maintained, and changes; described consequences of changes within the category; and showed how this category relates to others.

Constant Comparative Method

Comparison is examining multiple incidents to identify what is similar and different (Locke, 2001). Glaser & Strauss (1967, p. 106) state the defining rule of the constant comparative method: "while coding an incident for a category, compare it with the previous incidents in the same and different groups coded in the same category." The lowest comparison level used initial codes that captured individual statements or suggestions within the transcripts. Focused codes described the similarities and differences of ideas related to the research questions. Focused codes related to maintenance strategy selection were more thoroughly studied and combined into theoretical categories. The new codes were added or combined with existing focused codes as interviews were completed and coded. After updating the focused codes, the researcher re-examined their meaning and relationships. The memos capturing the descriptions of the theoretical categories were then revised. Continuous comparison and analysis continued until theoretical saturation.

Theory Building

In Grounded Theory research, data collection aims to construct theory. In this research, interviewing was the primary tool for generating the focused data to construct the abstract conceptual categories. Interviews provided the opportunity to learn from local experts how ALM programs vary among airports and the reasons for those variances. The theory developed from the data analysis captures those factors and describes how they affect maintenance programs and strategies.

Research Quality Evaluation

Validity and reliability in qualitative research carry different connotations than in quantitative research (Creswell, 2014). Ensuring qualitative validity requires procedures to check the findings' accuracy, while qualitative reliability requires consistent approaches across researchers and projects (Creswell, 2014). The research method incorporates several recommended validity checks summarized below. However, Charmaz (2014) argues that validity and reliability are not useful measures of the quality of grounded theory research. Instead, Charmaz (2014) proposes using the criteria of *credibility*, *originality*, *resonance*, and *usefulness* to evaluate quality. This section evaluates the quality of the research in terms of all six of these criteria.

Reliability

"Reliability is a matter of whether a particular technique, applied repeatedly to the same object, yields the same result each time" (Babbie, 2013, p. 148). This research achieves reliability by strictly adhering to the established constructivist grounded theory approach developed by Charmaz (2014) described in the earlier methodology chapter. In addition, the data collection and analysis process is documented in the interview protocol, the transcripts, a codebook, memos, and analysis charts, as Yin (2009) recommended. Gibbs (2007) recommended ensuring that code definitions did not drift over time. A peer reviewer checked the transcripts and codebook developed from the initial six interviews to look for drift specifically.

Peer Reviewer. An AFL subject matter expert conducted a peer review following the initial six interviews by auditing the development of the initial and focused coding prepared by the researcher from the transcripts. Determining the initial codes, also called line-by-line codes, was straightforward because a code was assigned to each line or stated thought in the transcript. Therefore, the researcher and peer reviewer concentrated on the consistent development of the focused codes. First, the researcher derived these codes by finding relationships between initial codes and describing them with a term or phrase. As a result, focused coding is more subjective than initial coding because the coder determines the groups and the code name. The peer reviewer only reviewed the initial six transcripts because this allowed the feedback to be applied to future coding. Then, the researcher explained the code-selection rationale over a series of discussions while the peer reviewer confirmed that the application was consistent. The goal of the peer reviewer was to ensure the consistency of the codes assigned by the researcher across the six transcripts. The peer reviewer was not a second coder. No foundational grounded theory text requires multiple coders or recommends interrater reliability testing (Grinter, 2010). McDonald, Schoenebeck, and Forte (2019) state that seeking code agreement is unnecessary when codes are the process, not the product, using an expert researcher, and applying a grounded theory methodology. A second method for ensuring data collection consistency included standardizing the participant selection process and procedures for conducting the interview.

Standard Interview Protocol. The interview guide included the mandatory interview topics with recommended non-leading, open-ended questions. The topics stayed the same for every interview to ensure the data collected addressed the research questions. However, the interviewer varied the questions to allow detailed investigation specific to each airport and management staff. In addition, the interviewer supplied time to clarify any points at the end of the interview. Lastly, a single interviewer and coder conducted all the data collection.

Single Interviewer and Coder. A single interviewer conducted all interviews and assigned all codes to increase consistency. A single interviewer and coder are appropriate because the grounded theory method uses coding simply to develop theory (Glaser & Strauss, 1967, Charmaz, 2006). Using multiple coders and showing agreement among code choices is inappropriate for grounded theory research. The goal of coding in the grounded theory method is not agreement; instead, it yields concepts and themes (McDonald et al., 2019).

Validity

External validity "refers to the degree to which the results drawn from the sample can be accurately generalized beyond the participants taking part in the study to the population at large," and internal validity "refers to drawing correct conclusions about the sample, especially regarding causal effects" (Vogt et al., 2012, p. 355). Because of the methodology used, generalizability for the research should be examined using qualitative rather than quantitative research standards. The Constructivist Grounded Theory (CGT) methodology follows an *interpretivist* rather than the *positivist* research paradigm standard in quantitative research (Charmaz, 2014). "Interpretivism prioritizes the understanding of human behavior over the prediction and generalization of causes and effects" (Macionis & Gerber, 2010, as cited in Carminati, 2018, p. 2096). Carminati (2018) argues that generalizability for quantitative research primarily refers to *probabilistic* generalizability based on randomly selected samples representative of the population.

In contrast, generalizability for qualitative research is better described as *theoretical* generalization. This term infers transferability of the results "on the basis of both a theoretical analysis of the aspects generating the outcomes and the effects of the context" (Eisenhardt, 1989; Yin, 1994 as cited in Carminati, 2018, p. 2098). In CGT, the theory is constructed by analyzing data in detail and then applying abductive reasoning to develop a generalized conclusion for what the data represents. The study methodology incorporated the seven features described below to establish validity further.

Pilot Interview. The researcher conducted a pilot (pre-research) interview with one airport within the population sample to test the interview protocol. The goal of the pilot interview was to streamline the process of recruiting participants, identifying qualified interviewees, scheduling interviews, conducting telephone interviews, transcribing the recording, uploading the transcript to the CAQDAS software, performing coding, and generating reports with the data. The research did not incorporate the data from the pilot interview. The airport management staff recommended ways to improve the initial contact and suggested questions that helped identify the differences between maintenance programs.

Triangulation of Data Sources. The initial sample targeted airports with various weather types and operational demands so interviewees could answer questions from multiple perspectives. Data source triangulation is "examining the consistency of different data sources within the same method" (Patton, 1999, p. 1193). This study uses purposeful and theoretical sampling to ensure the selection of a variety of data sources. Patton (1999) explains that the goal is not to verify that different data sources yield the same results; instead, the goal is to expect differences and discover the reason for those inconsistencies.

Bias Clarification. "Good qualitative research contains comments by the researchers about how their interpretation of the findings is shaped by their background" (Creswell, 2014, p. 202). Creswell spoke of the researcher's gender, culture, history, and socioeconomic origin. For this study, the researcher is a registered professional electrical engineer with 22 years of experience planning, designing, and constructing airfield lighting systems but no expertise in performing airfield lighting system maintenance. As an engineer and designer, the researcher understands airfield lighting system theory and design but may have an idealized perspective of how maintenance should work. On the other hand, interviewees had practical experience in how their respective airports conduct maintenance. For example, designers may include cable insulation monitoring systems in airfield lighting system designs but go unused due to a lack of training or time for data analysis.

Flexible Interview Structure. Interview questions used an open-ended structure because of the exploratory nature of the research. The open dialogue maximized the opportunity for interview participants to contribute information not previously considered by the researcher. In addition, the interview protocol allowed varying the questions between interviews while keeping the discussion within topics related to the research questions.

Audit Trail. The constructivist grounded theory method generates an abundant audit trail that includes interview transcripts, initial coding results, focused coding results, memos, and diagrams. Memos are the informal record of the researcher's thoughts and ideas during data collection and analysis. Memos document categories, their properties, and their relationships. In addition, the memos include explanations of the rationale for each theoretical sample.

Negative Case Analysis. Data analysis found *negative cases* or cases that "demonstrate sharp contrasts with the major pattern" (Charmaz, 2014, p. 198). For example, while some maintenance programs have significantly reduced maintenance costs by installing new LED lighting fixtures, the staff at other locations found this recent technology too immature for use in critical areas.

Use of Quotes. Where possible, the researcher's interpretations are supported with verbatim interview quotes when appropriate. Doing so helps illustrate that the theory created is based on information collected during interviews.

Credibility

"Credibility begins with having sufficient relevant data for asking incisive questions about the data, making systematic comparisons throughout the research process, and developing a thorough analysis" (Charmaz & Thornberg, 2020, p. 11). This research achieved data saturation after interviewing 23 staff from 15 different airports. The required number of interviews for grounded theory research is variable, as described in the earlier section on sample size. However, the simplicity and non-controversial nature of the research questions and the similarities between airport maintenance requirements contributed to fully describing all theoretical categories within this sample size.

Glaser and Strauss (1967) argue that the greater knowledgeability of the researcher contributes to their ability to recognize when categories are fully described and bring the research to a close. For example, the researcher has eight years of facility management experience in the U.S. Air Force, followed by 22 years of experience designing airfield lighting, power, and control systems. As a result, no learning curve was needed for the technical aspects of airfield lighting, allowing the interviews to focus on management aspects of maintenance. In addition, airfield lighting equipment and federal regulations are standard among airports, allowing the researcher to focus further questions on how the local staff built their maintenance programs to address local conditions.

However, using interview transcripts and coding the conversations in detail helped ensure that the analysis generated results based on the collected information rather than the researcher's opinions. The CGT methodology requires multiple interactions with the data, including initial coding, focused coding, and category development. Assigned codes may evolve as new information is collected and compared to previous data. Furthermore, coding is an interim step in the CGT methodology and not a final product that requires testing (McDonald et al., 2019).

A constructivist approach requires examining and considering how researcher bias may affect the analysis (Charmaz, 2014). The researcher had the benefit of already understanding the technical aspects of ALM and the process of installing new systems. However, the researcher’s lack of maintenance experience was valuable because it helped minimize pre-conceptions of typical maintenance practices. As a result, a short learning curve can be observed in the data as the interviewer asked for more detailed explanations of maintenance procedures during the earlier interviews.

Originality

Original research offers insights or fresh perspectives on recognized problems (Charmaz, 2014). Most maintenance strategy research discovered during the literature review focused on single or multiple facilities under joint management. However, the research population for this study differs from extant research because most airport facilities operate independently. The individual airport management organizations provide an opportunity for this research to examine how maintenance programs can evolve differently even though airfield lighting systems are similar in design and operation across airports. The effective functioning of the national aerospace system requires rigid standardization among airport facilities and operations despite their independence.

The current FAA advisory circular on visual aids maintenance includes detailed descriptions of technical maintenance practices and supports the technical training of maintenance staff. However, the circular provides little guidance for managing a maintenance program. This study attempts to discover the commonly used practices of airfield lighting maintenance, specifically the various methods of selecting maintenance management strategies. Airport maintenance staff can use these results to support the training of maintenance managers by providing an understanding of alternative maintenance strategies and the factors that affect their selection.

Resonance

When qualitative research resonates, the work has effectively constructed concepts illuminating the participants' experience (Charmaz & Thornberg, 2020). Standardized infrastructure managed by separate ownership is necessary for transportation networks to operate on a continental or worldwide scale. However, a small number of manufacturers are stakeholders at many locations because the market for specialized systems such as airfield lighting is limited mainly to airport facility managers.[2] All airports within the research population have standardized lighting system designs, performance requirements, and equipment purchased from a limited number of

[2] FAA AC 150/5345-53 Airport Lighting Equipment Certification Program requires manufacturers to obtain third-party certification from an FAA-approved testing laboratory stating that the manufacturer's testing has demonstrated that the products comply with FAA equipment design specifications. The FAA publishes an addendum to the this advisory circular on a quarterly basis that updates the list of certified products by manufacturer and part number.

manufacturers. As a result, the study participants' maintenance practices, challenges, and solutions will likely apply to other similar-sized airports within the research population.

The best trained and equipped ALM staff likely exist at airports with the highest numbers of operations because these airports are likely to have larger operating budgets and have more significant impacts if the lighting system fails. However, Figure 6 illustrates that 90.6% of U.S. commercial service airports have 2-6 designated runway approaches, and only 60 of those airports have CAT II approaches (FAA, 2019a). In addition, approximately 90.7% of airports reporting data to ATADS had less than 300,000 annual operations in 2019 (FAA, 2019a). This data, which includes the entire research population, highlights that approximately 9.3% of U.S. commercial services airports have significantly higher average annual operations than the remaining 90.7% of the research population. Because a higher number of airport operations typically results in higher airport revenues (ACRP, 2009), those airports will likely have more complex maintenance requirements due to reduced access to the RSA. On the other hand, 90.7% will have comparatively more access to the RSA. These differences suggest that maintenance training provided to ALM technicians responsible for the busiest airports may not be appropriate for most airports within the research population and the NPIAS.

ALM staff at airports with more runways and higher operations will likely experience a broader range of AFL problems than at airports with fewer runways and operations (FAA, 2014a). More lighting equipment and greater wear and tear create more failure opportunities (FAA, 2014a). Differences between airports in the ALM urgency and workload create significant differences in the demands on the maintenance organization. For example, airports with lesser ALM demands may not find it cost-effective to keep an electrician on full-time staff. However, in some ways, the technical complexities of ALM are the same among airports regardless of maintenance demands. As a result, airport maintenance staff at smaller airports must identify ways to perform technical maintenance without the same resources available to larger airports. The research examines how the differences between airports affect maintenance strategy. The results provide a list of alternative maintenance strategies to be considered by airport maintenance managers. Additionally, the theory of ALM maintenance strategy selection constructed from the research could be used to develop tools to recommend strategies based on airport characteristics, as described later in the discussion chapter.

Usefulness

"Usefulness includes clarifying research participants' understanding of their everyday lives, forming a foundation for policy and practice applications, contributing to new lines of research, as well as revealing pervasive processes and practices" (Charmaz & Thornberg, 2020, p. 12). The primary usefulness of the research results is to provide a better understanding of ALM management is affected by airport characteristics. Maintenance managers can evaluate their airports using the theoretical categories, identify similar airports, note similarities and differences, observe alternative maintenance approaches, and then reconsider how they approach their maintenance challenges. Additionally, maintenance managers can review the list of commonly used maintenance strategies and consider whether using one or more could improve their maintenance program.

Additionally, the study results include diagrams of the ALM workflow based on information provided by the interviewees. The workflow diagram illustrates the changes required when implementing maintenance strategies incorporating data collection and analysis. Further, the diagram explains how some maintenance strategies drive changes to the workflow process and require additional training and equipment.

The analysis also sparks further research. All interviews indicated that selecting ALM management strategy falls to the maintenance managers, who either retain existing practices or change the maintenance program. Managers selected their strategies using input from managers with experience or ALM training. However, the theory constructed from the research results provides the opportunity to develop a quantitative process for selecting a strategy that could serve as a tool for future maintenance decision-making.

Lastly, this research is useful because the results facilitate a maintenance manager's ability to use asset management philosophy without fully implementing a resource-intensive asset management program. The list of alternative strategies provides tested options that maintenance managers can consider when optimizing their practices. Additionally, this study explains the key paradigm shift offered by the asset management philosophy. Compliance with Part 139 requirements is still the top priority, but senior airport managers should also monitor the costs of achieving compliance. Evaluating performance requires more than simply closing work orders; senior managers should monitor the life-cycle cost of the airport asset systems. Regularly calculating asset life-cycle costs allows senior managers to predict the potential value of increasing investment in preventive maintenance. This perspective on maintenance performance allows the calculation of objective, quantitative recommendations for potential program changes.

Summary

The CGT methodology using the interview data collection allows a wide range of maintenance managers from diverse airports to develop a standard theory of maintenance selection. The method allows the researcher to investigate emerging concepts through theoretical sampling efficiently. For example, factors such as the local ground traffic, airport design, and local environment consistently affect maintenance strategy decisions, but in different ways depending on the airport. Therefore, managers should investigate these factors to understand their impact on decisions. By examining decision-making within the maintenance workflow process, the researcher constructed a theory describing a common method of ALM strategy selection. The research methodology incorporated various measures to enhance reliability and validity. In addition, this section describes how the research addresses Charmaz's (2014) four criteria for evaluating the quality of the constructivist grounded theory research: credibility, originality, resonance, and usefulness.

Chapter IV: Results

Introduction

This chapter begins with four sections describing the results related to the four research questions. Next, the chapter describes ALM management practice based on the interviewees' information. This practice description identifies the additional steps related to asset management programs and practices some airports use. Finally, a short section highlights variations among airports resulting in differences in maintenance strategies and practices.

Table 3 lists the demographic characteristics of the 23 participants and 15 airports that provided information for this research. The data presented is limited to provide confidentiality for the interviewees. However, the table illustrates the variety of responsibilities held by the participants and the extent of their airport experience. Interviewing mid-level and senior managers allowed investigation of their different perspectives on factors influencing strategy decisions. The differences in experience levels illustrate how programs might vary simply because of the capabilities of the responsible individuals. Differences among airports are described indicating the hub type and extent of snowfall. Research results confirmed the initial assumptions that the extent of snowfall significantly affects ALM management strategy.

Table 3

Participant and Airport Characteristics

Participant				Airport	
Airport #	ID#	Role	Years' Experience (Airport + Other)	Hub Type	20-Yr Avg. Snowfall
1	1	Electrical Foreman	16 + 14	Medium	Heavy
2	2	Shift Captain	5	Non	Heavy
3	3	Airport Director	29 + 4	Non	Light
	4	Lighting Maintenance Lead	8		
	5	Maintenance Technician	20		
4	6	Civil Engineer	N/A	Medium	Light
	7	Lead Electrician	24		
5	8	Operations Manager	2 + 20	Non	Light
	9	Electrician	16 + 20		
6	10	Facilities Maintenance Director	NA	Large	Light
	11	Facilities Technician	NA		
7	12	Assistant Airport Manager	NA	Non	Heavy
	13	Maintenance Lead	NA		
8	14	Maintenance Supervisor	19 + N	Small	Light
9	15	Maintenance Supervisor	16 + 20	Small	Moderate
10	16	Energy & Infrastructure Engineer	18	Large	Light
11	17	Maintenance Crew Chief	6 + NA	Medium	Light
	18	Electrician	15 + NA		
	19	Electrician	9 + 18		
12	20	Senior Engineer	20	Medium	Light
13	21	Facility Superintendent	14	Large	Heavy
14	22	Senior Trades Manager	28 + 7	Large	Heavy
15	23	Operations & Maintenance Supervisor	2 + NA	Small	N/A

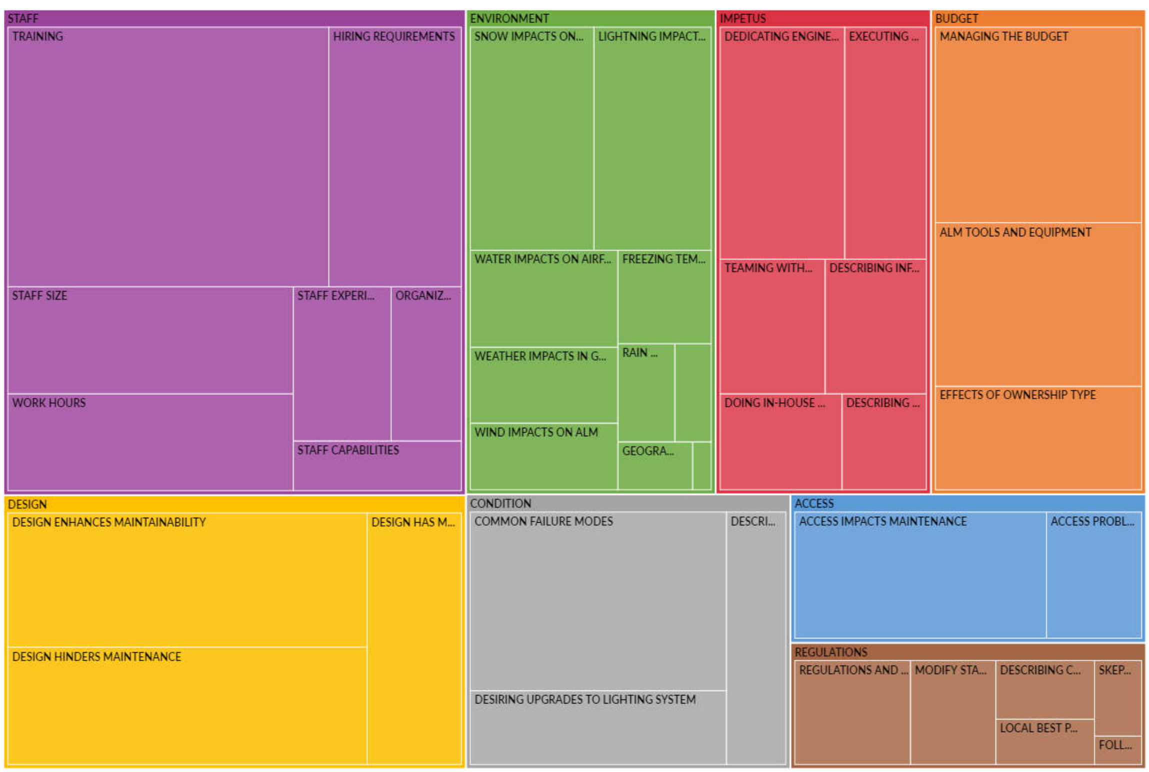
Note: Light snow is less than 24 inches. Moderate snow is greater than 24 inches but less than 60 inches. Heavy snow is greater than 60 inches. Horizontal lines group together interviewees from the same airport. 'NA' means the information was not available.

RQ1 – Factors Affecting Maintenance Strategy Selection

This research identified eight primary factors that airport maintenance management staff use to select their maintenance strategy: *access*, *budget*, *condition*, *design*, *environment*, *impetus*, *regulations*, and *staff*. During the interviews, participants described the factors their local maintenance management staff considered when selecting their maintenance management strategy. Figure 12 illustrates these eight factors in the form of a treemap. The size of the rectangles illustrates the relative number of coded references assigned to each factor.

Figure 12

Treemap of Eight Factors Affecting Maintenance Strategy Selection



Note. Each rectangle encompasses focused codes used to describe that factor. These focused codes are described in more detail later in this chapter.

For example, Figure 12 illustrates that *staff* was the most commonly referenced subject when discussing maintenance strategy selection factors. Each factor began as a focused code and was promoted to a category because the term or phrase best represented the data. Furthermore, the *staff* factor summarizes seven focused codes, which in turn summarize portions of other focused codes or line-by-line codes taken from the interview transcripts. Additionally, the researcher hierarchically constructed the seven focused codes from other focused codes and initial (line-by-line) codes. Appendix F includes the cluster maps associated with each category that illustrate the various hierarchies and additional focused codes.

The research methodology uses the term *category*; however, decision-making tools discussed later use the term *factor* for the same term. Therefore, the terms *factor* and *category* are used interchangeably for the remainder of this paper. In addition, interviewees were selected from a broad range of airport types and locations. Therefore, each factor applies differently to each airport and how the ALM manager uses them in their maintenance strategy selection process. For example, the *environment* category affects all airports differently and to differing extents.

Table 4 illustrates the contribution of each airport to each factor by the number of individual references during the portion of the interview regarding factors affecting maintenance strategy selection. The highest number of references used to describe a category is 383 for the *staff* category, and the lowest number of references used is 92 for the *access* category. The nature of the data collection does not support the quantitative analysis of these totals. Therefore, the column totals do not necessarily represent the importance of a factor. Instead, these totals correlate with the amount of discussion about each factor or references made to the factor. For example, the smallest column total in Table 4 falls under the *regulations* factor.

Nevertheless, a maintenance strategy ensuring compliance with Part 139 requirements was critical to all airports interviewed. In addition, the semi-structured interview format and open-ended questions allowed the interviewee to provide as much detail as they felt was necessary to describe their point. As a result, each airport's references would vary according to the interviewee's desire to provide concise or wordy answers to questions and the interviewer's need for a detailed explanation.

Table 4

Matrix Coding Query of Airport Interview References to Factors Influencing the Maintenance Strategy Selection

AIRPORT #	STAFF	DESIGN	ENVIRONMENT	BUDGET	IMPETUS	CONDITION	ACCESS	REGULATIONS	LINE TOTAL
1	34	57	28	22	3	22	18	10	194
2	47	8	14	24	0	28	4	6	131
3	32	23	22	50	6	17	1	8	159
4	23	34	7	19	5	17	4	15	124
5	12	14	25	5	2	9	8	0	75
6	35	15	6	10	10	14	5	8	103
7	34	3	19	13	2	18	6	2	97
8	24	3	6	4	9	3	18	1	68
9	16	8	11	1	36	6	4	3	85
10	19	5	0	1	63	2	5	3	98
11	16	16	10	4	6	6	3	8	69
12	43	6	15	4	17	1	5	5	96
13	25	22	21	12	10	3	2	5	100
14	12	5	16	5	9	10	7	3	67
15	11	3	8	3	3	1	2	0	31
COLUMN TOTAL	383	222	208	177	181	157	92	77	1497

Note. Quantities in each cell illustrate the number of references from each airport interview transcript assigned to each category/factor. The warmer-colored cells indicate the highest number of references. The cooler-colored cells indicate the lowest number of references.

The line totals in Table 4 only reflect the number of references related to research question one (RQ1) regarding the factors affecting maintenance strategy selection. The totals do not include the references applicable to other research questions. The fewer references in the first four interviews compared to the later interviews illustrate that the interviewer became more familiar with how various factors affect maintenance and required less explanation.

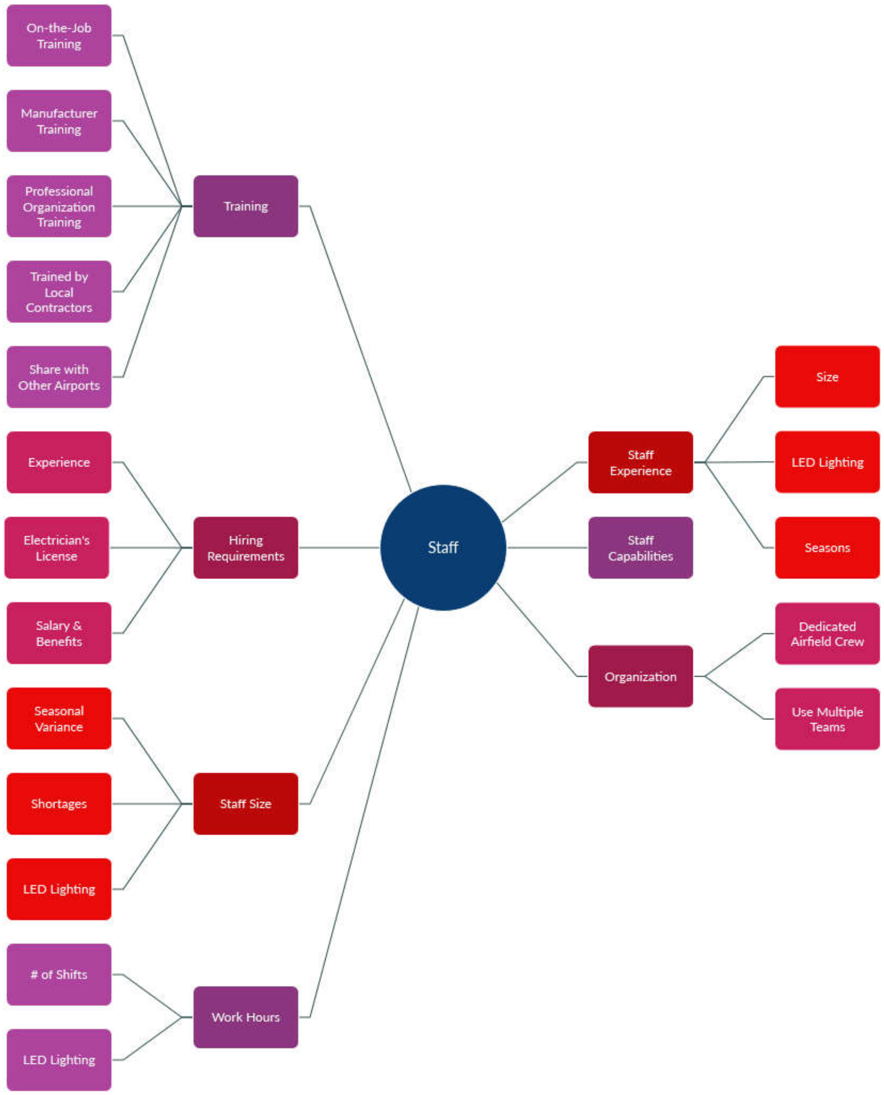
However, Table 4 does provide helpful information to understand how the interview data relates to the selected factors. For example, the table illustrates the distribution of the 1,497 references among the eight factors and the extent to which each airport interview contributed information. Furthermore, the consistently high number of references that each airport interview contributed to the *staff* factor strongly suggests that this factor is significant to decision-making regardless of airport size or environment.

Developing Factors/Categories

As previously described in the methodology chapter, the researcher created initial codes for every phrase or sentence in the interviewee's responses. CGT methodology also refers to initial coding as *line-by-line* coding. The initial coding of interviewee responses in all transcripts generated 2,416 initial codes. Because initial codes can apply to more than one focused code, the total number of references to the initial codes is 2,674. Table 4 illustrates that the eight factors are based on 1,497 transcript references. However, developing the categories required several iterations to examine the initial codes for similarities and assign a focused code to each group. Groups of related focused codes led to the development of higher-level focused codes.

Figure 13

Map of Focused Codes Used to Develop the Staff Category



For example, Figure 13 illustrates the hierarchy of focused codes used to develop the *staff* category. A total of 383 references (see Table 4) resulted in 18 focused codes, which led to seven higher-level focused codes. The similarities between these seven codes led to creating a higher-level focused code combining the staff-related factors that impact maintenance management strategy selection. Appendix F includes similar maps illustrating the focused codes used to develop each key category.

Category Properties

When focused codes became categories, the researcher investigated the characteristics and properties of the category and recorded the results in a memo. Properties constitute the essential elements of the category. Since categories were identified through the coding process, developing property definitions required reviewing the portions of the transcripts used to generate each line-by-line code to understand better the context of the interviewee's explanations. After identifying the initial core categories, explaining the property definitions became crucial for selecting airports during theoretical sampling. Data saturation resulted from identifying all relevant properties for each category and fully explicating each property. Table 5 lists the properties defined for each category. The following sections describe the coding used to develop each category and the properties defining each category.

Table 5

List of Categories Related to Maintenance Strategy Selection and Their Properties

Name	Level of Conceptualization
Access	Category
Traffic	Property
Weather	Property
Budget	Category
Availability	Property
Approval	Property
Condition	Category
Age	Property
Wear and Tear	Property
Proper Maintenance	Property
Design	Category
Quantity	Property
Technology	Property
Diversity	Property

Name	Level of Conceptualization
Involvement	Property
Environment	Category
Meteorological	Property
Geological	Property
Impetus	Category
Legacy	Property
Bottom-Up	Property
Top-Down	Property
Regulations	Category
Part 139	Property
FAA	Property
Staff	Category
Size	Property
Skills	Property
Experience	Property

Access

A large portion of the airfield lighting system critical to runway operations during low visibility is located within the Runway Safety Area (RSA) (FAA, 2018a). This equipment includes edge lights, centerline lights, touchdown zone lights, taxiway lead-in lights, guard lights, distance remaining signs, exit signs, hold signs, PAPIs, and associated cabling and transformers (FAA, 2018a). The RSA is "a defined surface surrounding the runway prepared or suitable for reducing the risk of damage to aircraft in the event of an undershoot, overshoot, or excursion from the runway" (FAA, 2012). Airfield lighting maintenance staff must keep runway fixtures operating within strict requirements (FAA, 2014a). For example, for a Category I runway to be considered operational, 95% of runway centerline lights must be serviceable, and no adjacent lights may be unserviceable (FAA, 2014a; Marking, signs, and lighting, 2004). However, under low visibility conditions, an airport may elect to close a runway entrance taxiway when the adjacent mandatory hold sign fails to illuminate because of the increased risk of a runway incursion.

Access to conduct lighting maintenance within the RSA is granted by controllers in the Air Traffic Control Tower (ATCT) (FAA, 2015; Pedestrians and ground vehicles, 2016). However, ATCT controllers will not allow personnel or vehicles within the RSA when a runway is being used for departure or takeoff. Therefore, heavy traffic can significantly reduce access to lighting equipment within the RSA.

Two properties are associated with the *access* category, *traffic* and *weather*. This research shows that traffic has a greater impact on access for maintenance. Weather impacts on accessibility varied based on location but tended to be minor. The *environment* category describes other more significant weather impacts.

Traffic. Since most air traffic is during the day, ALM teams at high-traffic airports have limited access for maintenance on equipment within the RSA during daylight hours. Depending on workload and other factors, high-traffic airports may require a night shift to accomplish maintenance and repair responsibilities within the RSA. For example, interviewee #2 completes most of their lighting repairs at night "because it is easier for us to get out on the airfield and be undisturbed." Interviewee #20 stated, "… we have a curfew at night for commercial flights. So, our principal timeframes for getting major work done out there is after hours at night or very early morning before the traffic starts picking up …" and "getting out there during the day is a struggle." However, Interviewee #10 is from a high-traffic airport and "… had a crew that was actually rotating 24/7. Since we went to LED lighting we improved our methods of inspection and what not. We've been able to reduce to one shift, five days a week."

Interviewee #20 explained that their airport upgraded to LED equipment following staff downsizing with the expectation that the new technology equipment would reduce their workload. These examples illustrate the relationship between the *access* and *design* categories. Well-considered airport design can improve RSA access for maintenance.

When night-work and technology upgrades do not provide a complete solution, more pre-planning and careful scheduling of day-work is needed. ALM staff must coordinate with operations to stay aware of all planned closures, schedule work orders to coincide with those closures, and adjust work goals according to the closure length. Multiple interviewees stressed the importance of taking advantage of planned closures. ALM staff spends more time preparing by selecting the work to be completed, defining work goals more precisely, stocking their work vehicle with the necessary parts and tools, and ensuring they know exactly where to find the work areas on the airfield.

ALM staff will typically request runway closures only for emergencies or complicated repairs. Interviewee #11 described the difficulties of troubleshooting problems in underground cables within the RSA, “we'll get together and come up with a game plan, then coordinate with our operations division to get those areas closed.” Interviewee #10 stated, “We have to pre-plan for a closure to do anything. We have a meeting weekly … with all the stakeholders … and we schedule it out.”

Airports with lesser amounts of ground traffic have fewer access restrictions. For example, Interviewee #8 stated that the runway “can be accessed at any time. For how long is the question.” Interviewee #11 noted that their lesser traffic provides opportunities to do more thorough troubleshooting and repair on lighting equipment rather than only performing minimum maintenance, stating, “So we're small enough to where that works for us. Chicago O'Hare and Atlanta, maybe, maybe not." Even at large airports, there are times during the 24-hr day that access increases. Interviewee #1 noted that "other times of the night, it might be completely dead. It's like a ghost town out there."

Weather. Adverse weather can reduce productivity and create safety hazards for maintenance. The type and timing of the impacts are highly variable based on the season and the airport location, making these impacts challenging to account for in planning.

Maintenance managers at airports with extreme heat or cold seasons try to reduce outdoor work during these periods. Such patterns may drive maintenance managers to increase scheduled maintenance during the fair-weather season and prepare for increased reactive maintenance during the harsh weather season. In addition, airports in these conditions are more likely to have a well-stocked maintenance vehicle to help minimize exposure during priority repairs in poor weather.

Airports operating in low visibility conditions may prohibit maintenance except in emergencies. However, advisory circulars require increased visual inspections during low visibility where SMGCS systems are installed (FAA, 2020). Maintenance managers can minimize these inspections by installing electronic monitoring on specific lighting systems (FAA, 2020). The maintenance staff at airports regularly operating in low visibility indicated increased inspections and scheduled maintenance during good weather. Operations staff are more likely to do checks during low visibility than electricians. In this case, an effective system of communicating findings between the two shops is essential.

Maintenance managers keep track of the weather and coordinate work schedules with operations. Where weather conditions are highly variable, a daily coordination meeting may be required. Additionally, adverse weather in the region may result in diverted traffic arriving at the airport. Such unexpected increased traffic levels require flexible planning.

Budget

The *budget* category refers to the money available to invest in the airfield lighting system and the maintenance program. This category also refers to the process of the annual maintenance budget approval. Two properties are related to the *budget* category, *availability* and *approval*.

Availability. This research suggests that funds for maintenance requirements were more available at larger airports. Interviewee #1 stated that “If we need it, we generally get it.” Interviewee #10 also said that “we get funded based on our needs.” Interviewee #16 also had few budget concerns stating, “budget doesn’t really have an impact on what we do. Like every airport, we budget. But, if for some reason we need to do something that blows our budget, so be it. We’ll do it if it’s a safety issue.” Interviewee #22 is “fairly fortunate to have a pretty robust budget.” These four interviewees are from airports with three or more runways and high passenger or cargo traffic levels.

Interviewees from airports with one or two runways expressed more limited availability of funds. Interviewee #2 expressed a desire to transition from a paper-based to a computer-based work order logging system; however, “The last couple years, costs have been a deciding factor on that and why it hasn’t happened yet.” Interviewee #2 added, “I’d say budget is our biggest factor [affecting their approach to maintenance]. It always comes down to budget. … The amount of things we are responsible for. There’s only so much money to go around." Interviewee #3 also stated, "Money definitely is a restricting object that prevents us from doing certain things that we want to do … we put safety and security at the top of our list." Interviewee #23 noted, "I'm kind of constrained by the budget. So that does have a factor in how we approach things like buying new lights and lenses and globes and stuff like that." These three interviewees describe having just enough funds to meet basic compliance requirements.

These statements show that ALM staff at different airports have access to varying amounts of funds, regardless of having similar responsibilities, and those differences affect their approach to maintenance. Where funds for maintenance are limited, ALM staff may adapt maintenance strategies requiring less cost. The impact of limited maintenance funds extends to staff size, staff qualifications, and availability of training. Of the 15 airports within this research sample, the three commercial service airports with the lowest annual operations did not have electricians on their maintenance staff. Suppose the number of annual operations was considered a proxy for available funds for staffing. In that case, many other low-traffic airports may be performing airfield lighting maintenance without electricians on staff. Suppose all airports with fewer annual operations than these three airports operate without electricians. In that case, approximately one hundred commercial services airports, roughly one-quarter of the research population, perform airfield lighting maintenance without electricians on staff.

Approval. Airports within this research sample were owned and operated by a city, county, state, or airport authority. Regardless of the ownership type, the property of budget *approval* refers to whether the airfield maintenance budget is competing with only other airport requirements or with all the infrastructure needs of an entire city or county.

Interviewee #3 argued that airport directors from a city or county-owned airport had more significant challenges than authority-owned airports when pursuing budget increases. Interviewee #3 stated, “if you’re part of a city or county … you’re part of a large organization. Sometimes your department is way down the totem pole.” Interviewee #3 said that public roads are often a higher priority for city or county maintenance funds than runways and taxiways. At Interviewee #20’s airport, city-wide staff, salary, and benefit reductions resulting from an economic downturn affected the airport maintenance staff just as the entire City’s public works staff was affected. However, the difficulties of finding and hiring qualified airfield electricians should make the retention of such staff a higher priority than other maintenance staff.

ALM managers should consider the amount of funds available for staff, training, parts, and equipment when selecting maintenance strategies. Managers should also consider the difficulty of obtaining approval for non-budgeted expenses. Reactive maintenance is typically associated with higher rates of unplanned expenses. Preventive maintenance programs may cost more per year but are more likely to reduce un-planned costs and result in more consistent annual maintenance costs.

Condition

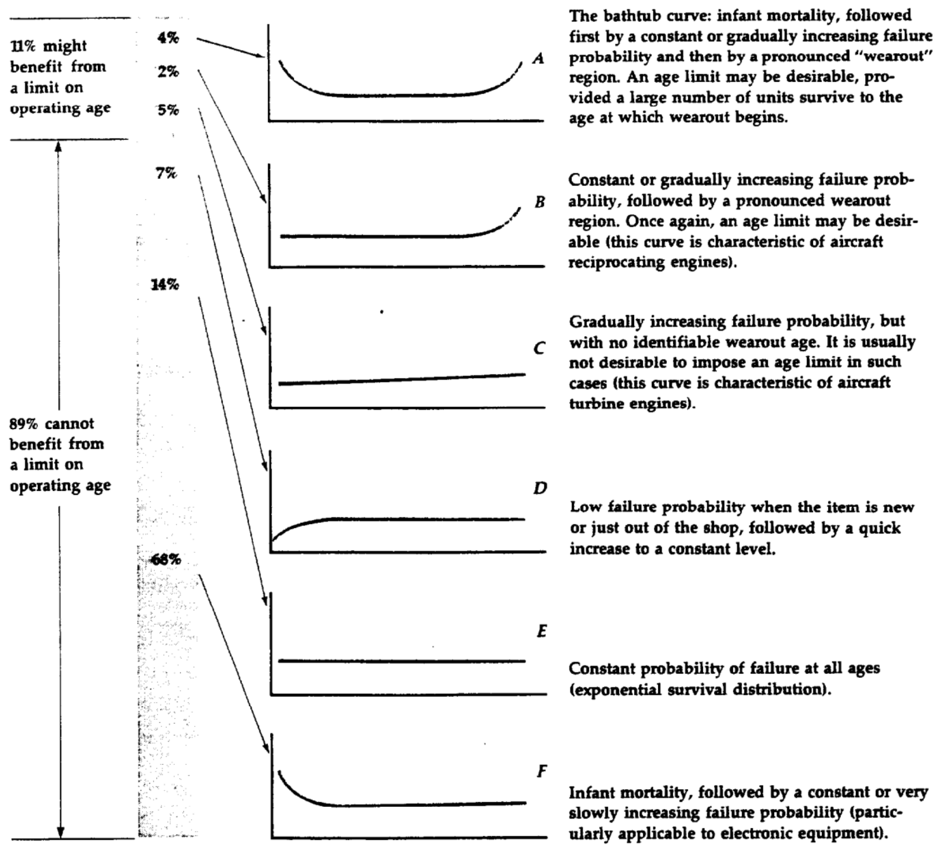
The condition category refers to the physical state of the airfield lighting infrastructure and the factors that resulted in the current condition. The *condition* category has three defining properties: *age*, *wear and tear*, and *proper maintenance*. Each of these properties should be considered by managers when selecting their maintenance strategy. For example, the AFL system condition degrades over time but improves through maintenance and refurbishment of equipment. As a result, systems in good condition will likely operate more efficiently and require less reactive maintenance and repairs. The opposite is true for systems in poor condition.

Age. The initial installation or refurbishment date establishes the *age* of the asset. Where possible, ALM managers should keep records of all equipment installation and refurbishment dates. In combination with asset design life estimates, managers can evaluate the asset's remaining useful life (RUL). This data can help determine when replacement projects should be planned and help justify those projects. Rates of failure for physical assets vary over time. In their seminal work on reliability-centered maintenance for the airline industry, Nowlan and Heap (1978) identified the six age-reliability patterns illustrated in Figure 14. These results show how asset deterioration curves can take different shapes. Determining the appropriate pattern for each asset requires specific research. However, once that research is complete, the results would be helpful to all ALM staff working to predict failure rates more precisely.

Wear and Tear. An asset's ‘wear and tear’ refers to the deterioration rate resulting from local and external factors such as weather, geology, the amount of traffic, and physical location. Increased wear and tear may reduce the RUL of the asset at a higher rate than similar assets, resulting in an earlier replacement. In some cases, higher rates of wear and tear may increase the maintenance and repair requirements. ALM managers can benefit from conducting inspections, recording the changes in asset condition over time, then using that information to improve upon RUL estimates. Where records include deterioration rates and the asset location, ALM managers can identify problematic equipment locations and possibly identify ways to make the asset more durable.

Figure 14

Age-Reliability Patterns



Note. The vertical axis represents the conditional probability of failure and, the horizontal axis represents operating age since manufacture, overhaul, or repair. The percentages show the percentage of items studied that fell into each of the basic patterns. Reprinted from *Reliability-Centered Maintenance* by Nowlan & Heap, 1978, Office of Assistant Secretary of Defense. In the public domain.

Proper Maintenance. Accomplishing *proper maintenance* is essential to maximizing asset value (ACRP, 2012a; ACRP, 2017). However, there may be situations where completing recommended maintenance is not feasible. Airport staff may be too small, have insufficient funds, or have inadequate training. Interviewees consistently stated that airport managers prioritize compliance with Part 139 requirements, safety, and security. However, 14 C.F.R. Part 139.311 requires airports to “properly maintain” marking, signs, and lighting and states that the FAA advisory circulars contain the methods and procedures for maintenance (Marking, signs, and lighting, 2004). The FAA advisory circular for visual aids maintenance requires “a qualified person, per the definition in NFPA 70E, performs maintenance work” (FAA, 2014a, p. 6) and states, “it is essential that a preventive maintenance program be established to ensure reliable service and proper equipment operation” (FAA, 2014a, p. 24). Managers at small and non-hub airports may be financially justified for not hiring a trained airfield lighting electrician because the hazardous ALM workload may not justify a full-time electrician on staff. In those situations, airport managers can meet requirements by outsourcing the dangerous portions of ALM to locally qualified airfield lighting electrical contractors. Contractors can provide regular maintenance, training to *unqualified* staff performing lighting maintenance, and emergency on-call repair services. Where airports do not have trained airfield lighting electricians on staff, Part 139 effectively requires contract services to avoid violating NFPA 70E safety standards. Interviewee #3 described hiring a local contractor to inspect their lighting system and provide guidance:

> We’re going to tag along and see what they do. We’re going to see if there is anything we can do, kind of steal or borrow some things that they are doing and maybe our guys can do it. Maybe it's something we need to do annually or biannually, or whatever we need to do (Interviewee #3).

Recognition of previous or current improper maintenance practices is critical to selecting a maintenance strategy and organizing a maintenance program. In some cases, compliance with all FAA and manufacturer maintenance standards may not be financially possible within the airport operating budget. For example, the FAA requires routine photometric testing for all lighting systems installed with Airport Improvement Program (AIP) funds (FAA, 2014a). Photometric testing verifies that light fixtures are correctly installed and functioning according to standards using detailed measurements of light fixture output (FAA, 2014a). In addition, the lighting maintenance advisory circular requires monthly photometric testing until experience supports adjusting the interval (FAA, 2014a). However, the price of photometric testing at such a frequency can be prohibitive to small and non-hub airports. Five of the 15 sample airports do not do regular photometric testing. One interviewee suggested that senior managers avoid testing because the results may require the airport to complete expensive repairs. With appropriate guidance or training, ALM staff may determine a frequency of photometric testing suitable to their local operations and environmental conditions without each airport needing to perform costly empirical testing for several months.

When recognizing improper maintenance, airport managers should consider that the lighting system equipment may be degrading at a higher rate. The increased rate of deterioration caused by inadequate investment in routine maintenance typically results in more frequent requirements for capital repair projects (ACRP, 2017).

Design

The *design* category refers to the physical design of the airfield lighting system. FAA standards apply to all airfield lighting systems, but each airport has a custom design based on local operational requirements. This category has three properties that affect maintenance programs: *quantity*, *technology*, *diversity*, and *involvement*.

Quantity. The *quantity* property refers to the total number of assets in the airport's lighting system. Based on interviewee descriptions of their organizations, airports with larger airfield lighting systems will generally require a more extensive ALM staff and equipment. The relationship appears obvious, but research to quantify the correlation could help undersized ALM staff trying to increase preventative maintenance that does not necessarily contribute to compliance with Part 139 requirements but does reduce asset life-cycle cost. Currently, airport managers lack guidance for determining the appropriate mix of size and experience within their ALM shops. Staff is another category affecting maintenance strategy selection and is discussed later.

Technology. The installation of modern *technology* in airfield lighting systems created significant changes to the maintenance program. The two primary technologies discussed during the interviews were LED lighting and CMMS installations. Most interviewees found that LED lighting installation reduced the frequency of lamp burnouts and reduced energy usage. For example, one large airport in a warm climate dropped 24-hour staffing and began on-call support at night because of the reduced number of burnouts. In addition, following a staff reduction, one mid-size airport installed LED lighting and successfully reduced the workload on the airfield lighting maintenance staff. However, there is no reduction in the number of fixtures damaged by ground vehicles, particularly snow removal equipment.

Some airport managers have decided not to install LED lighting at this time because of concerns over their visibility to Enhanced Flight Vision Systems (EFVS) and Enhanced Visions Systems (EVS), and Night Vision Goggles (NVGs) (FAA, 2011).

Additionally, one airport expressed concern over the inability of LED lighting to melt snow when set to lower intensity settings.

LED lighting installation appears to reduce the overall reactive maintenance resulting from burnouts but not impacts. This change significantly reduces the amount of reactive maintenance during most of the year. However, the increased cost of the LED fixture compared to the incandescent fixture results in higher fixture replacement costs, particularly during the snow removal season when breakage is more frequent. In any case, the reduced energy usage of LED fixtures can significantly reduce life-cycle costs.

Most sample airports had CMMS to support operations reporting and records, emergency response software, work order management, and asset management. Operations software supplies a wide range of capabilities such as aircraft accident response support, passenger manifest list management, Safety Management Systems (SMS), maintaining records for Part 139 inspections, and more. In addition, small and non-hub airports may use emergency response software for work order management, where the ARFF staff also perform operations and maintenance. Work order management software keeps track of the opening and closing of work orders, the associated labor hours, and the expenses. Finally, asset management tools supply work order management tools, keep records for each asset, and provide tools to analyze data and generate reports.

Arguably, the operations and emergency response software discussed above are not designed for maintenance management. However, at some airports, the operations or ARFF staff serve as the primary airfield lighting inspectors, and those inspectors first record their results in those software databases. The airfield maintenance staff receive copies of these results in various ways. Where this occurs, the practice makes the operations software a part of the maintenance workflow. Any facility maintenance CMMS may then need to interface with the operations software.

Interview results suggest that CMMS is underutilized at many locations. Interviewees reported using a small part of software's capabilities, such as IBM's Maximo. For example, Interviewee #15 said that all work orders on the runway had been assigned to a single asset number for the runway. This practice prevents the analysis of historical data about individual lights or signs on the runway. Interviewee #19 described their CMMS as overly complicated and said they only used about one-fifth of the data fields on each work order.

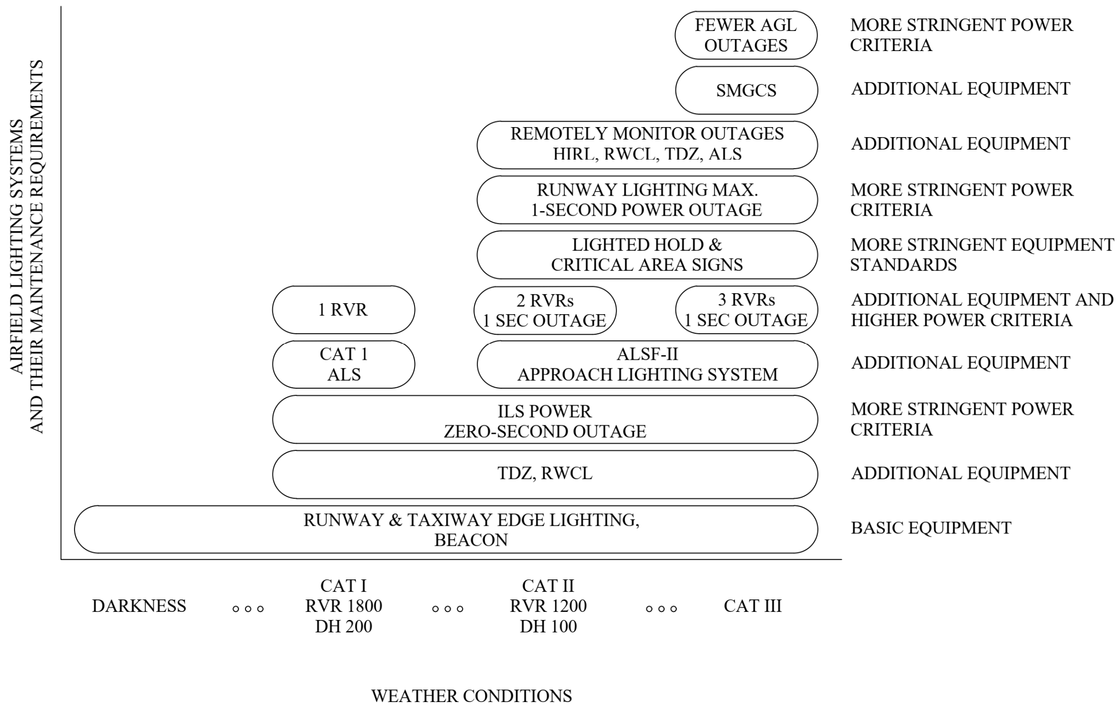
Generally, the interviewed ALM staff use CMMS for work order management, labor accounting, and expense accounting. Few reported using the software for data analysis to find ways to improve local maintenance. Some interviewees understood the value of increased record-keeping but lacked the training to use these capabilities. Others used the CMMS to research the work order history of assets when recurring problems were suspected. Of all interviewees, the only data held in the CMMS and regularly requested by senior management was the status of work orders.

Diversity. Design *diversity* refers to the variety of lighting equipment installed at an airport. Diversity increases with the number and type of instrument approach categories used on runways at the airport. For example, each runway approach with an instrument landing system (ILS) is assigned a category number that defines the minimum decision height a pilot may use for landing or the minimum visibility criteria available to try a landing. Airports install more lighting equipment and enforce higher reliability standards for runway approaches used during low visibility conditions. Each designated runway may have a different approach lighting system design based on the assigned approach category.

For example, a Category I runway approach has a decision height of not lower than 200 feet or allows landing with a Runway Visual Range (RVR) of 1800 feet (FAA, 2018c). Figure 15 illustrates the basic systems required for that runway approach. The horizontal axis shows the increasing criteria for operating at lower visibilities, while the vertical axis shows the growing number of lighting systems and higher operating standards. Furthermore, meeting the higher equipment operating standards for low visibility operations requires more complex equipment such as generators, transfer switches, and uninterruptible power supplies. Other additional monitoring and control systems that may be necessary to support low visibility operations include, for example, Airfield Lighting Control Systems (ALCMS), Surface Movement and Guidance Control Systems (SMGCS), Land and Hold Short Operations (LAHSO) lighting, apron lighting control systems, Visual Docking & Guidance Systems (VDGS), taxiway centerline lighting systems, and runway status lighting systems (RWSL).

Figure 15

Airfield Lighting Systems for Category I/II/III Approaches



Note: This figure summarizes lighting system requirements included in AC 120-118 *Criteria for Approval/Authorization of All-Weather Operations (AWO) for Takeoff, Landing, and Rollout* and AC 120-578B *SMGCS*. The figure only shows three category levels, but several levels exist between these with modified criteria and requirements.

Airports supporting various aeronautical activities such as general aviation, commercial service, and heliports require a broader range of airport lighting equipment. Runways supporting commercial service operations typically use high-intensity lighting, while runways supporting general aviation traffic often use medium-intensity lighting fixtures. The two types of fixtures are not interchangeable. Therefore, spare parts for both types of fixtures must remain in stock. Many airports are transitioning to LED lighting from incandescent lighting. LED and incandescent fixtures are not interchangeable because they are perceived differently by the pilot's eye (FAA, 2018a). Over concern that incandescent centerline fixtures would soon become unsupported by manufacturers, Interviewee #16 started a purchase of 1,000 spare fixtures to accommodate any future failures that might occur before the airport can upgrade all the centerline fixtures to LED.

Diversity is also greater when airports have more than one manufacturer for one type of equipment. The practice of cannibalizing parts from older fixtures to repair new fixtures becomes less effective when parts are not interchangeable. Spare parts for every manufacturer must be bought and kept on hand. Interviewee #7 said, "You just want to make sure, no matter what happens, you can get something up and running to keep the lights on." AFL maintainers must learn troubleshooting and repair procedures for each type of equipment and manufacturer.

Diverse assets increase maintenance costs because of increased stock levels, training requirements, and maintenance tools. However, having various lighting system assets may be unavoidable when the condition results from strategic operating decisions about the services of the airport. In addition, public procurement laws may require competitive bidding for new equipment, which severely limits the ability to select specific manufacturers.

Involvement. The last property of design refers to the *involvement* of the maintenance perspective in capital planning and project execution. Asset management practices encourage the reduction of asset life-cycle costs. Finding capital projects that result in life-cycle cost reduction is part of executing asset management. Input from the ALM staff should be part of the planning process. Interviewee #15 said, "My guys … are seeing the trends. They're seeing where we're having concerns. They're seeing where they’re struggling with things … they’re the eyes on everything.” Data collected by the ALM staff, such as insulation resistance measurements, can suggest which fiscal year to schedule cabling replacement projects. Interviewee #15 further described how, in a recent project, the airport’s engineers did not uncover that certain airfield lighting design features were noncompliant with FAA advisory circulars, resulting in reduced asset life and increased maintenance difficulty. Interviewee #1 describes how a cabling replacement required the application of heat shrink to all connections per FAA standards. Gaps in the heat shrink collected water and reduced the performance of the insulation for eight years. Only field inspections provided the visibility of the problem, and collaboration with the planners and engineers prevented a repeat of the issue.

Interviewees #16 and #20 described how their airport organizations assigned engineers to work with the facility maintenance staff to help supply technical guidance for near-term problems. In most of the interviewee’s organizations, the engineers focus on executing contracts to design and construct capital improvement projects. However, minimizing life-cycle costs requires engineers’ and maintainers' collaboration to find projects and prepare design documents for capital projects to reduce operation and maintenance costs.

In some cases, airport maintenance staff completed capital projects. For example, day staff at Interviewee #21’s airport completed cable replacement and LED sign replacement projects. Interviewee #19 described how their team completed LED sign retrofits. Airfield electricians are working with Interviewee #14 on a long-term program to replace regulators one at a time. Interviewee #23’s airfield maintenance team replaced several thousand feet of centerline lighting cables on the runway using in-house staff.

Electricians working with Interviewee #15 replaced high mast apron lighting fixtures. Interviewee #15 notes that the in-house team can take their time and do high-quality work without the same budget pressures as commercial contractors. Also, in-house electricians are installing equipment that they must support. Performing the installation supplies them with a better understanding of the function of each system, and in-house staff is motivated to make the extra effort to ensure the work is high quality.

Involvement by maintenance staff in capital projects' planning and design effort is valuable for all airport types and organizations. Discussing and reviewing airfield lighting system designs can supply practical training to the staff. Design engineers should be trained in airfield lighting design but will not typically have experience working on the airfield. Therefore, the maintainer's experience at the airport and personal investment in the quality of the results are valuable contributions to the design effort.

Environment

The environment category refers to the various conditions at an airport location and how those conditions impact maintenance. The category has two properties: *meteorological* and *geological*.

Meteorological. The local weather conditions are likely the most significant factor affecting maintenance strategies after runway accessibility. This section describes how various weather conditions affect ALM strategies and the overall design of the maintenance program.

Snow. Most weather-related interviewee comments were about snow impacts. Snow itself can obscure in-pavement and elevated light fixtures. Snow drifts can cover sign panels. However, snow removal operations can cause several problems. Snowplows routinely knock down elevated fixtures, lighted signs, and approach lighting in large quantities. Interviewee #2 described spending a day fixing taxiway lights and signs after a winter storm. Interviewee #1 stated that their airport typically loses hundreds of light fixtures each year due to snowplow damage. Interviewee #23 noted that while the airport sometimes hires additional staff in winter, those augmentees do not help with lighting repairs. Interviewee #21 said that snowplow damage to edge lights is their number one source of daily Part 139 inspection discrepancies during the winter months.

Addressing snow-removal-related damage is reactive maintenance; however, some airports take preventive measures by installing reflective rods on elevated fixtures in areas prone to damage to help make those fixtures more visible to snow removal teams. In addition, interviewee #21 found that curved sign faces can deflect the snow and are more resistant to snowblower damage.

Some interviewees from medium, small, and non-hub airports noted that the ALM staff became part of the snow removal team during a winter storm. For example, interviewee #14 said the electrical superintendent at their airport leads one of the snow teams during removal operations.

At moderate climate airports, where snow does not fall consistently through the winter, the unpredictability of snowfall complicates maintenance. Interviewee #21 describes how their geography makes the airport more susceptible to rapid weather changes. When snow events occur, the airport rapidly transitions to snow removal operations; however, the urgency of snow removal leads to more snowplow and snowblower damage to fixtures and signs. Interviewee #14 states that their airport typically has 1-2 significant snow events per year. As a result, the airport does not maintain large snow removal crews and will virtually stop all airside and landside maintenance temporarily to reassign those workers to snow removal operations.

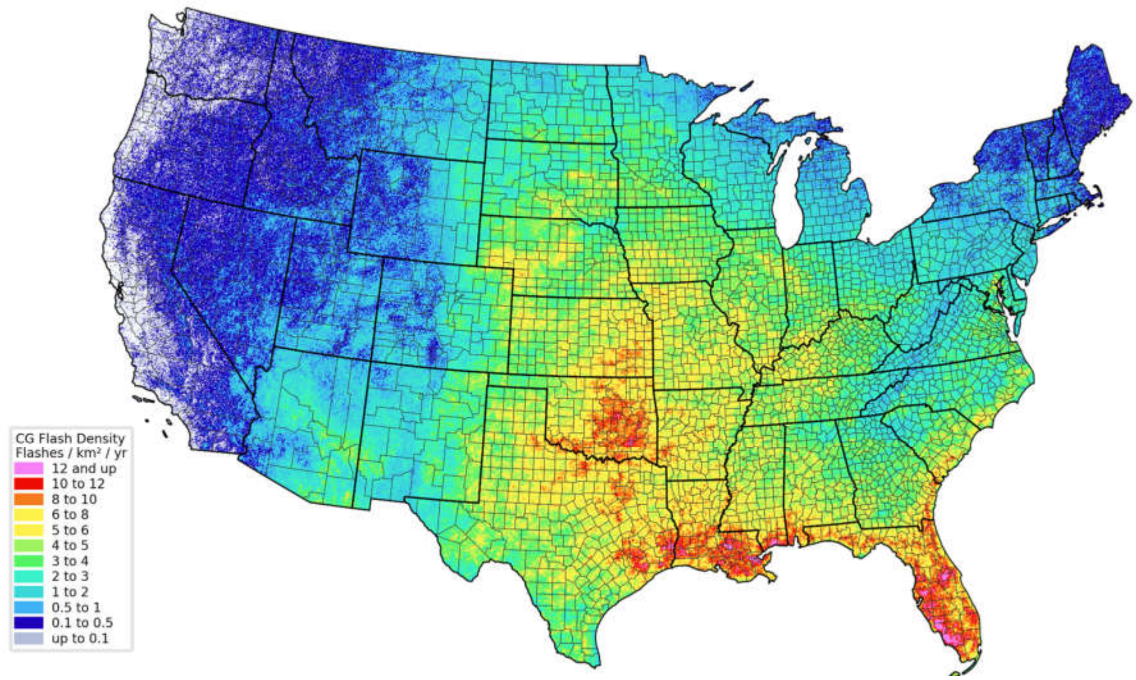
ALM strategy is affected by the average snowfall at the airport. Airports can staff accordingly when there is consistently snowy winter weather, allowing ALM to be more consistent in the Winter. However, when snow removal operations are unpredictable, the ability of the ALM staff to adhere to scheduled maintenance in the Winter may become more challenging.

Lightning. Lightning impacts were the second most common weather-related comments from interviewees. Fixture 16 illustrates the areas of the United States with higher and lower average numbers of lightning strikes over five years.

Interviewees stated that the unpredictability of lightning strikes is the most significant impact on maintenance strategy. High points on airports, such as the Air Traffic Control Tower and the airfield beacon, are common strike points, according to Interviewees #11 and #19. However, the location and extent of damage from lightning strikes are highly variable. For example, one interviewee was frustrated when a lightning strike damaged more runway edge light fixtures than they had spare parts to replace. Good relations with a nearby airport facilitated quick access to additional fixtures, but locating a qualified electrician took time and resulted in issuing a NOTAM for several days. Interviewees #3 and #11 described lightning damage to their PAPI units requiring electrical repair expertise. Interviewee #8 described lightning damage as the most challenging type of repair, "first you have to find where it's struck. That's not always easy. It's not like there are always burn marks on top saying, look, trouble here!"

Figure 16

Average U.S. Cloud-to-Ground Flash Density in 2015-2019



Note: *Vaisala Annual Lightning* Report 202*0*,

(https://www.vaisala.com/sites/default/files/documents/WEA-MET-Annual-Lightning-Report-2020-B212260EN-A.pdf). Copyright 2021 by Vaisala. Reprinted with permission.

Ensuring that the lightning protection system is designed correctly in the first place is the primary preventive method that ALM staff can do to minimize the risk of lightning damage. In addition, ALM managers should consider that areas with more average annual lightning strikes will result in higher levels of reactive maintenance. Statistical analysis of historical lightning damage may assist ALM managers with determining the times of year that lightning damage is frequent and possibly help estimate an annual budget allowance for lightning damage.

Winds. High winds are a property that affects maintenance at some airports more than others. After replacing their PAPI units, Interviewee #13 noticed that "they're not as beefy as the other ones, and we are always having to readjust these new ones because of the winds. The last ones … the only time we had to adjust them was when someone would knock them with a plow." Because of steady high winds and sand, Interviewee #4 said, "once per year we have to open, pull the panels [of their signs], wipe them down inside and out, and literally take a leaf blower and blow all the dirt out of the structure itself." Interviewee #11 found that winds shake the light fixtures and cause damage, stating, "In the Wintertime, it's really windy. We probably have three times the burn-outs." Interviewee #15 described the occasional "joy ride" where high winds drive aircraft off the centerline and into the runway or taxiway edge lights.

Winds are likely to increase the amount of reactive maintenance activities due to the unpredictable nature of the damage's occurrence, location, and extent. Therefore, statistical analysis of historical wind damage may assist ALM managers with determining the times of year that wind damage is more likely, and possibly help estimate an annual budget allowance for wind damage.

Rain. The negative impact of rain on airfield lighting maintenance is primarily filling the underground duct system with water. The cables, connectors, and isolation transformers are more susceptible to damage when the water does not drain from the duct system. Water is the most common cause of problems in airfield lighting systems, facilitating metal corrosion and higher rates of electrical insulation deterioration (FAA, 2014a). ALM managers can minimize the problem by ensuring that capital improvement project designs include drains for the duct system. Where the duct systems will not drain naturally, ALM staff can remove water using pumps. However, according to Interviewees #6 and #11, removing standing water from duct systems is much more difficult in areas with frequent rain or high water tables. Using analysis of work order history and an understanding of the airport topography and soil types, ALM managers may find areas of the lighting system with greater exposure to standing water. After locating these areas, managers can expect higher rates of asset failure in those areas and recommend measures to improve drainage.

Freezing Temperatures. Water freezing inside light bases can damage transformers, cable connections, and crush the bottom of the base (Interviewee #1). Repair time significantly increases when the light base that holds the isolation transformer and electrical connections is a block of ice (Interviewee #1). Frozen soil makes excavating damaged cables more time-consuming and expensive (Interviewee #12). Freezing temperatures reduce battery life on tools (Interviewee #23). Work productivity is very low in the winter, so ALM managers try to complete extensive repairs during warm weather (Interviewee #22).

Sunlight and Heat. Sunlight causes sign panels to fade, causing them to exceed FAA color tolerances, particularly the south-facing panels (Interviewees #3 & #8). Interviewee #21 found that curve-sided signs fade slower than flat-sided signs. Because color is an essential factor for identifying the purpose of a sign, annual Part 139 inspections may include the examination of sign panel conditions. Furthermore, extreme heat reduces maintenance productivity (Interviewee #8).

Geological. The ability of the underground conduit system to drain water can significantly impact the lighting system's reliability and maintainability. The capability of the conduit system to drain can depend on the type of soil and the elevation of the water table. Interviewee #6 described how the conduit systems fill with water when farmers flood nearby fields. Interviewee #1 is trying to ensure that future lighting system projects include conduit drainage systems because of standing water's impact on maintaining the lighting, especially when it freezes.

Engineers can design airfield lighting conduit systems to be *wet* systems that allow water infiltration and facilitate the rapid drainage of water into the soil or *dry* systems with sealed openings to prevent water infiltration (Schai, 1986). The appropriate decision depends on the local soil conditions and water table (Schai, 1986).

Where conduit systems hold water, the rate of deterioration is higher for lighting cables, transformers, and connector kits (FAA, 2014a). The higher rate of decline may slightly increase reactive maintenance for cable faults each year. Because of the reduced expected life, the life-cycle cost of systems with standing water is higher than systems that will drain. However, the increased cost is spread over many years and may not be obvious. Designing and installing a conduit drainage system requires surveyors, engineers, and heavy equipment that may be unavailable to airport maintenance staff. Therefore, these upgrades are more appropriate for capital improvement projects. However, planners and engineers may not be aware of the impact of standing water on maintenance. Also, there is no benchmark data for maintainers or engineers to compare and determine if the cable deterioration rate of their system is more significant than should be expected.

Impetus

The *impetus* category refers to the need for a driving force to instigate changes to the maintenance program. Three properties describe the impetus of a maintenance management program: *legacy*, *bottom-up*, and *top-down*.

Legacy. ALM managers inherit *legacy* maintenance programs developed by their predecessors. Interviewee #14 described how operations and maintenance have worked together for many years and developed a program that works very well. Interviewee #16 states, “I think if you take a look, in most large organizations, things get done because this is the way they’ve always been done.” Even in smaller organizations, there may be no apparent reason to initiate change. Interviewee #9 described continuing the same practices since beginning the job five years prior. Legacy programs may perform well, but ALM managers should rely on data demonstrating that the maintenance program successfully meets objectives. Legacy maintenance programs often lack tools that measure success, as discussed later in the section on measures of performance effectiveness.

Bottom-Up. The *bottom-up* property refers to when ALM staff identify and implement changes to the maintenance program based on their training or experience. For example, maintenance staff routinely monitor cable insulation resistance degradation to determine when to repair a cable. However, Interviewee #1 analyzed multiple insulation resistance trends and contacted the engineering department to plan a large-scale cable replacement project. By predicting cable failure years in advance, Interviewee #1 could reduce excessive reactive maintenance in the future. Interviewee #10 describes how the director of facility maintenance regularly solicits improvement ideas from the shop superintendents. This approach led to accomplishing a long-term project to retrofit lighted signs with new LED technology and reduce the asset failure rate. Many lighted signs are located outside the RSA, which allowed the maintenance staff to do the modifications during both day and night shifts.

Top-Down. *Top-down* changes occur when senior airport managers initiate programs that result in changes to the maintenance management programs. The implementation of asset management programs is an example of a top-down change. Airport energy audits have identified that transitioning to LED lighting technology can reduce electrical utility costs and have been the initiative behind lighting and signage upgrades (Interviewee #3).

Part 139 CertAlert No. 14-03 Preventive Maintenance of In-Pavement Lighting Systems might be considered a top-down initiative for change to ALM programs nationwide initiated by the FAA resulting from lessons learned. However, the CertAlert did not change maintenance requirements; instead, the document emphasized the importance of complying with the requirements already described in FAA advisory circulars.

Regulations

ALM managers must develop maintenance programs in compliance with the airport regulations. The two types of regulations with the most impact on maintenance strategy selection are *Part 139* and *FAA* requirements. The airport must comply with Part 139 requirements to operate. FAA inspectors check compliance by performing annual inspections. Compliance with FAA advisory circulars is equally binding for most airports; however, airports must internally police their compliance with the FAA AC requirements.

Part 139. ALM managers must prioritize ensuring their maintenance approach per the requirements of 14 C.F.R. Part 139. Airports within the research population must operate under Part 139 with specific requirements defined in their FAA-approved Airport Certification Manual (ACM) (General requirements, 2004). Part 139 requires airport managers to provide and maintain airfield lighting and signage per FAA advisory circulars (Marking, signs, and lighting, 2004; FAA, 2018a). Paragraph 139.311 defines *proper maintenance* as “cleaning, replacing, or repairing any faded, missing, or nonfunctional item; keeping each item unobscured and clearly visible; and ensuring that each item provides an accurate reference to the user” (Marking, signs, and lighting, 2004). Paragraph 139.327 requires airport staff to conduct daily inspections, document the conditions found, document the taken actions, and maintain the inspection records for at least 12 months. Paragraph 139.339 states that where any lighting system, hold sign, or ILS sign is malfunctioning, the airport staff shall notify air carriers and issue a NOTAM.

Following daily inspections that identify problems with airfield lighting equipment, the standard action is to open a work order with the airfield maintenance staff. Depending on the type of failure, the maintenance staff will respond immediately or schedule the repair for a more convenient time. Identifying asset deficiencies or failures through inspections and then making repairs is considered reactive maintenance. The size of the airfield lighting system and its exposure to weather and aircraft traffic will inevitably lead to unexpected asset failures. Some amount of reactive maintenance should be expected for any airfield lighting maintenance program because making an entire lighting system immune to failure would be impractical. However, as discussed later, making repairs by reacting to inspection findings is an inefficient maintenance method. Part 139 does not recommend a maintenance strategy. Instead, Part 139 establishes the minimum standards. A maintenance program that complies with Part 139 requirements alone is not necessarily safe or efficient unless the program also addresses FAA AC 150/5340-26 *Maintenance of Airport Visual Aid Facilities*.

FAA Requirements. Two FAA advisory circulars are directly relevant to airfield lighting maintenance, FAA AC 150/5340-26 *Maintenance of Airport Visual Aid Facilities* and FAA AC 150/5345-30J *Design and Installation Details for Airport Visual Aids*. The latter AC describes the design of airfield lighting systems and can be a reference for training, modifications, repairs, or replacements (FAA, 2018a). The AC for maintenance includes the requirements for safety, maintenance management, preventive maintenance programs, troubleshooting practices, and the required performance standards for the airfield lighting equipment and system. The AC for maintenance states, "In general, use of this AC is not mandatory. However, use of this AC is mandatory for all projects funded with federal grant monies through the Airport Improvement Program (AIP) and with revenue from the Passenger Facility Charges (PFC) program" (FAA, 2014, p. i). The General Accounting Office (GAO) found that from 2009-2013 large and medium hub airports funded 39% of their capital projects using AIP or PFC funds, and small and non-hub airports funded their projects with 73% AIP and PFC funds (GAO, 2015). Therefore, for most small and non-hub airport projects, compliance with the FAA AC for visual aids maintenance is mandatory. Large hub airports may generate sufficient revenue to fund some projects without federal support.

Staff

Three properties describe the staff category: *size*, *skills*, and *experience.*

Size. The staff size property refers to the number of staff performing ALM. Because staff capabilities vary depending upon their training and responsibilities, ALM managers should consider the staff size within each of the following categories:

- non-electrician – multi-tasked
- non-electrician – dedicated to ALM
- electrician – multi-tasked
- electrician – dedicated to ALM

Safety regulations limit non-electricians to only performing maintenance that does not expose them to electrical safety hazards. Therefore, ALM managers without electricians must augment the staff with qualified electricians to perform hazardous maintenance and repairs, typically by a subcontract. To do so, the ALM manager must understand which tasks require qualified electricians and which do not.

None of the interviewees discussed outsourcing for safety reasons alone; however, several described hiring contractors for work that requires special skills, such as working on the lighting control system computers. This type of outsourcing was common for ALM staff at airports of all sizes. Interviewees also described hiring contractors to perform repairs that demanded more time from the in-house staff. On the other hand, one interviewee preferred to avoid out-sourcing work. They felt that in-house electricians perform a higher quality of work because they know they must maintain the completed work in the future. Also, completing the job with in-house staff allowed them to understand the equipment details better.

When ALM is only a portion of the maintainer’s responsibilities, there may be limited time for preventive maintenance. Reduced maintenance may reduce the equipment's remaining useful life (RUL) and increase the system's life-cycle cost. The maintenance manager should compare the asset life-cycle costs with and without preventive maintenance to determine whether the savings justify dedicated staff's increased labor costs. However, maintenance managers at small and non-hub airports may not have the training or the time to perform such analysis.

Skills. The skills property includes professional training and skills acquired by ALM staff before and after hiring. Below are the four basic types of training applicable to ALM staff:

- electrical journeyman’s license
- on-the-job training
- manufacturer training
- AAAE ACE Training

ALM staff at some medium and all large hub airports interviewed for this research required an electrician’s license for all ALM staff. Managers at small and non-hub airports would use multi-tasked, non-electricians to perform lighting maintenance because the airport's lighting and power maintenance workload does not justify a full-time electrician. When no trained electricians are on staff, airport managers must organize maintenance programs to avoid exposing non-qualified persons to electrical hazards.

All interviewed ALM staff conducted on-the-job training. AFL systems are unique to airports, and each lighting system is custom-designed for each airport. As a result, all interviewees stated that they do not expect new applicants to have training or experience with airport systems. Each airport must develop its training program based on its needs and resources. Training programs should consider whether the individual has experience as an electrician. Training should also consider the equipment and tools available to the trainee to perform maintenance. Despite complying with identical maintenance requirements for the same equipment, maintenance practices at small and large hub airports will differ because of differing priorities and resources. Establishing and implementing a basic training program can be challenging for a small or non-hub airport with limited resources.

Interviewee #2 stated their management considered hiring a contractor to perform insulation resistance testing. FAA standards recommend testing each circuit monthly (FAA, 2014a). The test measures the condition of the cables and helps predict when repairs are required (FAA, 2014a). Again, the cost of performing regular insulation resistance testing should be compared to the impact on the life-cycle cost of cabling when not performing such testing. There may be justification for establishing a recurring testing contract or installing automated testing equipment and training staff to read the results, particularly in older cables. This kind of outsourcing is an example of how managers might modify their maintenance approach to reduce asset life-cycle costs.

ALM managers may utilize skilled staff by accomplishing capital improvements with in-house personnel. Capital improvements are typically large projects that improve the infrastructure and are completed by construction contractors. However, Interviewees #10 and #15 described using in-house staff for a long-term program to replace lighting equipment over time. When in-house staff has the appropriate skills and time, such projects can significantly reduce asset system life-cycle costs by reducing the installation cost.

Within the United States, training outside the airport is available from one industry organization and several manufacturers. AAAE provides training courses and certifications for various airport fields, including airfield lighting maintenance (AAAE, 2021). However, the curriculum covers maintenance and repairs that unqualified persons should not perform, and the virtual course does not provide hands-on equipment training. Manufacturers' training is unregulated, so it can be customized to the needs of the attendees and is more likely to include hands-on training. Additionally, such training often includes travel expenses that limit accessibility for many staff.

While training courses are available, ALM managers typically train new staff on the job. As a result, worker efficiency and proficiency increase with experience. In addition, training and experience are necessary to design an ALM program and select maintenance strategies appropriate to the airport. Managers may hesitate to change legacy practices when such expertise is unavailable locally. The section on the category of *impetus* previously discussed this hesitancy.

Experience. Managers should consider the staff's experience with airfield lighting when selecting a maintenance strategy. In general, previous experience with electrical maintenance is beneficial, but experience performing airfield lighting maintenance is the most valuable. As previously described, training is difficult to obtain, and developing proficiency requires the regular practice of skills. Additionally, maintenance practice changes according to the various categories described in this research. The uniqueness of airports means that experienced ALM staff are critical to minimizing life-cycle costs.

RQ2 – Maintenance Strategies in Use at U.S. Commercial Service Airports

The interviewer asked participants to describe their maintenance strategy rather than ask for their strategy's name. Based on the descriptions of maintenance strategies provided by the representatives from each airport, the researcher developed a taxonomy of the various strategies currently being used at the sample airports. This study divides ALM maintenance strategies into two groups, corrective and preventive. Both are essential to ALM maintenance; however, preventive maintenance is more efficient. Interview results show that managers try to minimize corrective maintenance and maximize preventive.

Table 6 summarizes the coding results for interview questions seeking to identify maintenance strategies currently in use by airfield lighting maintenance staff. A total of 907 code references supported the development of 19 high-level focused codes divided among the eight categories shown as subtables. The second and third columns indicate the number of references from transcripts and the percentage of total transcripts referenced. Higher quantities and percentages represent that more airports contributed comments related to the focused code listed in the first column. A smaller percentage indicates fewer airports described their maintenance strategies using comments related to the focused code. For example, the focused code *staying aware of construction projects* was developed using comments from only three transcripts. This small number indicates that fewer airports discussed keeping track of capital construction when describing their maintenance strategy.

Table 6

Number of References for Each Focused Code Related to Categories Describing Current Maintenance Strategies

Focused Code	No. of Transcripts Referenced	Percent of Transcripts Referenced	No. of Individual References
Outsourcing			
Using Contractors to Help	14	93%	79
Total	14	93%	79
Prioritization			
Prioritizing Work	15	100%	115
Total	15	100%	115
Reactive Maintenance			
Describing Reactive Maintenance	12	80%	33
Total	12	80%	33
Record Keeping			
Describing Record Keeping – What	13	87%	32
Describing Record Keeping – Where	12	80%	55
Describing Record Keeping in General	8	53%	57
Explaining the Work Logging System	13	87%	91
Total	15	100%	235
Responsibilities			
Addressing Safety Hazards	6	40%	18
Conducting Inspections	14	93%	80
Describing Lighting Maintainers Responsibilities	14	93%	58

Focused Code	No. of Transcripts Referenced	Percent of Transcripts Referenced	No. of Individual References
Describing Who Does Inspections	11	73%	35
Describing Specific Maintenance Tasks	11	73%	37
Describing How Parts Stock is Managed	13	87%	48
Staying Aware of Construction Projects	3	20%	6
Overcoming Challenges	10	67%	23
Total	15	100%	305
Scheduled Maintenance			
Describing Scheduled Maintenance	13	87%	79
Total	13	87%	79
Scheduled Work			
Managing the Work Schedule	4	27%	25
Total	4	27%	25
Technology			
Describing the Impact of New Technologies	4	27%	18
Describing Remote Monitoring	5	33%	18
Total	9	60%	36

The matrix coding query in Table 7 graphically illustrates which category contained the most references and the extent to which each airport staff contributed comments. The table indicates that the most significant part of the discussion on this topic was maintenance staff responsibilities and record-keeping methods. The table also illustrates that reactive and scheduled maintenance discussions were relatively limited.

The lesser discussion time for these topics likely indicates that the strategies were easily described by the participant and well understood by the interviewer. Lastly, note that the number of comments on the responsibilities category tends to decrease in the later interviews. The downward trend partly illustrates the interviewer's learning curve and the reduced need for detailed explanations of maintenance strategy during the later interviews. These maintenance strategies are fully described in the following sections.

Table 7

Matrix Coding Query of Airport Interview References to Each Category Related to Maintenance Strategies Currently in Use

AIRPORT #	OUTSOURCING	PRIORITIZATION	REACTIVE MAINTENANCE	RECORD KEEPING	RESPONSIBILITIES	SCHEDULED MAINTENANCE	SCHEDULED WORK	TECHNOLOGY	LINE TOTAL
1	0	9	1	14	33	9	4	12	82
2	5	2	3	17	36	5	1	3	72
3	13	32	1	18	28	10	0	1	103
4	1	15	2	4	28	11	5	2	68
5	3	7	1	8	18	3	0	1	41
6	7	8	12	13	18	10	11	0	79
7	7	8	1	7	11	1	0	0	35
8	4	3	0	6	15	7	0	10	45
9	1	1	1	19	8	5	0	0	35
10	8	5	2	18	23	0	0	0	56
11	1	4	2	27	27	8	0	0	69
12	2	7	5	31	12	0	0	2	59
13	4	2	0	23	14	8	0	1	52
14	2	1	1	16	15	4	0	0	39
15	1	1	0	3	9	5	0	4	23
COLUMN TOTAL	59	105	32	224	295	86	21	36	858

Note. Quantities in each cell illustrate the number of references from each airport interview transcript assigned to each category/factor. The warmer-colored cells indicate the highest number of references. The cooler-colored cells indicate the lowest number of references.

Corrective Maintenance

This study defines corrective maintenance as "activities undertaken (or repair actions taken) due to observed or measured conditions of an asset after or before the functional failure. These repair actions will restore the asset to normal operating conditions” (Gulati, 2021, p. 73). The strategies identified during this research include the three types explained below. Interviewees regularly described the use of both types of reactive maintenance. Interviewees did not describe using Run-To-Failure maintenance; however, the description below differentiates the practice from reactive maintenance.

Some interviewees seemed to consider reactive maintenance a bad practice. Reactive maintenance is less efficient than other maintenance strategies because the approach can be disruptive to work schedules and cause higher repair costs (Gulati, 2021). However, the analysis concludes that reactive maintenance is unavoidable in airfield lighting maintenance because of the inability to control all factors affecting the equipment, such as lightning strikes or runway/taxiway excursions. All staff interviewed described using reactive maintenance practices at least a portion of the time.

Also, reactive maintenance is the default program when no maintenance program or a minimal program exists. Reactive maintenance occurs when staff reacts to problems after identifying them. Airports with limited maintenance staff may need to use primarily reactive practices for airfield lighting because preventive maintenance is considered optional. Larger maintenance organizations typically implement other forms of maintenance but always include reactive maintenance to some extent. Reactive maintenance takes two forms, emergency and scheduled.

In this study, performing routine inspections is not considered corrective maintenance. However, the actions taken due to inspection findings are corrective maintenance.

Reactive Maintenance (Emergency). Emergency reactive maintenance is often required when inspections identify an unsatisfactory condition or functional failure of a high-priority asset, and ALM staff must take action immediately. For example, this may include the runway edge lighting circuit losing power unexpectedly during low visibility while the runway is open. The urgency may also depend on the frequency of aircraft operations or the ability to reroute traffic to another runway. Emergency response requires ALM staff to be at the airport or on-call if the response time allows.

Reactive Maintenance (Scheduled). Scheduled reactive maintenance is required upon identification of an unsatisfactory condition or functional failure of the asset, and ALM staff can schedule the repair at a convenient time. For example, when routine inspections identify that a single runway edge light is out and they forward the inspection finding to the maintenance staff to address. Because Part 139 requires daily airfield checks and inspection logs, scheduled reactive maintenance is another standard part of airfield lighting maintenance. Often, the operations staff perform daily lighting inspections. At larger airports, where separate operations and facility maintenance departments exist, work logging requires a process to communicate the opening and closing of inspection findings.

Run-To-Failure (RTF). When the cost and impact of preventive maintenance are greater than the cost and impact of asset failure, maintenance managers may elect not to perform routine maintenance on certain equipment and choose to replace the asset after identifying a failure. Selecting this strategy may be a logical choice based on the maintenance economics. Obstruction light maintenance is an example because these fixtures are often in difficult-to-reach locations. Installing a dual obstruction lamp means that a second lamp will continue to operate and provide the obstruction warning when a lamp fails. Maintainers then replace both lamps when upon discovering the outage. No interviewee mentioned using a run-to-failure strategy in their program. However, maintainers may still use this strategy even though they do not recognize that forgoing maintenance is a reasonable approach in some situations. Recognizing which equipment is using a run-to-failure strategy is vital so that measures are in place to ensure maintenance staff notice failures when they occur and can provide corrective maintenance within an acceptable timeframe.

Preventive Maintenance (PM)

PM is "activities involved in systematic, planned inspection and component replacement, at a fixed interval, regardless of the asset's condition at the time" (Gulati, 2021, p. 74). Inspections are considered PM. Two types of inspection programs are described below. PM also includes maintenance tasks. Maintenance tasks may be completed based on inspection results, warning devices, or a schedule. None of the interviewees described the use of Predictive Maintenance (PdM) as defined herein, but PdM is discussed later as a potential alternative strategy.

Operator-Based Inspections. This term comes from production line maintenance, where the equipment operator assumes specific maintenance responsibilities (Gulati, 2021). In this case, the term *operator* refers to the airfield operations staff performing daily airfield inspections. However, due to airport staff size limitations, the operations staff regularly perform lighting maintenance at small and non-hub airports. At airports of all sizes within this research, the operations staff routinely participates in airfield lighting maintenance by conducting inspections and work scheduling decisions. Therefore, operator inspections are a crucial part of the ALM process.

Interview discussions found that operations staff frequently record findings in a database separate from those of the facility manager. The duplication of effort likely occurs because of the Part 139 requirement for the operations staff to maintain records of inspections conducted and the resulting actions. Where airports keep separate databases, interviewees described various methods to bridge the data regarding inspection findings and resolution of problems.

Time-Based Inspections. The FAA and manufacturers recommend that ALM staff perform maintenance on airfield lighting assets regularly. Where regular inspections identify unsatisfactory conditions or functional failures, a reactive maintenance action is conducted immediately or scheduled in the future.

In this description of time-based maintenance, different skill levels require the separation of some inspections. As previously discussed, the operations staff conducts regular, time-based maintenance inspections. For example, some interviewees reported that operations staff, rather than electricians, will perform photometric testing at their airports. Identifying a fixture that is not functioning requires little training. However, troubleshooting and safely repairing the fixture may require specialized training and equipment.

Time-Based Maintenance. Some maintenance actions are scheduled for completion regularly without requiring an inspection to justify the work. For example, ALM staff may elect to replace a group of light fixtures or individual lamps rather than individually inspect each asset for condition or function and then make spot repairs. This maintenance approach can be costly because it requires a larger stock of fixtures. However, the cost may be justified when maintenance access time on the runway is limited and the consequences of fixture failure are high. Furthermore, the practice can increase overall maintenance efficiency by reducing inspections, reducing the need to prepare work orders for individual failures, and reducing the number of spot fixture repairs. The average usable life of fixtures receiving regular maintenance is likely longer than the life of fixtures that do not receive such maintenance. Therefore, the fixture life-cycle cost is less for the routinely maintained fixture.

Condition-Based Maintenance (CBM). A condition-based maintenance strategy involves scheduling maintenance as needed based on the asset condition. Maintainers measure an asset's condition using an inspection or remote monitoring device. For example, airfield lighting cables typically use CBM. The FAA maintenance AC recommends that ALM staff measure each cable's insulation resistance regularly. Results are recorded for analysis while also noting weather conditions. ALM staff can estimate the future state of lighting cables by comparing the changes in measurement data on similar weather days over time. CBM is less costly than time-based methods because the method allows for performing maintenance only when needed (Gulati, 2021). In addition, because CBM can predict and address failures before they occur, the approach should result in fewer outages compared to using time-based inspections with reactive maintenance.

Reliability-Centered Maintenance (RCM). In the 1960s, United Airlines developed RCM for aircraft maintenance when actual operating data began contradicting the intuitive assumption that equipment reliability was directly related to scheduled maintenance (Nowland & Heap, 1978). The United team sorted through potential maintenance tasks, identified those necessary for safety or function, and then evaluated the remaining tasks to determine if they were economically advantageous (Nowlan & Heap, 1978). The principles of RCM stem from the examination of three questions:

- How does failure occur?
- What are the consequences?
- What good can preventive maintenance do? (Nowlan & Heap, 1978).

The asset management program described by the ACRP recommends using an RCM program (ACRP, 2012a). However, none of the ALM staff interviewed described using RCM techniques in their maintenance programs. As described in the earlier literature review, implementing an asset management program is a multi-step process of creating an asset inventory, finding individual asset failure modes, estimating residual life, calculating life-cycle costs, setting target levels of service, and determining the business risk. With this data, the manager can select a suitable maintenance strategy.

To be precise, RCM is a maintenance strategy selection method recommended for asset management programs rather than a single strategy. However, since United originally designed RCM for aircraft maintenance, the system does not consider other factors such as runway access time or working environment appropriate for extensive asset systems such as airfield lighting. Furthermore, many airports may not have the resources to implement an asset management program fully or to conduct the required equipment analysis. Therefore, maintenance managers may consider only using RCM for assets critical to operations and expensive to maintain. Fitzgerald & Seamster (2019) recommend that maintenance managers consider first implementing asset management on a small scale to prove the program's benefits.

Predictive Maintenance (PdM). Some authors describe PdM interchangeably with CBM (Gulati, 2021; Kim et al., 2016); however, this study distinguishes PdM as a practice using advanced data analysis of condition assessments. Poor et al. (2019) describe PdM as a feature of the fourth industrial revolution, the development of the internet. In addition to using advanced sensors and wireless networks to collect maintenance condition data, PdM also takes advantage of the Internet of Things, Big Data, Cloud computing, and artificial intelligence (Poor et al., 2019). For example, the software Maximo Predict analyzes the collected maintenance data and "looks for patterns in asset data, usage, and the environment, and correlates those patterns with any known issues to help reliability engineers and maintenance managers predict failures and share data and scoring" (IBM, n.d.).

Like Run-To-Failure, none of the interviewees mentioned using PdM practices. However, several interviewees said their airport uses Maximo software to support asset management. Potentially, ALM staff or automated sensors could upload maintenance data. Then, a cloud-based artificial intelligence could analyze the data and generate maintenance recommendation reports. Because medium and large hub U.S. commercial service airports likely already have computers monitoring and controlling their airfield lighting systems, a large portion of the needed infrastructure already exists. In addition, at least one airfield lighting equipment manufacturer already provides a cloud-based maintenance data management service (ADB-Safegate, 2021). While the service does not advertise data analysis for predictive maintenance, the system includes the necessary infrastructure for cloud-based predictive maintenance.

RQ3 – Theory of Airfield Lighting Maintenance Strategy Selection

The presented theory provides a normalized description of the current process of maintenance strategy selection used by ALM managers at U.S. primary commercial service airports. Interviewee input and data analysis generated the eight criteria that summarize factors relevant to the maintenance strategy decisions. The decision alternatives are a list of current maintenance strategies and two options suggested by the literature. The current practice uses intuitive decision-making rather than the rational processes typical of MCDM. Therefore, developing a rational approach may improve the quality of maintenance strategy selection decisions.

Table 8 includes the focused codes generated from interview discussions consolidated under a category called *Decision-Making*. The second focused code regarding the impact of third parties was generated from interview discussions about how outside agencies such as the airlines, the FAA, or the public affect maintenance. Data analysis indicated that third parties are not an influential factor in selecting maintenance strategy. Comments about airfield lighting maintenance from third parties were shown to be uncommon. However, the occasional third-party comments can affect daily decision-making by managers because such concerns often become high-priority maintenance tasks.

Additionally, the research showed that mid-level and senior-level managers primarily make maintenance strategy decisions based on their training and experience. None of the interviewees discussed the use of quantitative measures in decision-making. The matrix coding query Table 9 illustrates the number of references from each airport interview that contributed to developing the three focused codes listed in Table 8.

Table 8

Quantity of References for Decision-Making Category

Focused Code	No. of Transcripts Referenced	Percent of Transcripts Referenced	No. of Individual References
Making Maintenance Decisions	14	93%	68
Describing How Third Parties Impact Maintenance	9	60%	36
Working With Operations	7	78%	17
Total	14	93%	121

Table 9

Matrix Coding Query of Airport Interview References to Each Category Related to the Strategy Selection Process

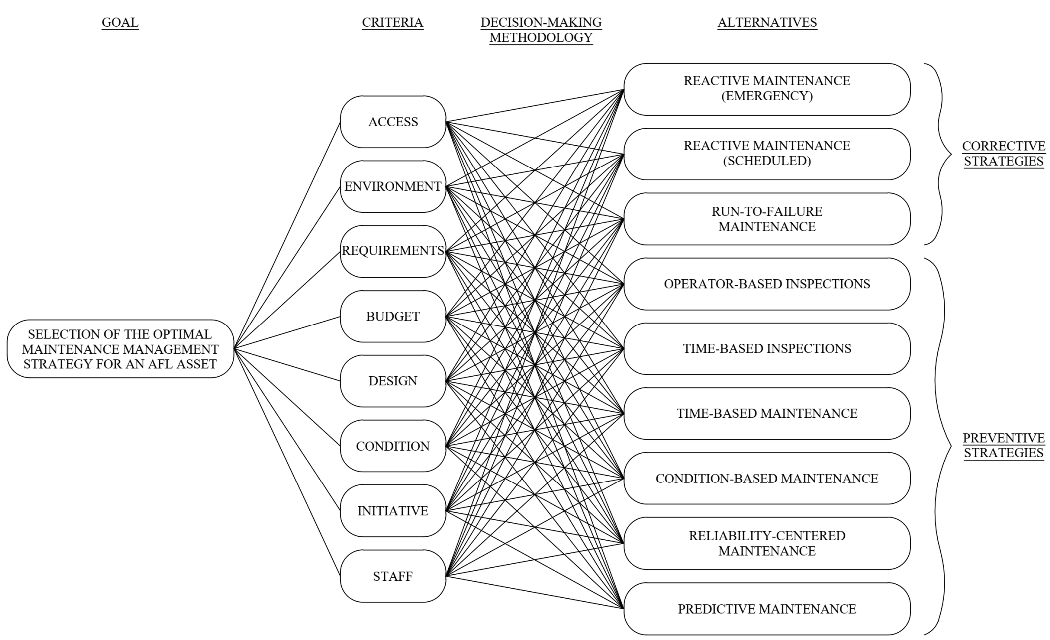
AIRPORT #	DECISION MAKING
1	8
2	1
3	13
4	16
5	11
6	9
7	4
8	13
9	11
10	8
11	8
12	9
13	1
14	6
15	0
COLUMN TOTAL	118

Overview of the Theory

The constructed theory describes the current process of selecting the proper maintenance management strategies for airfield lighting assets considering the relevant criteria. Data analysis indicated eight relevant criteria and nine potential maintenance strategy alternatives. Figure 17 illustrates the goal question, criteria, and alternatives using the format of a Multiple-Criteria Decision-Making (MCDM) problem (Shafiee, 2015). In the MCDM approach, a decision-maker selects or ranks alternatives using a set of weighted criteria according to their importance. Additionally, the illustration highlights that a form of decision-making methodology is also needed to solve the problem. The selection methodology depends on the problem to be solved.

Figure 17

AFL Maintenance Strategy Selection Process Modeled as an MCDM Problem



Note. The author developed the diagram based on the research.

Goal

The problem goal is to select the optimal maintenance management strategy for airfield lighting assets. Individual assets may have different maintenance strategies, so maintenance managers should use the process separately for each asset, adjusting the criteria appropriate to local conditions.

Criteria

The criteria are those factors uncovered from the research that significantly impact the maintenance strategy selection for the asset. The MCDM method allows the criteria to be either qualitative or quantitative. The level of impact of the criteria varies based on the airport and the asset. For example, light fixtures on the runway at airports with high ground traffic may require preventive maintenance more frequently than similar fixtures at airports with lower traffic levels. On the other hand, ground traffic may not affect the maintenance of lighting control equipment within the airfield lighting vault facility.

Maintenance managers may have limited control over criteria such as access, environment, and regulations. However, managers may be able to exert influence over the other listed criteria. For example, changes to the design of the airfield lighting system, such as the installation of automated insulation resistance metering, could assist in establishing a condition-based maintenance strategy for airfield lighting cables.

Alternatives

Alternatives are the potential maintenance strategies assignable to individual assets determined through the investigation of research question two (RQ2). U.S.

commercial service airports contacted during this study currently use all the strategies shown in Figure 17, except for Run-to-Failure and Predictive Maintenance.

Decision Methodology

To select or rank the alternatives, the MCDM approach allows various decision-making approaches such as utility theory, simple additive weighting (SAW), analytic hierarchy process (AHP), analytic network process (ANP), the technique for order of preference by similarity to ideal solution (TOPSIS), Višekriterijumsko kompromisno rangiranje (VIKOR), elimination and choice translating reality (ELECTRE), and others (Shafiee, 2015). While SAW is the simplest method, the AHP method is the most widely used (Shafiee, 2015).

However, this research found airports using intuitive rather than rational decision-making approaches when selecting maintenance strategies. Decision-making approaches vary based on available staff expertise. For example, at one small hub airport without electricians on staff, the interviewee said that the Aircraft Rescue and Fire Fighting (ARFF) manager or shift captain made important maintenance decisions. On the other hand, the lead electrician at one large airport noted that senior management was unfamiliar with the technical aspects of airfield lighting maintenance and highly regarded the maintenance staff's recommendations. The interviewee at a mid-size airport had several experienced electricians on staff, allowing for discussion of maintenance decisions before they were final. In virtually all cases, high-cost maintenance actions require the approval of senior airport management.

Unfortunately, many companies still avoid quantitative decision-making methods, perhaps because managers fail to appreciate that such tools are human-centered processes

(Bernroider & Schmöllerl, 2013). Furthermore, Asadabadi et al. (2019) argue that decision-makers lack confidence in such tools because even the most popular methods, such as AHP and ANP, can generate irrational results.

Interview results illustrate that some strategic maintenance decision-making occurs at high organizational levels, often involving the Operations department and the airport director. For example, according to Interviewee #1, senior management was the driving factor in converting light fixtures to LED technology, despite a lack of positive consensus from the ALM staff. However, there is a limit to the extent of maintenance strategy changes directed by ALM managers. Senior airport managers or city board members are involved in decisions potentially resulting in high costs, according to Interviewees #6, #12, #14, and #17. For example, according to Interviewee #16, the high cost of outsourcing photometric testing resulted in senior management directing the ALM staff to obtain equipment and training so that airport staff could do the work.

Some airports have engineering staff assigned to support the airfield maintenance staff, while others only use engineers to manage the planning and execution of capital projects. For example, Interviewee #16 was an engineer dedicated to improving lighting system maintainability and reducing life-cycle costs using asset management practices. However, Interviewee #15 stated that engineers rarely provide input to maintenance activities at their airports.

ALM managers solicit maintenance strategy input from staff outside and inside the electrical department. For example, Interviewee #14 stated that they would discuss any significant changes to maintenance with the Operations staff before implementation;

whereas, Interviewee #15 encouraged group decision-making, possibly because of the availability of other senior airfield electricians on staff.

The data illustrate that some ALM staff will collect input from stakeholders and pursue consensus among available technical experts when considering changes to maintenance strategy. However, ALM staff with less training and experience, as appears to be frequent at small and non-hub airports, may initiate fewer proposals for maintenance improvement. Additionally, ALM staff must prepare proposal arguments with sufficient clarity and simplicity to convince non-expert managers. Changes that increase costs require approval from senior airport or city managers. Using a deliberative approach to decision-making such as those described in the earlier section on MCDM may support arguments for change, especially when the change involves a technology investment. For example, suppose ALM staff can demonstrate that the industry-standard decision-making method for maintenance suggests their airport should purchase and install a condition-monitoring device to reduce life-cycle cost. In that case, their argument might be more compelling.

In sum, the decision-making methods vary extensively among airports. Where local ALM experts are available, interviews indicate their employment history rarely includes work at other airports. That lack of breadth of experience may limit knowledge of suitable alternatives. On the other hand, a rational decision-making process may suggest a previously unconsidered option.

RQ4 – Performance Indicators

ACRP guidance for asset management recommends that airport executives be concerned with a small set of KPIs, such as flight delays, connecting times, and baggage delivery efficiency (ACRP, 2012a). According to a performance measurement framework, these should be hierarchically supplemented with additional lower-level KPIs (ACRP, 2012a). Performance indicators are measures tied to a team's performance and aligned with organizational strategy, whereas *key* performance indicators are those indicators that are crucial to the organization's success (Parmenter, 2020). Because performance indicators are part of the asset management approach, this research investigated which indicators are currently used by ALM staff. Results include both qualitative and quantitative indicators.

Table 10 lists the categories and high-level focused codes developed from the analysis of interview discussions regarding performance measures. The small numbers of transcripts and individual references in Table 10, relative to other categories, suggest that maintenance data analysis for performance measurement is uncommon. However, Table 10 also illustrates that maintenance organizations often use quantitative measurements to evaluate performance. These often included only two types of data: the number of open work orders and the last cable insulation resistance test results.

Table 10

Quantity of References for Data and Feedback Categories

Focused Code	No. of Transcripts Referenced	Percent of Transcripts Referenced	No. of Individual References
Data			
Describing Data Analysis	9	60%	33
Total	9	60%	33

Focused Code	No. of Transcripts Referenced	Percent of Transcripts Referenced	No. of Individual References
Feedback			
Describing Part 139 Inspections	10	67%	43
Measuring Performance by Customer Feedback	9	60%	29
Measuring Performance in General	14	93%	43
Measuring Performance With Hard Data	14	93%	59
Total	15	100%	131

The matrix coding query shown in Table 11 illustrates the number of reference contributions from the individual airports to the two categories. For example, the low numbers for the data category illustrate that interviewees rarely described formal data collection as a performance evaluation method. Conversely, the consistently higher number of references under the feedback column illustrates the lengthy discussions about performance feedback used or considered.

Table 11

Matrix Coding Query of Airport Interview References to Each Category Related to Performance Indicators

AIRPORT #	DATA	FEEDBACK	LINE TOTAL
1	0	12	12
2	0	14	14
3	0	17	17
4	0	11	11
5	3	4	7
6	4	21	25
7	0	4	4
8	1	7	8
9	7	9	16
10	10	15	25
11	3	7	10
12	4	9	13
13	2	16	18
14	1	11	12
15	2	7	9
COLUMN TOTAL	37	164	201

Qualitative

Some interviewees described performance assessment measures using colorful phrases such as “no news is good news,” “my greatest compliment is when they don’t mention my name,” and “my best day is when there’s nothing that happens.” These phrases reflect using the number of complaints to measure success. Among the reported complaints, customers usually gave them to senior managers, who then passed them on to ALM staff. Reported complaints typically related to problems such as signs that were difficult to read and apron lighting spilling over to adjacent neighborhoods, indicating airport design problems rather than maintenance problems. However, Interviewee #3 mentioned a complaint received because of delays to repairs that resulted from a lightning strike. The airport did not have an electrician on staff to perform the repair and required time to hire an electrician, purchase parts, and complete the repairs.

However, no interviewee indicated that they formally tracked complaints about performance. Because there is no guarantee that customers or stakeholders will always submit complaints when appropriate, this qualitative measure may not effectively monitor performance.

Quantitative

Interviewee #10 uses the number of open airfield lighting work orders as their single KPI. KPIs are checked twice weekly, and exceeding 15 open work orders at one time indicates a problem. Furthermore, managers give a higher priority to work orders submitted by individuals outside of the maintenance organization. Interviewee #10 considered implementing a weekly KPI for the percentage of working lights but found that system reliability was so high following an LED upgrade that there was no need. Interviewee #21 reported that the successful completion of daily preventive maintenance tasks indicates good performance. Senior management monitors the performance of the maintenance staff by tracking service calls completed, work orders open, and work order duration. Data is pulled from Maximo and uploaded to a data analysis program called Power BI, which creates formal reports.

Several interviewees described using insulation resistance test results as performance indicators. For example, Interviewee #7 reported that their local policy recommends conducting repairs when results return quantities under ten megohms. However, most interviewees monitor trends across multiple test results and use judgment to determine when to perform repairs.

Photometric testing was the third commonly reported performance indicator. This testing provides detailed assessments of light fixture output in situ or on the test bench to determine if the fixture output complies with FAA standards. Test results present a list of fixtures requiring maintenance or repair. The FAA recommends monthly testing (FAA, 2014), but that cost can be prohibitive for many airports.

The Practice of Airfield Lighting Maintenance

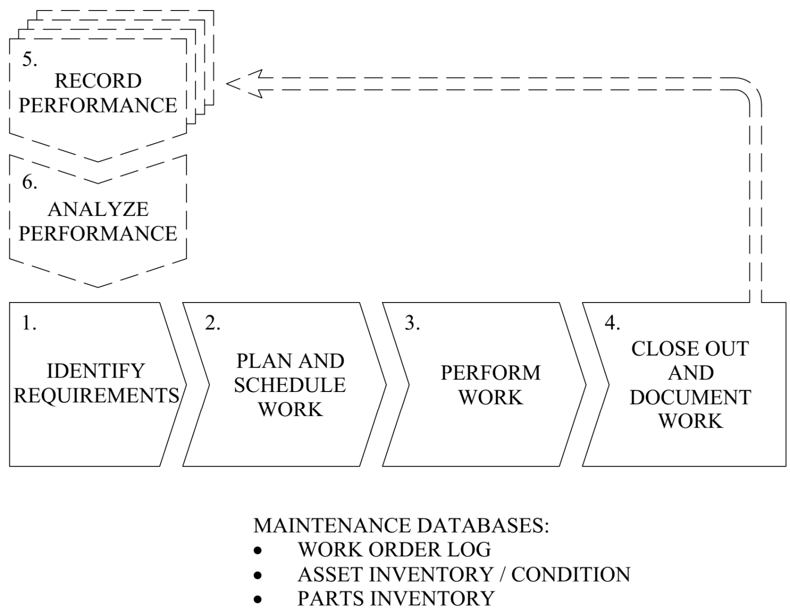
More sophisticated maintenance strategies require detailed record-keeping and data analysis. However, the interviewed staff members used various workflow processes. Some of those processes had limited record-keeping, and most had no data analysis. This section describes the common ALM workflow process to illustrate the different typical processes.

Boxes one through four in Figure 18 illustrate the fundamental steps of the maintenance management process common to all programs examined because they must comply with Part 139 requirements and maintain an accounting of the work. Box five illustrates updating a record containing information about the individual asset for which the maintainer completed the job. Finally, box six describes a process of studying the recorded data to determine new maintenance requirements or to change existing ones.

At the bottom of Figure 18 is a list of typical databases used by ALM staff. The work order log tracks the opening and closing of assignments. The asset inventory database includes a file on each maintained asset where staff can update the record each time they work on that asset. Lastly, ALM staff typically maintain a list of parts on hand to know when to order new stock.

Figure 18

Airfield Lighting Maintenance Common Process



Note. This diagram was developed based on the research.

The steps shown in boxes five and six in Figure 18 are unnecessary to comply with legal and accounting requirements. However, they are needed to implement maintenance strategies requiring historical data about the assets. Maintainers can also use the data to advocate for improvements to the maintenance program and changes to the airport design to enhance the ease or cost of maintenance.

Implementing a formal asset management program requires the additional steps shown in boxes five and six (ACRP, 2012a). While simply adding these extra steps does not constitute an asset management program, they provide the data needed to justify new maintenance strategies and potentially optimize maintenance. Below is a description of how ALM staff implement these six steps.

Identify Requirements

The two primary sources of ALM requirements are daily inspections and regularly scheduled maintenance. Daily airfield inspections are required by Part 139 and often performed by airport operations staff. ALM staff at some airports also perform daily inspections. Inspectors record any findings that require action in a work order log. While the inspections are considered preventive maintenance, any new work requirements resulting from the inspection findings are considered corrective maintenance.

Regularly scheduled maintenance is considered preventive maintenance. These are recurring maintenance tasks recommended by the FAA and equipment manufacturers. Scheduled requirements are entered into the work order log automatically by a CMMS or manually by the maintenance manager keeping a calendar with recurring work dates recorded.

Larger airports may assign work control staff to receive work order requirements and enter them into the work order log. However, small and non-hub airports often use a single computer or networked database where airport staff can enter work requirements directly into the log.

Plan and Schedule Work

The effort applied to planning and scheduling work varies among ALM programs. For example, small and non-hub airports may have a maintenance supervisor examine the work order log and assign planning or maintenance tasks as necessary. At some airports, the field maintenance staff will directly review the log and accomplish assigned tasks within their area of responsibility. To expedite the time to completion, some airport operations staff even e-mail work requests directly to the maintenance staff.

Work order log formats range from Post-It notes to network software databases. In several cases, the airport operations and facility maintenance staff recorded work requirements in separate databases. As a result, someone must transfer the data from one system to the other, which can cause delays in the maintenance staff receiving the work order. Maintenance staff copies the work orders manually at some locations or automatically by using Application Programming Interfaces (APIs) at others.

Complex work requirements may require the additional step of planning before scheduling the work for completion. The maintenance department may need to order parts before scheduling the work. Maintenance tasks taking a lot of time may need to be postponed to a part of the year where the RSA is more accessible. The work may be beyond the capability of the in-house staff and require outsourcing.

ALM staff using a CMMS typically tag the work order with a priority indicator. Assigning a priority tag was uncommon at small and non-hub airports. However, those interviewed stated that the maintenance staff already knows that the runway and support to commercial service operations are the priority. The person assigning priority also varied among airports. Options included the operations staff, electrical superintendent, facility manager, and airport director. One airport tried allowing the customers to assign priority but found that most customers listed their work as a high priority. Work that generates NOTAMs is a priority. At one airport, using semi-weekly KPIs, the manager emphasizes tracked items such as the total number of open work orders.

Perform Work

ALM staff at busier airports typically organize staffing and work hours to accomplish the scheduled maintenance and an expected amount of corrective maintenance within the timeframe allowed by Airport Operations. Maintainers often use daytime hours to perform ALM maintenance outside of the RSA. Nighttime or early morning hours are often used for work within the RSA. Airports with high numbers of cargo operations reported that nighttime hours were more restrictive than daytime hours and would schedule their work within the RSA during the day.

Airports with multiple runways provide better daytime RSA access in some cases. Where maintainers need access to a runway during the day, airports with numerous runways may move traffic to a different runway under certain circumstances. For example, Interviewee #21's airport rotates the active runway on a scheduled basis, allowing more predictable scheduling of airfield maintenance with the benefit of working during the day. Some single-runway airports experience busy seasons during which daytime RSA access becomes restrictive for a few days or weeks.

Close Out and Document Work

The minimum effort to meet Part 139 requirements is to document that maintenance staff addressed any inspection findings. This level of documentation was the extent of record-keeping at some small and non-hub airports, typically because of limited staff and a broad range of responsibilities. Additionally, some airports document the time required and the parts used to assist with accounting for costs of maintenance work. However, maintenance and repair documentation can potentially include more data to assist with future work.

The work order log and individual work order descriptions provide data to help plan repairs. For example, Interviewee #21 has access to a database of ten years of work order history. Interviewee #3 described how their database helps track the frequency of bulb replacement. This data assists in planning for appropriate stock levels. The ALM staff at Interviewee #23's airport use paper rather than computer records, which can verify that work was completed but have limited use for data analysis.

Asset Records

Several interviewed airports' ALM staff maintain asset registries. An asset registry is "a record of asset information considered worthy of separate identification including inventory, historical, financial, condition, construction, technical, and financial information about each" (ACRP, 2012a, p. 105). With such historical information, ALM managers can perform various analyses to discover problem trends within specific equipment, areas of the airport, or times of the year. However, additional time and training are required to ensure that the maintenance staff enters information into the asset database after completing the work.

Also, ALM managers must have time to analyze the data and generate useful reports. Interviewee #1 noted that some electricians were not supportive of the additional record-keeping when implementing a new CMMS. However, the tool enabled the ALM manager to generate reports that more accurately reflected the current and forecasted condition of the airfield lighting system.

Several electronic tools are available to assist with data collection. For example, tablet computers allow maintainers to use electronic maps to locate fixtures. In addition, wifi-enabled tablet computers can interface with the CMMS to facilitate rapid information entry into the database. Because the value of data collection is less evident to the maintainer performing the work, tools can simplify the effort needed to record maintenance data.

Analyze Performance

The asset registry keeps track of each asset's original installation date and current condition. This information can help predict the asset's remaining useful life (RUL). Therefore, using an estimate of the actual life of an asset rather than simply using a standard expected life can improve the accuracy of the asset life-cycle cost. In addition, the ability to regularly update asset life-cycle costs provides a quantitative tool for ALM managers to assess whether the maintenance performed is adequate. For example, an ALM manager could vary the frequency of routine maintenance to determine optimal frequency before unacceptable asset degradation occurs.

Most interviewed airports already use condition-based maintenance practices and asset condition reports for 5kV cable maintenance. Because insulation resistance measurements are primarily helpful when observing trends, most ALM staff already maintain these records in paper or digital format. Managers are familiar with examining the test result trends to forecast the failure of the cable.

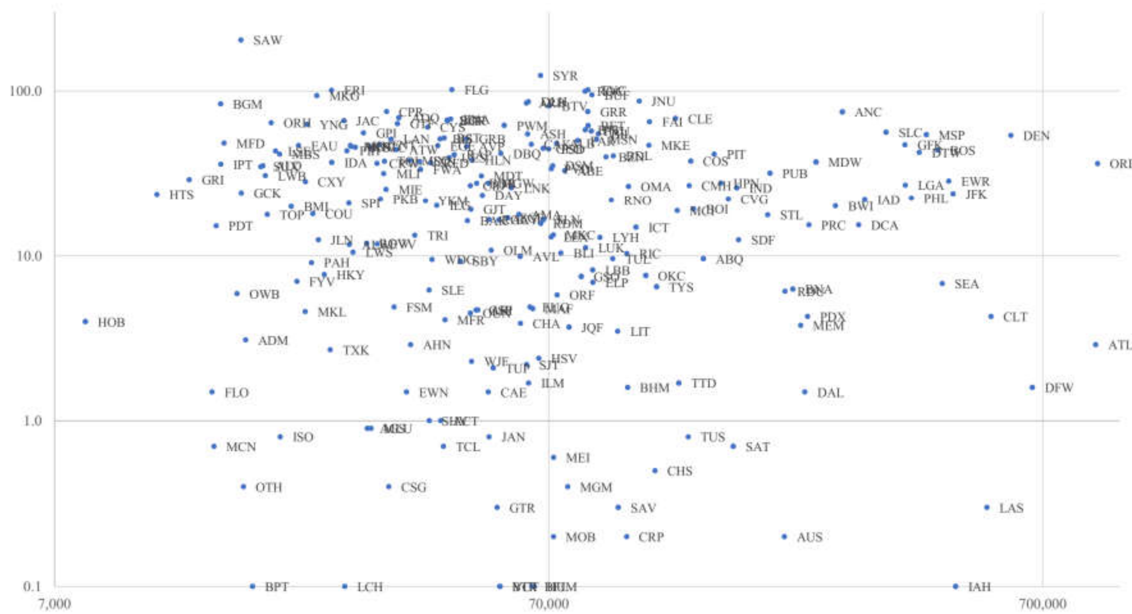
Interviewee #20 described an effort to optimize the frequency of measuring bolt torque because of reduced maintenance staff. This effort required keeping records of the torque and performing analysis of the data. At least one manufacturer offers an electronic torque wrench that automatically records torque measurements on a database along with geographic coordinates of the associated fixture.

Variances Among ALM Organizations

Despite the similarities among ALM organizations, maintenance programs and policies must consider local conditions. For example, in Figure 19, each point represents a U.S. commercial service airport located on the chart according to its annual operations and average yearly snowfall. The chart's purpose is to illustrate the wide range of conditions at airports that will impact the maintenance strategy suggesting no single approach is suitable for all airports.

Figure 19

Research Population Airports Compared by Annual Operations and Average Snowfall



Note. The horizontal axis shows the number of annual operations on a logarithmic scale in 2018 reported to ATADS. The vertical axis shows the 30-year average annual snowfall on a logarithmic scale from 1981-2010 as reported to NOAA. The data include 292 airports where data were available from both ATADS and NOAA.

Airports with higher operations will likely have less access to the RSA and require more stringent planning of the maintenance time and increased reliability to reduce maintenance demands. In contrast, airports with lesser traffic will have more maintenance options. While the busier airports to the right side of the chart likely have more sophisticated maintenance programs, they probably do not represent the needs of most airports. Similarly, the approaches used at severe weather airports will differ from the fair-weather airports. When ALM managers want to examine maintenance program alternatives at airports with similar conditions, those close to their airport on this chart would be good options.

Summary

Analysis of the interview data generated eight criteria influencing the maintenance strategy selection for airfield lighting assets. Currently, ALM managers use two types of corrective maintenance strategies and five types of preventive maintenance strategies. In addition, this study examined the Run-To-Failure maintenance strategy because the strategy is likely in current use despite not being identified by interviewees. Finally, this study also examined predictive maintenance because some airports are beginning to implement the monitors and record-keeping required by this approach.

The theory models maintenance strategy selection as an MCDM problem. However, no ALM staff used quantitative tools to assist with strategy selection. Instead, airports typically rely on the knowledge and experience of their ALM staff to select appropriate strategies. However, such experts require years of experience in this specialized area, so many airports might benefit from a quantitative tool to assist with strategy selection decisions.

The goal of implementing maintenance strategy changes should be to improve the performance of the maintenance staff and lighting system. The researcher found that few ALM staff used performance indicators to measure performance. The number of open work orders was the most common quantitative performance indicator. When not using quantitative indicators, ALM staff typically described assessing performance by the number of complaints received. However, all the interviewees stated that complaints were rare.

Additionally, the researcher prepared a standard model for the workflow of airfield lighting maintenance to illustrate how specific maintenance strategies require additional steps. These extra steps are not necessary to meet the primary goal of Part 139 compliance but are essential to provide the data needed by maintenance staff to optimize life-cycle costs.

Chapter V: Discussion, Conclusions, and Recommendations

Discussion

This chapter begins with an examination of the extant literature on maintenance management and strategy selection. This review is followed by a discussion of the findings for each research question.

Comparison Between Study Findings and the Literature

This review divides the literature into five research categories: types of maintenance strategies, using performance measurements, how strategy affects maintenance, Multi-Criteria Decision-Making (MCDM), and maintenance strategy selection. The review ends with a short discussion of the conclusions.

Types of Maintenance Management Strategies. Fraser (2014) named 37 distinct maintenance models in a literature review of popular maintenance management models. Fraser classified each model as *holistic* or *singular*. Holistic models require an organization-wide focus, and singular models apply to individual equipment. However, the research only found 12 models based on empirical evidence (practical examples). Most of that evidence came from four models: Total Productive Maintenance (TPM), Reliability-Centered Maintenance (RCM), Condition-Based Maintenance (CBM), and Condition Monitoring (CM). Of these four, CM was the only singular-type model. While 8,416 research papers discussed these four models, there was limited research for the remaining 33 models. A list of 37 maintenance models illustrates that many options exist in addition to the preventive maintenance model suggested by the FAA advisory circular for airfield lighting maintenance.

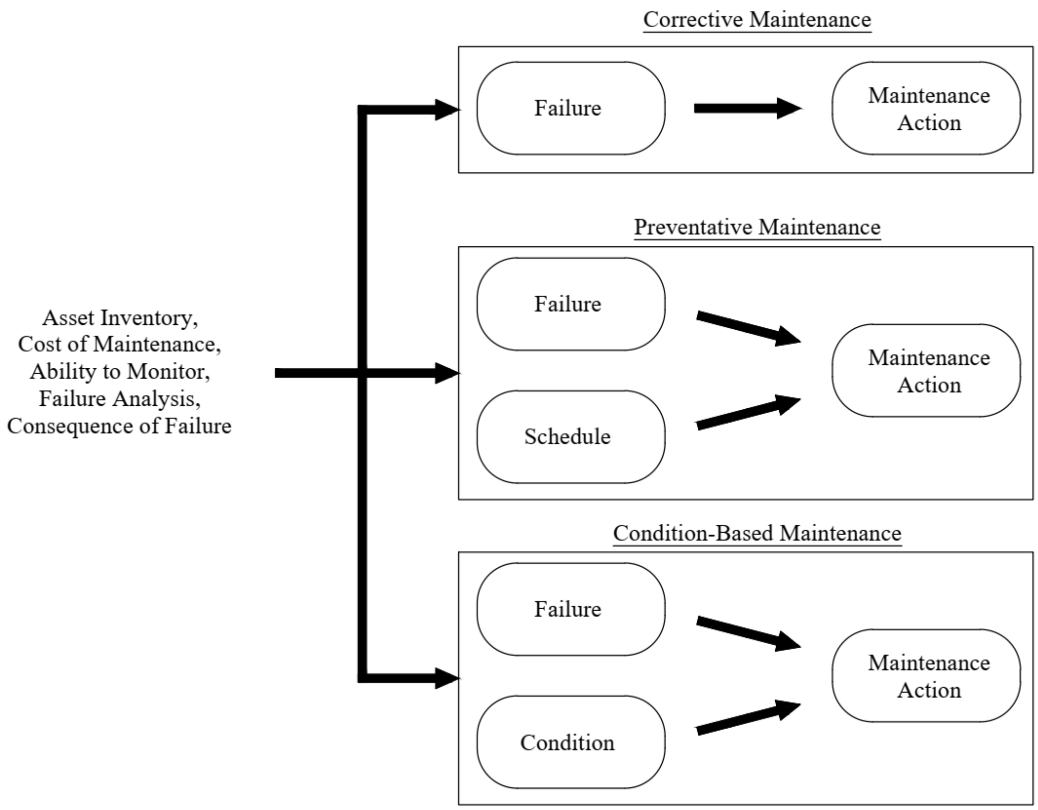
Horner et al. (1997) suggest that one maintenance strategy is unsuitable for all equipment in the asset inventory. The consequences of failure and the design characteristics of the asset should determine the maintenance strategy (Horner et al., 1997). Research suggests that integrating three maintenance strategies, corrective, preventive, and condition-based, is the best approach (Horner et al., 1997). In a corrective maintenance strategy, an element stays in use until it breaks down. Other terms used for corrective maintenance are failure-based or unplanned maintenance. The use of corrective maintenance can be expensive if a failure occurs at inconvenient times or damage occurs to other property because of the loss (Horner et al., 1997). A preventive strategy requires the performance of maintenance tasks at predetermined time intervals. This strategy improves corrective maintenance by allowing work performance at convenient times and finding problems before consequential damage occurs (Horner et al., 1997). A condition-based maintenance strategy requires continuous or regular monitoring of specific condition parameters for signs of deterioration. A predetermined amount of wear indicates a requirement to begin a maintenance action. Objectives for building maintenance include the following.

- Ensure the building is in a safe condition.
- Ensure the building is fit for use.
- Ensure the building meets all statutory requirements.
- Carry out work to maintain the value of the assets and stock.
- Carry out work to maintain the quality of the building (Horner et al., 1997).

Maintenance management should accomplish these objectives “by enhanced planning and implementation using appropriate materials and tools at the right time and minimum total life-cycle cost" (Horner et al., 1997, p. 274). A maintenance management decision diagram describes the "logical process used to select an appropriate and cost-effective maintenance strategy for each item or group of items in a building" (Horner et al., p. 276). The aim is to find the optimum maintenance strategy for each item. The first step in developing the diagram is to create an inventory of all assets and then analyze failure modes, effects, and consequences. Based on the results, the manager divides the items into three categories: the Health, Safety, and Environmentally Significant Items (HSESIs) category; the utility-significant category; and the non-significant category. HSESIs are those items where failure creates a possibility of injury, death, or violation of environmental standards. Utility-significant items are where maintenance costs are less than the cost of failure, both direct and indirect. Non-significant items are those which do not apply to the categories above. The second step is to select the best maintenance strategy for each item in the building. Figure 20 illustrates how the strategy depends upon the characteristics of each asset.

Figure 20

Diagram of Maintenance Management Strategy Selection According to the Process Outlined in Building Maintenance Strategy: A New Management Approach



Note. Adapted from R. Horner, M. El-Haram, and A. Munns, 1997, *Journal of Quality in Maintenance Engineering, 3*(4). Copyright 1987 by Emerald Group Publishing Limited. Adapted with permission.

Lavy and Bilbo (2009, p. 5) conducted a 14-question survey to "identify and analyze how facilities maintenance is planned, managed, and carried out by large public schools in the State of Texas." The Department of Education (DOE) concluded that while extreme environmental conditions and lack of funding contributed to facility deterioration, the poor conditions were mainly due to the reduced maintenance staffing and poor local maintenance management practices (US Department of Education, 2003;

Lavy & Bilbo, 2009). Lavy and Bilbo’s research was similar to this research; however, they used a quantitative approach to confirm the usage of the DOEs best practices. The study examined the use of short and long-range maintenance plans, named stakeholders involved in plan development, listed the frequency of accomplishment of facility condition assessments, and showed the level of detail used to carry out these assessments. Lavy & Bilbo (2009) found (a) only 64% had well-conceived maintenance plans, (b) 43% did not include teachers or students in their planning, (c) 75% did not do proper facility assessments, (d) less than 50% of the schools used their assessment findings for long-term planning and for establishing benchmarks for service life, and (e) 31% performed facility audits every three to five years instead of annually. This study illustrates that local school facility management staff did not follow best practices despite the DOEs publishing efforts. Airfield lighting maintenance staff do not have a set of best practices for maintenance management. The FAA supplies minimum maintenance recommendations (FAA, 2014a). Other organizations have published best practice recommendations for specific lighting system components such as LED lighting or in-pavement fixtures (ACRP, 2012a; ACRP, 2015a; IPRF, 2008; Schai, 1986). This study suggests that implementing, rather than publishing, proper maintenance management practices is the more significant challenge.

Using Performance Measurements. Loosemore and Hsin (2001) did a research project investigating benchmarking in managing facilities in health, education, hotel, and government industries. While specifically referring to health care facilities, they note that “by far the greatest influence upon an organization’s core objectives is the functional performance of its property which can account for 80-90 percent of its total costs”

(Loosemore & Hsin, 2001, p. 465). After the 1970s, the facility management workforce transitioned from a commonly in-house crew to a largely outsourced function, which helped create facilities management as a profession (Loosemore & Hsin, 2001). Researchers measured the performance using three main components: physical, functional, and financial (Loosemore & Hsin, 2001). They found that the worst understanding of the relationship between business core objectives and managed facilities occurred in industries with little competition, such as hospitals and government. In general, the measurement of facility performance was over-simplified and subjective (Loosemore & Hsin, 2001). In addition, many respondents did not use benchmarks to assess performance and had little knowledge of corporate KPIs (Loosemore & Hsin, 2001).

Shohet (2006) sought to develop KPIs for healthcare facilities maintenance based upon a set of KPIs designed for public acute care hospital facilities in Israel. Building upon the Israeli model, Shohet (2006) developed KPIs in four categories: asset development, organization and management, performance management, and maintenance efficiency. Asset development includes the following physical facility parameters: built area, occupancy of the asset, and facility age. Parameters of organization and management include the number of employees per 1000 m^2 built area, the scope of facility maintenance outsourcing, the managerial span of control, and the maintenance organizational structure. The single performance management parameter is the Building Performance Indicator (BPI), a numerical value between 0 and 100. The BPI expresses the building's current state and system performance based on a subsystem's weighted sum of performance factors. Finally, the maintenance efficiency category includes annual maintenance expenditure per square meter, annual maintenance expenditure per *output* unit, and a maintenance efficiency indicator. The maintenance efficiency indicator examines maintenance expenditures in relation to facility performance. The four KPIs in the Israeli model could be adapted to airfield lighting maintenance using factors such as the *cost of annual maintenance per light fixture* or the *cost of annual maintenance per runway*. These indicators show how facility development, management, and efficiency could also be factors measuring performance.

Parida et al. (2013) performed a literature review of performance measurement in maintenance and proposed a framework and approach to Maintenance Performance Measurement (MPM). The evolution of performance measurement occurred in two phases. The first phase, known as the cost accounting orientation phase, began in the 1880s. A second phase started in the late 1980s as businesses tried to apply a more balanced and integrated view to performance measurement. Performance Indicators (PIs) should be multilevel and hierarchical to ease tracing deficiencies in high-level indicators to the lowest level. PIs can be *leading*, warning about objectives, or *lagging*, indicating a condition after it has occurred. The selection of performance indicators depends on the business' overall concept or framework for performance measurement. In their literature review, Parida et al. (2013) found much of the writing to be too superficial and that many studies ignore the complexity of designing a performance measurement system. Future needs include mapping maintenance processes, mapping maintenance activities, and finding performance killers and drivers to develop a balanced MPM system.

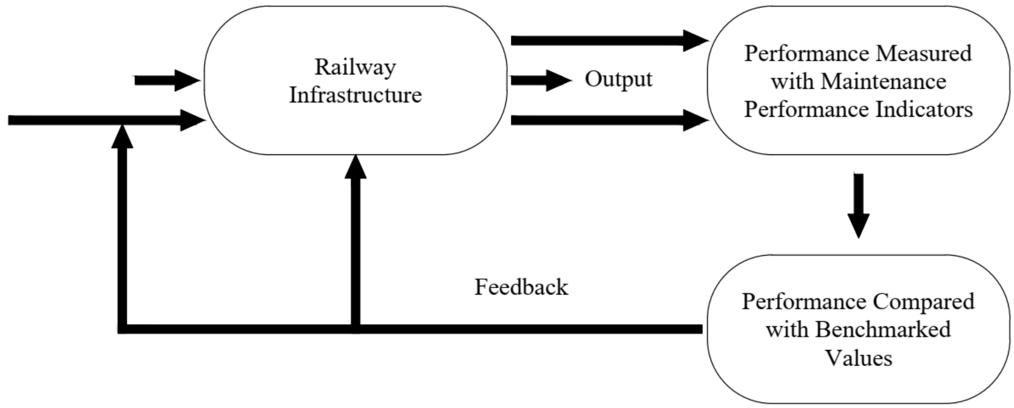
Åhrén and Parida (2009) conducted case studies of Swedish and Norwegian rail administrations responsible for the Iron Ore Line between the two countries. The goal of the case studies was to figure out which Maintenance Performance Indicators (MPIs) confirmed that maintenance costs directly affected the overall business goals. The research found that both agencies had ten similar MPIs used at the regional and central levels. However, the authorities shared two significant problems, monitoring the actual track-use in terms of gross tonnage and number of passengers and the inability of the financial system to capture the cost for specific tasks and components. The Swedish and Norwegian authorities had similar operation and maintenance costs per track meter; however, the Norwegians had much higher corrective maintenance and overhead expenses per track meter. Results showed that they could compare costs related to the number of assets. However, overhead costs were proportional to the organization's size rather than physical assets. Comparable indicators between organizations usable for benchmarking include:

- “corrective maintenance cost/total maintenance cost including renewal;
- total maintenance cost/turnover;
- maintenance and renewal costs/cost for asset replacement; and
- maintenance cost/track meter.” (Åhrén & Parida, 2009, p. 255)

Åhrén and Parida recommended conducting future research on finding leading indicators based on parameters that make it possible to name cost drivers (e.g., labor, spare parts, actual maintenance cost, and resources per asset). Figure 21 below illustrates the cycle of continuous improvement used by the railway organizations. Maintenance organizations could adapt this cycle to many types of maintenance, including airfield lighting.

Figure 21

Linking MPIs with Benchmarking for the Effectiveness of Railway Infrastructure



Note. Adapted from "Maintenance Performance Indicators (MPIs) for Benchmarking the Railway Infrastructure," by T. Åhrén and A. Parida, 2009, *Benchmarking, 16*(2), p. 252. Copyright 2009 by Emerald Group Publishing Limited. Adapted with permission.

How Strategy Affects Maintenance. Swanson (2001) examined the relationship between maintenance strategy and performance using surveys of maintenance personnel in the metalworking industry and exploratory factor analysis. Swanson sent 708 surveys to 354 plants, achieving a response rate of 40.5%. He described three types of maintenance: reactive or breakdown, proactive including preventive and predictive, and aggressive. Table 12 summarizes the three types of maintenance described in the article. In addition, respondents reported the importance of nine different maintenance tasks and their estimate of the maintenance contribution to improved quality, availability, and cost reduction over the previous two years.

Table 12

Summary of Maintenance Strategies Used in Swanson (2001) Study

	Reactive	Proactive	Aggressive
Description	Run-to-failure, repair or replace as needed	Use-based or condition-based maintenance	Teams of engineers, production and maintenance staff continuously improve processes
Pros	Less workforce and cost	Reduced breakdowns, extended equipment life	Improved availability, reduced maintenance costs, and repair time
Cons	Unexpected outages, higher costs when catastrophic failures occur	Production must be interrupted to perform maintenance	

Swanson examined responses to the nine maintenance task questions using exploratory factor analysis to decide on maintenance strategies. The study used multiple regression methods to test the strength of the relationships between maintenance strategy and performance. The study confirmed that proactive and aggressive maintenance strategies positively correlated with improved performance. The reactive approach had a marginally significant negative correlation with performance measures. The FAA advisory circular for visual aids maintenance only describes a preventive maintenance philosophy (FAA, 2014a).

Maletič et al. (2012) performed a five-point Likert scale survey of 63 Slovenian organizations, primarily in the manufacturing industry, to examine the relationship between continuous improvement and maintenance performance. The surveys collected information on company perception of continuous improvement practices and their perception of company performance. The analysis found a strong correlation that continuous improvement "significantly and positively contributes to maintenance performance." Establishing a continuous improvement cycle and managing that cycle is a fundamental part of an asset management program (ACRP, 2012b). As a result of this strong correlation, interview questions will determine the extent of continuous improvement program implementation in airfield lighting maintenance management. Continuous improvement programs are not unique to asset management and might be a part of a Total Productive Maintenance (TPM) or Total Quality Maintenance (TQM) program (Maletič et al., 2012).

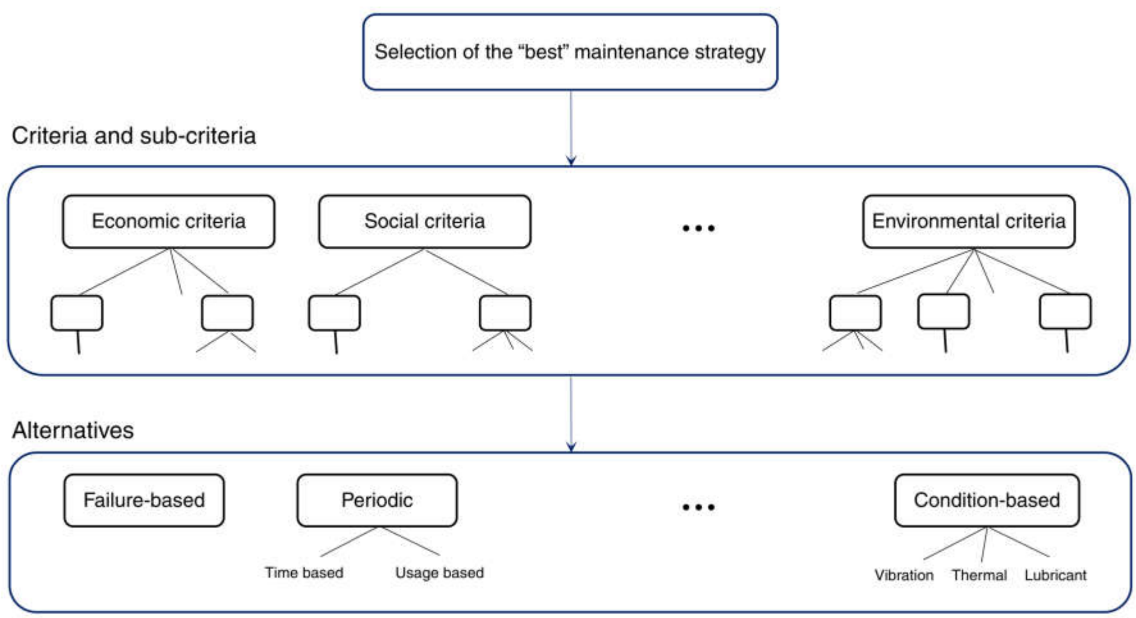
Multi-Criteria Decision-Making (MCDM). Analysis of the maintenance strategy decision-making at the airports of the interviewed maintenance staff followed similar patterns. Various criteria affected the decisions. The management team held discussions and chose from among several alternative strategies to find their desired approach. This decision-making process closely resembles the structure of an MCDM problem. This review includes investigating the MCDM approach to decision-making and current popular methods. Below is a discussion of two literature reviews illustrating the popularity of using the MCDM approach for maintenance strategy decisions and its use within facility infrastructure management.

The method has increased in popularity in recent decades. For example, Shafiee's (2015) literature review found 62 journal articles, 17 conference papers, two master and doctoral dissertations, and one book chapter examining the use of MCDM in Maintenance Strategy Selection (MSS) problems.

The primary reason for selecting a suitable strategy is to reduce the risk of failure in critical systems because the cost of such failure can be high (Shafiee, 2015). A secondary reason to optimize a maintenance strategy is to minimize operating expenses (Shafiee, 2015). However, numerous factors affect strategy decisions, such as initial investment, safety aspects, environmental issues, failure consequences, reliability of the strategy, and workforce utilization (Shafiee, 2015). Therefore, the MCDM approach to problem-solving may consider many qualitative and quantitative criteria. Figure 22 illustrates the MCDM process, including a stated goal, a list of criteria and sub-criteria, and potential alternatives.

Figure 22

A Hierarchical Structure of the Decision Framework for an MSS Problem.



Note: Reprinted from "Maintenance Strategy Selection Problem: An MCDM Overview," by M. Shafiee, 2015, *Journal of Quality in Maintenance Engineering, 21*(4), p. 379. https://doi.org/10.1108/JQME-09-2013-0063. Reprinted with permission.

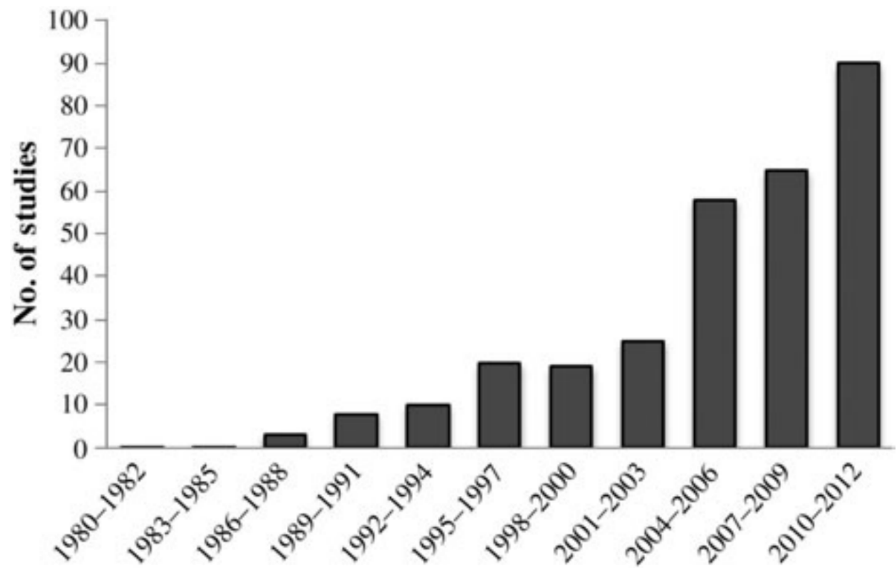
The MCDM method accommodates various decision-making approaches. Data collected about each criterion supplies the input for decision-making. Shafiee’s (2015) review found four typical data collection methods: experience or clinical trials, observing events, using historical data, and administering surveys. *Classical* MCDM models using *crisp* numbers are in roughly equal numbers to the use of *fuzzy* MCDM models, which in contrast use imprecise, subjective, or vague data. Studies used both quantitative and qualitative criteria (Shafiee, 2015).

The literature review performed by Kabir et al. (2014) found a growing interest in the MCDM for infrastructure management applications, as illustrated in Figure 23. The infrastructure studies included in this literature review covered water resources systems, water mains, wastewater mains, transportation, bridges, buildings, underground infrastructure, etc. In addition, the review included over 300 published papers reporting on MCDM applications in infrastructure management (Kabir et al., 2014).

Shafiee (2015) lists and describes seven of the more popular alternative selection methodologies in the literature, including utility theory, simple additive weighting (SAW), analytic hierarchy process (AHP), analytic network process (ANP), the technique for order of preference by the similarity of ideal solution (TOPSIS), Višekriterijumsko kompromisno rangiranje [Multicriteria Optimization and Compromise Solution] (VIKOR), and elimination and choice translating reality (ELECTRE). Shafiee (2015) noted that the MCDM method of preferred ranking organization method for enrichment of evaluations (PROMETHEE) was missing from the literature reviewed. Shafiee (2015) lists Goal Programming (GP) as a hybrid approach when combined with a previously mentioned method like AHP or ANP.

Figure 23

Infrastructure Management Studies Published Since 1980.



Note: Reprinted from "A Review of Multi-Criteria Decision-Making Methods for Infrastructure Management," by G. Kabir, R. Sadiq, & S. Tesfamariam, 2014, *Structure and Infrastructure Engineering, 10*(9), 1182. https://doi.org/10.1080/15732479.2013.795978. Reprinted with permission.

Maintenance Strategy Selection.

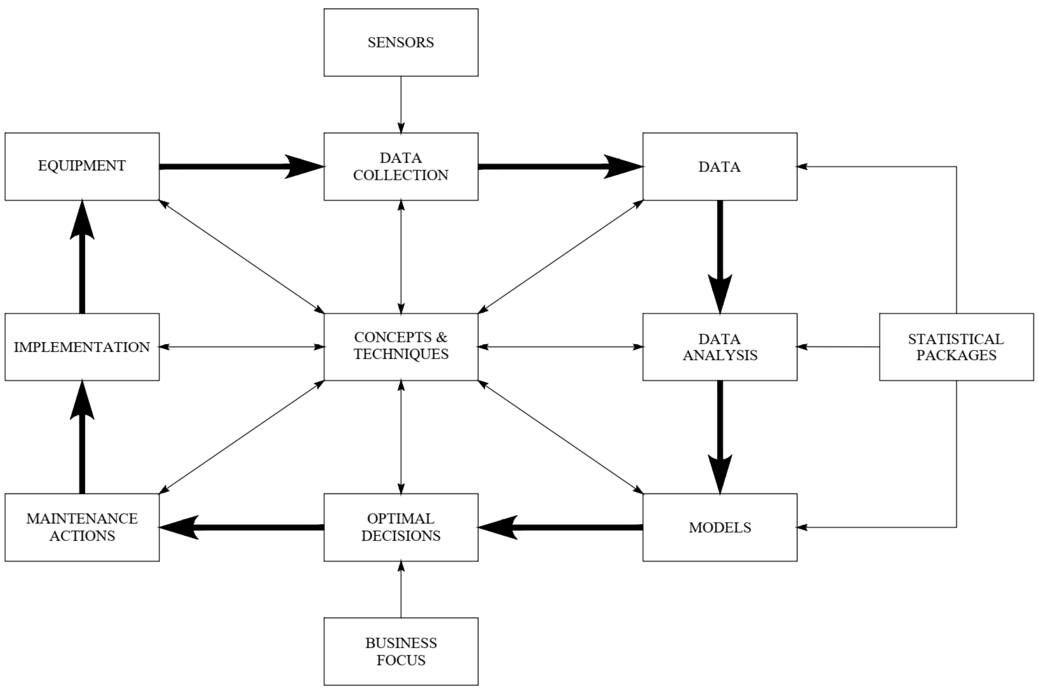
Early Evolution of Maintenance Strategies. Equipment maintenance approaches coincide with the four industrial revolutions. The first revolution, defined by the development of the steam engine by James Watt in 1795, is characterized by *corrective* or *breakdown* maintenance (Poor et al., 2019). About one hundred years later, the second revolution, defined by electrification and assembly lines, resulted in *preventive* maintenance practices (Poor et al., 2019). However, Murthy et al. (2002) argue that maintenance planning was not widespread until the development of the complex machines of World War II. Next, the arrival of computers sparked the third industrial revolution (Poor et al., 2019). Computers facilitated the automation of assembly lines and fueled the expansion of the science of operational research through the 1950s and 1960s (Murthy et al., 2002, Poor et al., 2019).

Complex Machines Lead to a New Maintenance Strategy. Murthy et al. (2002) credit the U.S. government with integrating maintenance actions and business approaches by requiring the use of life-cycle cost analysis as a feature in the acquisition of costly new defense systems beginning in the 1970s. During this period, Nowlan and Heap (1978) published their seminal work on aircraft maintenance that studied which types of scheduled maintenance to perform and how often the maintenance staff should accomplish those tasks. Moubray (1992) later generalized this research for industrial maintenance and established the basic principles of Reliability-Centered Maintenance (RCM). RCM principles are a fundamental part of the asset management program described by ACRP research (ACRP, 2012a).

RCM analyzes an asset system and finds each asset's most appropriate maintenance schedule. Nowlan and Heap (1978) acknowledge that managers should develop maintenance based on historical data; however, that is impossible if that data does not yet exist. Therefore, the system must be analyzed and understood to develop the maintenance schedule. RCM prioritizes maintenance based on the consequences of failure of each asset system and each asset (Nowlan & Heap, 1978). First, the maintenance staff must prepare a system diagram showing equipment relationships. Next, they must complete a Failure Mode, Effects, and Criticality Analysis (FMECA) for each asset. A manager must then prioritize their list of assets based on criticality. Finally, maintenance managers must prepare a maintenance schedule based on this information (Arno et al., 2015). These are the steps described in ACRP guidance for asset management programs and are the steps that maintenance management staff must perform for each airfield asset (ACRP, 2012a). For airports with fewer annual operations, the technical ability and available work hours may not be available, particularly when spreading the return on investment over the life of the assets.

Figure 24

Continuous Improvement in Maintenance.



Note: Adapted from "Strategic Maintenance Management," by D.N.P Murthy, A. Atren, & J.A. Eccleston, 2014, *Journal of Quality in Maintenance Engineering, 8*(4), p. 287-305. https://doi-10.1108/13552510210448504. Adapted with permission.

Integrating Organizational Management and Maintenance Strategy. Murthy et al. (2002) describe an iterative process for continuous improvement in maintenance management that effectively illustrates the components of RCM and asset management programs from the maintainer's perspective. For example, Figure 24 shows a continuous cycle of maintenance on equipment, data collected using inspections and sensors, analyzing data using mathematical models and statistical software, management reviewing the analysis with consideration for business impacts, then making changes to the maintenance program as needed. Murphy et al. (2002) describe their central concepts and techniques as Strategic Maintenance Management; however, the illustration also applies to asset management programs.

The Fourth Industrial Revolution. Finally, the growth of the internet brought the fourth industrial revolution and the ability to implement *predictive* maintenance economically (Poor et al., 2019). Predictive maintenance involves collecting and analyzing equipment data to find patterns and predict problems before they occur (Poor et al., 2019). Predictive maintenance becomes possible through sensors, the Internet of Things (IoT), Big Data, and Cloud computing (Poor et al., 2019).

Conclusions of the Literature Review. The analysis of the interview data showed that managers use a range of criteria to select their maintenance strategy. Managers then use a local decision-making process to select one or more maintenance strategies. Thus, the components of the theory for maintenance strategy selection include criteria, a decision-making process, and alternative strategies. A review of similar processes in other industries led to the decision to model the new theory using a Multi-Criteria Decision-Making (MCDM) model.

Shafiee (2015) says maintenance strategy selection is a complex multiple-criteria decision-making problem (MCDM). Airfield lighting maintenance strategy selection can be modeled as a multi-criteria decision-making (MCDM) problem. However, managers use an informal, intuitive decision-making process to select among alternatives rather than the deliberative and quantitative process commonly used in MCDM methodologies. One research recommendation is to develop such a deliberative decision-making process and automated tool to aid maintenance managers with insufficient training and resources to perform such analysis.

Additionally, the review describes the evolution of maintenance strategies from purely reactive maintenance used for centuries to predictive maintenance practices based on modern technology. By the 1980s, electronic technology and maintenance management research had evolved to support more sophisticated data collection and analysis techniques. The literature describes a proposed continuous improvement maintenance cycle that aligns with maintenance practices discovered through interviews. When making comparisons of current ALM decision-making practices and workflow processes to industry standards, areas for potential improvement become clear. The remainder of this section describes the research findings for each research question.

RQ 1 – Factors Affecting Airfield Lighting Maintenance Management Strategy

This research identified eight factors that impact maintenance strategy decisions for airfield lighting at U.S. commercial service airports. These factors are Access, Budget, Condition, Design, Environment, Impetus, Regulations, and Staff. The use of grounded theory and telephone interviews with airport maintenance staff ensured that these factors were developed using information from personnel currently performing the work. The results section included numerous interviewee quotes supporting the researcher's selection and development of these categories.

These eight factors describe the criteria that should be considered when selecting a maintenance strategy. For example, limitations in *access* to the RSA for maintenance due to ground traffic and weather vary significantly among airports. Limited access to the RSA increases the need for preventive maintenance programs to minimize emergency repairs, such as routine replacement of groups of fixtures regardless of their current condition. Furthermore, these airports need robust mobile capabilities for maintenance crews responding to emergency repairs. However, airport maintenance staff with more frequent access to the RSA can use more reactive maintenance, such as only replacing fixtures after finding a problem. Selecting the appropriate level of effort for maintenance will reduce operating and maintenance costs while maximizing the life of the lighting system.

Despite airfield lighting system design standardization, maintenance practices will vary based on local conditions. Therefore, airfield lighting maintenance staff should place greater weight on the experiences of the maintenance staff at airports similar in size and environment rather than follow industry-standard guidelines that do not consider local conditions and operational limitations.

RQ 2 – Airfield Lighting Maintenance Strategies Currently in Use

Terms such as *predictive* and *reactive* maintenance do not have consistent definitions within the maintenance industry. Therefore, the researcher asked the interviewees to explain their processes for identifying, prioritizing, assigning, and completing work for the various lighting equipment types at the airport. Based on these descriptions and standard definitions, the researcher identified the following types of corrective and preventive maintenance strategies described by the interviewees:

- Corrective Maintenance
    - Reactive Maintenance (Emergency)
    - Reactive Maintenance (Scheduled)
    - Run-To-Failure
- Preventive Maintenance
    - Operator-Based Inspections
    - Time-Based Inspections
    - Time-Based Maintenance
    - Condition-Based Maintenance
    - Reliability-Centered Maintenance
    - Predictive Maintenance

As previously stated, corrective maintenance is activities undertaken to address observed asset substandard conditions, and preventive maintenance is activities undertaken at fixed intervals regardless of asset condition (Gulati, 2021). The Results chapter includes detailed explanations of these strategies.

In general, interviewees preferred to minimize their use of corrective maintenance and maximize their preventive maintenance use. However, by design, airfield lighting fixtures and equipment are exposed to hazardous weather conditions such as lightning and vehicle impact accidents. As a result, unexpected damage and corrective maintenance strategies are inherent to airfield lighting maintenance.

Unexpected equipment failures may also result from routine wear, tear, and aging. Preventive maintenance practices minimize these failures using scheduled replacements, scheduled inspections, or prediction strategies. While these strategies can reduce unexpected equipment failures, they require more labor and financial resources than corrective maintenance.

The list of strategies includes two that interviewees did not describe: Run-to-Failure (RTF) and Predictive Maintenance (PdM). The omission of the RTF strategy may have occurred because some do not recognize that *intentionally avoiding maintenance until asset failure* is an acceptable strategy in some cases. RTF strategies are suitable when assets have a low consequence of failure, and the maintenance cost exceeds the replacement cost. Some airfield lighting assets, such as obstruction lights, meet these criteria. In addition, airfield lighting equipment manufacturers currently advertise tools and computer systems that support a PdM strategy. Some interviewees described using CMMS that supports a PdM but were not using the PdM features. The researcher concluded that some airports within the research population might use PdM, but sampling did not uncover those airports.

RQ 3 – Airfield Lighting Maintenance Strategy Selection Process

Interview results indicate that maintenance decision-making for airfield lighting follows an informal process involving managers and staff members most knowledgeable of the lighting system. New managers typically inherit a maintenance program designed by others, where a *program* refers to the personnel, equipment, and practices for maintenance. Managers with more airfield lighting training and experience appeared more likely to change the program, but maintainers with less background in airfield lighting tend to continue the existing program. Additionally, some interviewees stated that senior airport managers directed program changes due to implementing an asset management program or simply from budget restrictions.

In addition to maintenance managers and technicians, some interviewees stated that operations staff and engineers are also involved in key decision-making. For example, the field operations staff typically identifies problems on the airfield through their daily field inspections. Additionally, the operations staff coordinates with the airlines and informs the maintenance staff when portions of the airfield are accessible for maintenance. Airports with more extensive staff may have civil and electrical engineers. These airport engineers commonly support airport planning and capital improvement projects; however, some interviewees indicated that their maintenance staff has a collaborative relationship with the engineering staff that allows them to provide technical assistance as needed.

While those involved in maintenance decisions vary between airport organizations, the common thread is that the decision team considers local criteria and selects options from the known alternatives. The answers to research question one (RQ1) list the criteria that maintenance managers should consider. Next, the answers to research question two (RQ2) list the alternative maintenance strategies. Finally, the answers to research question three (RQ3) indicate that standard practice is that a small team of the most knowledgeable local maintenance staff will direct any changes to maintenance strategies as needed. The process for the selection of strategy can be modeled in three parts: a list of influencing criteria, a decision-making process, and potential alternatives. This process matches a Multiple Criteria Decision-Making model. Therefore, MCDM serves as the theoretical framework.

Theoretical Framework. Shafiee (2015) described the increasing use of the MCDM approach for maintenance strategy selection in energy, automotive, mining, and textile industries since the early 2000s. The constructed theory models this structure and extends the application to the airport industry. This study confirmed that airfield lighting maintenance programs regularly use a similar system except for local AFL experts' use of an intuitive decision-making process. However, the rarity of AFL experts suggests potential value in developing a quantitative tool designed by specialists in the field, similar to those used in other MCDM applications.

The constructed theory builds upon ACRP asset management research by guiding the optimization of maintenance investment, step seven of asset management program implementation, as shown in Figure 1 (ACRP, 2012a). In the current form, the theory lists the criteria generally considered to have the most significant impact on maintenance strategy and lists the successful maintenance strategies used by others. Chapter 4 describes how the criteria and strategies were determined, including the focused codes that capture the feedback received during the interview process. However, the constructed theory illustrates that maintenance management uses a small knowledgeable team for decision-making instead of the quantitive tools associated with MCDM. Decision-making is currently unstructured and illustrates how the training and experience of local staff affect the ability to optimize the maintenance program. MCDM provides the theoretical framework for selecting maintenance strategies considering each criterium or category. However, the MCDM model also illustrates how a quantitative decision-making tool could replace the current intuitive decision-making process. Such a tool could be developed using input from multiple ALM management experts and be made available to airfield lighting maintenance staff seeking additional expert input.

Bevilacqua & Braglia (2000) helped a new power plant select maintenance strategies for the equipment using an MCDM process with an AHP approach. This project was for a single facility but provided the opportunity to compare the intuitive recommendations of the maintenance staff with those generated by the mathematical model. The results were unsurprisingly similar because the same experts assisted with both analyses. However, the maintenance staff felt the AHP technique resulted in a more complete and thorough analysis while considering several factors. Additionally, the technique could effectively use both quantitative and qualitative information in the analysis (Bevilacqua & Braglia, 2000). This example supports the idea of building a quantitative decision-making tool that can offer expert advice to maintenance staff at multiple locations.

Alternative Decision Methodologies. Selecting the optimal maintenance strategy can be considered a ranking problem. A ranking problem orders options from best to worst using scores or pairwise comparisons (Ishizaka & Nemery, 2013). Because some airports may not have the resources to implement specific strategies, ranking identifies the next best solution. Modeling maintenance strategy selection as an MCDM problem illustrates how quantitative approaches provide alternative decision methodologies.

In an overview of MCDM approaches used for the selection of optimal maintenance strategies, Shafiee (2015) discussed seven popular approaches: utility theory, simple additive weighting (SAW), analytic hierarchy process (AHP), analytic network process (ANP), the technique for order of preference by similarity to ideal solution (TOPSIS), Višekriterijumsko kompromisno rangiranje (VIKOR), and elimination and choice translating reality (ELECTRE).

MCDM literature includes classical models that use crisp values for rating and criteria weights and fuzzy models that use statistical distributions to account for the vagueness of subjective criteria (Shafiee, 2015). Both criteria weightings can be combined with the previously listed approaches to develop decision-making tools.

However, Dong et al. (2009) described a method for selecting the optimal maintenance strategy that integrates qualitative and quantitative evidence while also considering uncertainty and incompleteness in the data. The evidential reasoning approach models the MCDM problem using a belief decision matrix that weights the criteria according to criticality.

RQ 4 – Performance Indicators

The research results indicate that airfield lighting maintenance staff uses the following data for performance measurement:

- Qualitative
    - Complaints
- Quantitative
    - Number of Open Work Orders
    - Insulation Resistance Test Results
    - Photometric Test Results

Maintenance managers indicated that receiving complaints is rare, but several interviewees considered “no news” as “good news.” In the researcher’s experience, this philosophy is common among facility maintenance staff because customers acknowledging continuous successful operation is uncommon, but complaints about unexpected failures are not. However, several non-hub, small hub, and medium hub airports used such verbal feedback as their only performance measure.

ALM managers from large hub airports used the total number of open work orders or the number of open high priority work orders as a performance metric reported to upper management. Additionally, one manager stated they attempted to track the lighting system availability percentage as a performance metric: the total time that lights were operating without problems divided by the total time. However, notable outages were so rare that the metric did not vary.

Insulation resistance and photometric performance test reports provide snapshots of the current power cable condition and light fixture output. However, non-hub and small hub airports often did not have personnel on staff with the skills to perform insulation resistance tests. Most, but not all, maintenance staff outsourced their photometric testing because of the cost of the equipment and specialized training required. FAA standards recommend completing photometric testing initially every month, then adjusting the frequency as appropriate according to traffic and the frequency of fixture cleaning (FAA, 2014a). However, the testing frequency should not fall below two times per year for runways with a precision approach (FAA, 2014a). The cost of testing at that frequency is prohibitive for many non-hub and small hub airports. Below is a brief discussion of alternative performance indicators potentially available to maintenance managers at a lower cost.

Alternative Performance Indicators. The researcher suggests three categories of indicators based on analysis of the results and maintenance management research: life-cycle-based, goal-based, and performance-based.

As stated earlier, the primary goal of an asset management strategy is to optimize the asset life-cycle cost (LCC). Therefore, maintainers should calculate these costs and update them regularly to indicate how maintenance actions, or lack of maintenance, affect life-cycle costs. The total LCC includes costs for initial installation, recurring maintenance, energy usage, repairs, and end-of-life disposition. In addition, the calculation consists of actual historical and projected costs based on assessments of assets remaining useful life (RUL).

Goal-based performance indicators compare actual with expected maintenance performance. For example, ALM staff could estimate the hours to be spent on preventive and corrective maintenance for each month. At the end of each month, managers compare the actual hours with projected hours, then consider if any deviations require further investigation of causes. For example, such a metric might help identify increased corrective maintenance due to equipment reliability or reduced preventive maintenance.

One performance-based indicator uses the results of regular photometric testing. While such tests are expensive, they objectively assess the quality of light fixture output. The indicator also measures the effectiveness of the fixture lens cleaning schedule. In addition, fixtures may be knocked out of correct orientation by snowplows, or fixture elevation change may occur due to frost heave, asphalt compression, or initial construction quality problems.

Conclusions

ALM staff consistently described ensuring compliance with Part 139 requirements as the top priority; however, almost none of the staff interviewed described minimizing asset life-cycle costs as a priority for senior staff. From the ALM staff's perspective, Part 139 compliance requires ensuring that critical lighting systems operate to FAA standards and that airfield inspection findings are addressed and documented. Interview analysis indicated that CMMS is common at airports of all sizes but is primarily used to track work order completion and associated costs. In addition, however, CMMS can store, organize, and analyze the results of previous maintenance to find ways to improve future work.

Airports can implement asset management programs more simply than the program described in ACRP Report 69. The guide describes conducting detailed inventories and analyses of existing assets, risk assessments, and evaluating existing maintenance and capital improvement programs. However, the implementation investment can be significant.

The most knowledgeable staff typically chooses maintenance strategy, sometimes with the assistance of management. The most qualified staff often have airfield lighting work experience from only one airport. As a result, this limits their familiarity with alternative solutions. Some ALM staff may feel they have insufficient expertise to change the current program, especially when ALM is only one of several responsibilities.

Airfield lighting maintenance training is costly and time-consuming. This challenge severely limits the ability of many maintenance staff to become adequately trained. In addition, senior airfield management staff may not realize that the FAA and

NFPA require ALM staff to receive specialized training to be considered *qualified persons*. The formal training offered by AAAE is most suitable for trained electricians because the course teaches troubleshooting and repair techniques that only electricians should perform.

This research supports the presumption that most maintainers are unaware of how other airports manage their programs. A small number of ALM staff work at multi-airport authorities, which gives those individuals broader experience. Four airports included in the research sample are part of a multi-airport authority. Facility maintenance managers have more opportunities to learn lessons from other airports through industry organizations; however, shop-level staff has fewer opportunities to learn from their peers. ALM staff primarily rely on each other, equipment manufacturers, and electrical contractors to provide technical assistance and occasional training.

Theoretical Contributions

This research constructed a generalized theory of maintenance management selection that describes how and why maintenance practices vary at U.S. commercial service airports. ICAO and FAA policies require standard airfield lighting system designs and equipment. As a result, many similarities exist in lighting systems across all airports. However, each airport has a distinct set of criteria that affect the design of the maintenance program. The application of grounded theory methods allowed the collection of information about ALM programs from various airport organizations across the United States. A better understanding of how various local factors affect maintenance will enable ALM staff to adapt FAA maintenance policy and AAAE training to their airport situation.

Practical Contributions

The construction of a theory describing maintenance strategy selection for airfield lighting can assist maintenance managers with optimizing their local practices by identifying key factors affecting the decision-making. For example, some ALM managers expressed concern over using corrective maintenance measures; however, the theory clarifies that corrective maintenance is an appropriate choice under certain conditions. Additionally, by listing the criteria affecting strategy decisions, the theory helps managers understand how airport conditions may limit their strategy choices. Finally, knowledge of the impacts of key criteria points to the differences between airports and clarifies that there is no "one size fits all" solution to maintenance programs.

Limitations of the Findings

This research did not develop a process to determine the *optimal* method of maintenance management. Instead, the goal was to identify the factors affecting decision-making and the *current* model of decision-making commonly used by ALM managers. Completion of these objectives creates a knowledge framework for future research.

The findings apply to U.S. commercial service airports; however, the maintenance programs at airports that are not required to comply with Part 139 are likely to be similar. For example, Part 139 requires daily inspections and that airport staff produces inspection reports during annual FAA inspections. Non-Part 139 airports are still likely to perform daily inspections and maintain records. Also, many non-Part 139 airports are eligible for AIP funding for capital projects. The terms for accepting such funding require that the airport complies with FAA requirements, such as the advisory circular for visual aids maintenance.

The constructed theory may apply to military airfield maintenance, but several conclusions and recommendations may not. The U.S. military provides centralized training for airfield lighting maintenance, enabling sharing of lessons learned among military airfields. In addition, military members are regularly relocated and can obtain experience working on various system designs in different environmental and geographical conditions.

The research population did not include non-primary commercial, reliever, and general aviation airports. The smaller number of operations at these airports suggests they have fewer maintenance demands, smaller staff sizes, and more access to the airfield. However, standard lighting system designs require installing equipment with many of the same maintenance challenges and safety concerns as larger airports. The population for this research included the busiest 382 airports within the NPIAS in 2019. As of February 2020, there were 3,304 airports within the NPIAS and 19,636 airports within the United States (FAA, 2021c, Table 1).

Recommendations

The recommendations for U.S. airports were drawn logically from the conclusions described previously. The grounded theory method helped determine the criteria affecting maintenance management strategy selection; however, quantitative methods could help develop decision-making tools and determine performance benchmarks.

Recommendations for U.S. Airports

Senior airport staff and facility managers should regularly evaluate asset life-cycle costs into maintenance performance measures. Calculating a life-cycle cost allows quantification of the impact of maintenance decisions. Simply ensuring that maintenance staff complete work orders promptly fails to consider whether the correct work is completed. Most airport staff recognized the value of increasing preventive maintenance but could not describe how they could ensure it is completed. Analysis of operating expenses from a life-cycle perspective may help justify increased investment in preventive maintenance or other maintenance program improvements. A life-cycle cost perspective also helps reinforce the need for effective communication between engineering and maintenance staff to identify, design, and execute capital improvement projects.

Small and non-hub airports might benefit from a more streamlined asset management approach by implementing the program on a piecemeal basis. A reduced program might provide a more rapid return on investment and allow working out the kinks before wide-scale implementation. Airfield lighting maintenance is a viable candidate because changing technologies such as LED lighting provides opportunities to reduce operating and maintenance costs when considering life-cycle costs.

A maintenance strategy selection tool based on industry expertise could benefit all airports. The tool might suggest previously unconsidered alternatives or may support the use of the current strategies. Such a tool may also help maintenance staff advocate for investment in maintenance tools and equipment to reduce asset life-cycle costs.

Senior airport managers should understand that some portions of airfield lighting maintenance are hazardous to non-qualified maintenance staff. Therefore, managers should restrict non-qualified maintenance staff from performing specific high-hazard tasks, and airport managers should consider making arrangements with local contractors to assist on an as-needed basis.

The airfield lighting industry, FAA, and AAAE should consider increasing the safety of ALM staff by developing basic and advanced training. Basic maintenance training should be inexpensive, easily accessed, and considered mandatory before work on airfield lighting systems is allowed. Advanced training should include technical skills but also maintenance management education. For example, such courses could explain regulatory requirements, manufacturer recommendations, how to adapt maintenance programs to local conditions, the various maintenance strategies, and the equipment and training associated with these strategies. Maintenance managers can determine which maintenance strategies are most appropriate for their airports using the eight categories used in this research. Additionally, the courses could teach how to develop statements of work for outsourcing electrical maintenance, evaluate contractors, and inspect their work.

Recommendations for Future Research

Methodology. The grounded theory method effectively collected information from the widespread target population. The method appears well suited for exploratory research because it identifies new ideas not previously considered by the researcher. Similar exploratory research to document standard maintenance methodologies may be appropriate for other airport-specific infrastructures such as baggage handling systems or liquid fuel storage and distribution.

Identifying performance benchmarks could be done by conducting experiments. For example, an experimental study could estimate the labor hours necessary to perform recommended preventive maintenance on runway lighting systems under various conditions. Labor hours could be divided into electrician vs. non-electrician work. Such data could assist in estimating in-house labor and outsourcing costs.

An archival study could estimate the number of labor hours spent in a given period for reactive maintenance under various conditions such as lighting system size, local weather, traffic, staff size, training, and maintenance strategies. Airports could use this data to compare program effectiveness to other airports and identify potential ways to improve effectiveness or efficiency.

Future Research Topics. Future research should further develop the MCDM tool by identifying the most appropriate decision-making methodology to replace the current intuitive process. First, using the criteria in the original theory, a team of subject matter experts from various airport locations should assign weights to the criteria and their influence on the selection of maintenance strategy for various lighting system assets. Next, construct a guide to advise maintenance managers on applying the quantitative tool. Finally, compare the results of the tool with intuitive decision-making results.

Identify potential benchmarks for efficiency in airfield lighting maintenance performance, considering the influential factors identified in this research. Recommend key performance indicators for various management levels.

Investigate the demand for maintenance training for non-electrician staff. Clarify which maintenance is suitable for non-electricians. Propose alternative methods to complete specialized maintenance, such as developing scopes of work to facilitate the outsourcing of work. Investigate whether the state aviation department could assist by executing bulk contracts with electrical contractors.

Perform Failure Mode Effects Analysis (FMEA) for critical airfield lighting equipment. Publish the results so airports can expand on the data to consider asset criticality and incorporate the results into risk-based maintenance management strategies.

Perform additional qualitative study on airports where non-electricians perform airfield lighting maintenance to identify what guidance is needed to perform more safely and efficiently. Identify lighting system design features suitable for airports without electricians on staff. Investigate airport management's understanding of safety in maintenance.

Operations inspection records required for Part 139 inspections are valuable information for better understanding airfield problems. Future researchers may consider collecting and analyzing this data to identify trends among the inspection findings.

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Appendix A

Permission to Conduct Research

Embry-Riddle Aeronautical University
Application for IRB Approval
EXEMPT Determination Form

Principal Investigator: David Burgess

Other Investigators: Dr. Mark Friend

Role: Faculty **Campus:** Daytona Beach **College:** Arts & Sciences

Project Title: A Constructivist Grounded Theory Study of Airfield Lighting Maintenance Management Strategy

Review Board Use Only

Initial Reviewer: Teri Gabriel **Date:** 06/25/2020 **Approval #:** 20-147

Determination: Exempt

Dr. Michael Wiggins
IRB Chair Signature: Michael E. Wiggins, Ed.D. Digitally signed by Michael E. Wiggins, Ed.D. Date: 2020.06.25 14:14:39 -04'00' **Date:** 06/25/2020

Brief Description:

The purpose of this study is to collect information about airfield lighting maintenance management practices from current airport maintenance staff and construct a theory describing how maintenance strategies are selected. Using telephone interviews, the primary researchers will collect data from the senior maintenance management staff at a wide variety of U.S. commercial service airports.

This research falls under the **EXEMPT** category as per 45 CFR 46.104:

☑ (2) Research that only includes interactions involving educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior (including visual or auditory recording) if at least one of the following criteria is met: (Applies to Subpart B [Pregnant Women, Human Fetuses and Neonates] and does not apply for Subpart C [Prisoners] except for research aimed at involving a broader subject population that only incidentally includes prisoners.)

☑ (i) The information obtained is recorded by the investigator in such a manner that the identity of the human subjects cannot readily be ascertained, directly or through identifiers linked to the subjects; (May apply to Subpart D [Children] involving educational tests or the observation of public behavior when the investigator(s) do not participate in the activities being observed.)

☑ (ii) Any disclosure of the human subjects' responses outside the research would not reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, educational advancement, or reputation; or (May apply to Subpart D [Children] involving educational tests or the observation of public behavior when the investigator(s) do not participate in the activities being observed.)

☐ (iii) The information obtained is recorded by the investigator in such a manner that the identity of the human subjects can readily be ascertained, directly or through identifiers linked to the subjects, and an IRB conducts a **Limited IRB review** (use the Limited or Expedited Review form) to make the determination. (Does not apply to Subpart D [Children])

EMBRY-RIDDLE
Aeronautical University
FLORIDA | ARIZONA | WORLDWIDE

25 June 2020

Human Subject Protocol Application

Campus:	**Worldwide**	College:	**COA**
Applicant:	**David Burgess**	Degree Level:	**Doctorate**
ERAU ID:		ERAU Affiliation:	**Student**

Project Title: **A Constructivist Grounded Theory Study of Airfield Lighting Maintenance Management Strategy**

Principal Investigator: **David Burgess**

Other Investigators: **Dr. Mark Friend**

Submission Date: **06/24/2020**

Beginning Date: **08/01/2020**

Type of Project: **Interviews**

Type of Funding Support (if any):

Questions:

1. Background and Purpose: Briefly describe the background and purpose of the research.

   The purpose of this study is to collect information about airfield lighting maintenance management practices from current airport maintenance staff and construct a theory describing how maintenance strategies are selected. Using telephone interviews, the primary researchers will collect data from the senior maintenance management staff at a wide variety of U.S. commercial service airports. This theory will incorporate the lessons learned from a wide range of airfield lighting maintenance staff so that knowledge can be used by others to evaluate strategy alternatives.

2. Time: Approximately how much time will be required of each participant?

   Each telephone interview is anticipated to take 45-60 minutes. In some cases, a follow-up telephone interview of 15-30 minutes may be necessary to clarify information or request additional information.

3. Design, Procedures and Methods: Describe the details of the procedure(s) to be used and the type of data that will be collected.

   The principal researcher will conduct all telephone interviews from their personal residence or work office located in Richmond, Virginia. Participants are expected to be at their work location. As sample airports are selected, the principal researcher will contact senior airport maintenance management staff, explain the research project, request permission to conduct the research with airport staff, and ask for recommendations of qualified staff to be participants. Potential participants will be contacted to discuss the research and interview and be provided an informed consent form for signature. Telephone interviews will be conducted after receipt of the informed consent form.

4. Measures and Observations: What measures or observations will be taken in the study?

Participants will be asked a pre-established set of open-ended interview questions. The list of interview questions will be e-mailed to the participant following the receipt of the informed consent form. The interview will be recorded and transcribed.

The list of interview questions provided to the participant following receipt of the informed consent form and prior to the telephone interview. The questions are open-ended to facilitate input from the participant with minimal direction from the researcher. The researcher will record the interview with a third-party telephone call digital recording service and a tape recorder as a backup. Third party digital recordings will be deleted from the cloud source after download.

5. Participant Population and Recruitment Procedures: Who will be recruited to be participants and how will they be recruited. Any recruitment email, flyer or document(s) must be reviewed by the IRB. Note that except for anonymous surveys, participants must be at least 18 years of age to participate.

The airport population is all U.S. commercial service airports. Airports will be purposefully sampled in accordance with the research methodology. The primary researcher will contact the senior maintenance staff at the airport to request permission to perform the research and identify qualified candidates. No recruitment materials will be used.

6. Risks or Discomforts: Describe any potential risks to the dignity, rights, health or welfare of the human subjects. All other possible options should be examined to minimize any risks to the participants.

The risks of participating in this study are no greater than what is experienced in daily life. If participants feel uncomfortable with a question they may skip it.

7. Benefits: Assess the potential benefits to be gained by the subjects as well as to society in general as a result of this project.

There are no direct benefits to be gained by the participant. However, the results of the research may assist practitioners by summarizing the lessons learned of many airfield lighting maintenance management staffs into to a usable theory for optimizing maintenance management practices.

8. Informed Consent: Describe the procedure you will use to obtain informed consent of the subjects. How and where will you obtain consent? See Informed Consent Guidelines for more information on Informed Consent requirements.

The informed consent will be presented to participants after being recommended as a participant by senior airport maintenance management staff. The informed consent form will be e-mailed by the principal researcher directly to the participant for signature. The signed consent form will be returned by e-mail.

9. Confidentiality of Records: Will participant information be anonymous (not even the researcher can match data with names), confidential (Names or any other identifying demographics can be matched, but only members of the research team will have access to that information. Publication of the data will not include any identifying information.), or public (Names and data will be matched and individuals outside of the research team will have either direct or indirect access. Publication of the data will allow either directly or indirectly, identification of the participants.)?

Confidential

9b. Justify the classification and describe how privacy will be ensured/protected.

Individual information will be protected in all data resulting from this study. Pseudonyms will be assigned to participants, locations, and organizations. The key code linking pseudonyms with participants will be securely stored on a password-protected flash drive separate from the research data. No one other than the researcher will have access to the key code. Data will be retained for five years for future research studies; however, any identifiable private information will be deleted upon completion of this research.

10. Privacy: Describe the safeguards (including confidentiality safeguards) you will use to minimize risks. **Indicate what will happen to data collected from participants that choose to "opt out" during the research process.** If video/audio recordings are part of the research, describe how long that data will be stored and when it will be destroyed.

Audio recordings and the pseudonym key code will be stored on a password-protected flash drive. Transcripts generated from the audio recordings with no personal information will be stored on a separate password-protected computer. Data from those who choose to opt out of the study will be deleted.

11. Economic Considerations: Are participants going to be paid for their participation?

No

By submitting this application, you are signing that the Principal Investigator and any other investigators certify the following:
1. The information in this application is accurate and complete
2. All procedures performed during this project will be conducted by individuals legally and responsibly entitled to do so
3. I/we will comply with all federal, state, and institutional policies and procedures to protect human subjects in research
4. I/we will assure that the consent process and research procedures as described herein are followed with every participant in the research
5. That any significant systematic deviation from the submitted protocol (for example, a change in the principal investigator, sponsorship, research purposes, participant recruitment procedures, research methodology, risks and benefits, or consent procedures) will be submitted to the IRB for approval prior to its implementation
6. I/we will promptly report any adverse events to the IRB

Electronic Signature:

David Alan Burgess

Appendix B

Informed Consent Form

INFORMED CONSENT FORM

A CONSTRUCTIVIST GROUNDED THEORY STUDY OF AIRPORT LIGHTING MAINTENANCE MANAGEMENT STRATEGY

Purpose of this Research: I am asking you to take part in a research project for the purpose of collecting information on airport lighting maintenance management strategies at U.S. commercial service airports. This research will use telephone interviews to collect relevant data from selected airports. Data will be used to develop a theory describing the current methods for selection of maintenance management strategies for airfield lighting. The results of the data analysis may be shared with the aviation community. The primary telephone interview is anticipated to take 45-60 minutes to collect research data. A follow-up telephone interview of about 15-30 minutes may be needed to clarify data collected during the primary interview or to ask additional questions generated by other interviews.

Audio recordings of the telephone interview will be made for the purpose of preparing an interview transcription to support data analysis. Prior to the start of the telephone interview, the principal researcher will state the telephone interview is being recorded and request any non-participants not to speak during the entirety of the telephone call. The recording will include the interviewee's name, job title, years of experience at the airport, and responses to interview questions.

Eligibility: To be in this study, you must be a resident of the U.S. and 18 years of age or older. You must be an airport employee.

Risks or discomforts: The risks of participating in this study are no greater than what is experienced in daily life. You do not have to answer any question you are uncomfortable in answering.

Benefits: While there are no benefits to you as a participant, your assistance in this research will help the quality and accuracy of the research results. Research results will provide data to help airfield lighting maintenance staff select maintenance strategy.

Confidentiality of Records: Your individual information will be protected in all data resulting from this study. While the members of the research team will have access to your personal information, publication of the data will not include any identifying information. You will be assigned a number; the key code will be stored separately from the data. Access to audio recordings will be limited to the principal researcher. The computer and data storage device will be stored at the personal residence of the primary researcher. The computer will be password protected with access limited to only the primary researcher. Audio recordings during the telephone call will be maintained on a third-party server until the principal researcher downloads the recording to a personal computer. At that time, the recording on the third-party server will be deleted. The principal researcher may also create a backup audio recording on a hand-held device. This recording will be deleted after the interview is successfully transcribed. Audio records will not be retained for future research and will be deleted following the preparation of the interview transcription. Interview transcriptions will be retained for five years to support future research.

Compensation: There is no compensation offered for taking part in this study.

Contact: If you have any questions or would like additional information about this study, please contact David Burgess, burgesd5@my.erau.edu, or the faculty member overseeing this project Dr. Mark Friend, frien9b8@erau.edu. For any concerns or questions as a participant in this research, contact the Institutional Review Board (IRB) at 386-226-7179 or via email teri.gabriel@erau.edu.

Voluntary Participation: Your participation in this study is completely voluntary. You may discontinue your participation at any time without penalty or loss of benefits to which you are otherwise entitled. Should you wish to discontinue research at any time, no information collected will be used. Any personal information that can identify you will be removed from the data collected and after removal of this information the data collected may be used for ***future research studies*** or ***distributed*** to another investigator for future research studies without additional informed consent from you.

CONSENT. By signing below, I certify that I am an airport employee, a resident of the U.S. and I am 18 years of age or older. I further verify that I understand the information on this form, that the researcher has answered any and all questions I have about this study, and I voluntarily agree to participate in the study.

Signature of the Participant_______________________________ Date:______________

Printed Name of Participant_______________________________

Appendix C

Data Collection Device

Interview Questions

The associated research question is indicated by ***R1***, ***R2***, ***R3***, or ***R4*** at the end of each interview question.

Background

- How did you get your start in airport lighting maintenance?
- How is airport lighting maintenance different at this airport than other airports?

Type(s) of Maintenance Strategy Used

- Describe how you identify, prioritize, and schedule maintenance activities. ***R2***
- Do you use different maintenance strategies for different lighting systems? ***R2***

Key Indicators Used

- What data or metrics are regularly maintained by the maintenance department? ***R4***
- Do you use predictive measures for maintenance? If so, how do you estimate the likelihood of failure for assets? ***R1***, ***R2***, ***R4***
- What other maintenance records are kept? ***R4***

Selecting Maintenance Strategies

- What factors influence the selection of the maintenance management strategy? ***R1***, ***R3***
- Are maintenance staff involved in the selection of a maintenance strategy? ***R3***
- Has your organization tried other strategies? ***R3***

Factors Affecting Maintenance Strategy

- What factors about the airport, the airlines, the FAA, or the airport organization positively impact airfield lighting maintenance? ***R1***
- What factors about the airport, the airline, the FAA, or the airport organization negatively impact airfield lighting maintenance performance? ***R1***
- What would you change about your airport lighting maintenance organization or processes if you could? ***R1***

Open Input

- What advice would you give to other airport lighting maintenance organizations?
- Were there any topics that we missed that are important to how you organization performs maintenance?

Principal Researcher: David Burgess

Appendix D

Category Memo

Category Memo
Focused Code: CONDITION

DEFINITION:

Condition refers to the current state of the airfield lighting system as determined by the three properties below.

EXPLICATION OF PROPERTIES:

- **Age.** Each component of the system has its own age. Possibly there is some way to calculate and aggregate age.
- **Wear and Tear.** Fixtures in snow regions are subject to snowplow scrapes. RWCL, IPRGL, TDZ, and TWCL fixtures are more susceptible to aircraft wheel loading. Fixtures in radii are more susceptible to torsional loads.
- **Proper Maintenance**. A properly maintained system will have a regularly scheduled maintenance program designed according to the specific system needs and have a predictable amount of reactive maintenance.

CONDITIONS UNDER WHICH THE CATEGORY ARISES, IS MAINTAINED, AND CHANGES:

- Replacing equipment resets the age to zero with new equipment. Installing used equipment is sometimes cost effective but will affect the expected end-of-life estimate for that equipment. Managers can control the age of their equipment but may not know a part's Remaining Useful Life (RUL). Knowing the RUL can help managers estimate maintenance costs and estimate when to plan for replacement.
- Since AGL is fixed in place, the amount of wear and tear is dependent on the equipment location. Centerline fixtures are more likely to be impacted by aircraft traffic compared to edge fixtures. Edge fixtures located at fillets are more likely to be damaged than fixtures in straight sections. Managers do not have much control over wear and tear; but, by knowing which fixtures deteriorate faster then managers can better plan maintenance and replacements.
- Proper maintenance. Managers have control over the maintenance program. Proper management should ensure that the maximum amount of life is obtained at the minimum cost.

CONSEQUENCES:

- Keeping old equipment in place too long risks a higher failure rate. Old equipment is subject to becoming obsolete.
- Replacing equipment before it has reached its expected life potentially increases the life cycle cost.
- Some wear and tear is inevitable, but some can be reduced by routine maintenance and clever design. For example, one loose fixture bolt is a minor problem. As more bolts become loose, the fixture becomes a FOD hazard as well as the bolts.

- Based on their location, some fixtures warrant more thorough inspection and maintenance.
- Generally, inadequate maintenance will result in increased repairs and replacements sooner than expected. The wrong type of maintenance can result in the same. However, excessive maintenance can result in increased costs with no added benefits or risk reduction.

RELATIONSHIPS WITH OTHER CATEGORIES:

RECORD KEEPING. Without documentation of the manufacture date and installation date it is impossible to know the age of system components. Without documenting maintenance for each piece of equipment, it is impossible to know the maintenance history of the equipment and whether it has received proper maintenance. (This category applies to Research Question 2 and was not used in theory for maintenance strategy selection).

BUDGET: Replacing old equipment has a cost. Maintenance and repair also have a cost. Maintenance managers should try to optimize the life cycle cost of their equipment by performing the amount of maintenance that maximizes the equipment life. Failure to perform proper maintenance may result in early equipment failure and replacement, which increases life cycle cost.

Appendix E

Transcript Excerpt

Transcript

INTERVIEWER:
Let's start with your background. Can you tell me how you got your start in airport lighting maintenance?

Interviewee #14:
Well, I guess when I started to work here, it was 19 years ago. It was just an opening. Coming out of construction just really want to make this type position and this one was open in there I go.

INTERVIEWER:
Can you describe your department there? How many people do you have?

Interviewee #14:
I have five electricians. We work Monday through Friday on a day shift. So, course we're setting to be on call constantly and the five will take, in a rotation, are responsible for a weekend from Friday 330 to Monday 7am. to be if something happens in someone's needed, they will be the first one that comes to be called.

INTERVIEWER:
You're hiring qualifications, do they have to be journeymen to be hired?

Interviewee #14:
Yes, sir. They have to be a licensed journeyman electrician.

INTERVIEWER:
Okay, but I just do you have any other requirements for being for hiring an electrician?

Interviewee #14:
Not really just being familiar with radio operations, comfortable with talking to one or two frequencies or so at the same time. As you know, airfield lighting is sort of a specialized field that not many people … in fact none of us have ever had any experience until we came to work here. So it was sort of a little bit of an on the job training. And in, in outside training as best we could. But so therefore that being said, being a licensed electrician is a major step forward. For us anyway, we're comfortable with his knowledge there or would be able to pick it up, have a foundation.

INTERVIEWER:
Now, for the OJT aside from just straight OJT learning from each other. Do you have any other training that you require? Like ACE certification or ADB or Crouse Hinds training, that kind of thing?

Interviewee #14:
Yes, we do some ADB training, and Crouse Hinds, because we use a lot of ADB fixtures and so forth but mostly Crouse Hinds, as soon as we can we get them into a Crouse Hinds training because that's what our control system is. And then we have our tech from our Crouse Hinds comes twice, a minimum of twice a year, just for just for training and to you know answer questions look our system over and that sort of thing. But then again, they then they come anytime we need them.

INTERVIEWER:
Can you generally describe the facilities and equipment that you have for airfield lighting, maintenance. Do you have your own shop or multiple shops?

Interviewee #14:
We have our own shop, matter of fact, the maintenance facilities and other departments we just moved into a new building. So all of our field maintenance, our police department, operations department, and the warehouse are all in a new building and about three or four weeks ago, We have all of our snow removal here. And we just bought literally we come in the front door we're on the AOA, because we have to badge through. We walk out the back door we get in our trucks and just drive out to the airfield.

INTERVIEWER:
Do you have anything special that you've modified on your trucks or special equipment that you carry aside from standard electrical meters?

Interviewee #14:
We built this, several of us built a homemade rack and we can we can rack our lights vertically in a row so that we can maximize space and not damage the light, the inset fixtures, you know, just bouncing around in the truck. That's really about it. I'm trying to think off top of my head. Other than being able to have a speaker mounted under the truck so that we can listen to that airfield radio when we are out of the vehicles doing some work.

INTERVIEWER:
How about photometrics? Do you have a MALMS unit?

Interviewee #14:
No sir we do not. We had that demonstrated to us and we just we just opted it off of that. It was not required to my knowledge. We decided not to. As a matter of fact, they left one with us that we could use, and then we had for a couple of times had a contractor come out with one pull behind his truck.

INTERVIEWER:
How about any other things like bolt torque measuring tools? I understand they've got some meters that will automatically record that with a with a torque wrench. Are you using any of those kind of tools?

Interviewee #14:
No sir. We use a torque wrench when we have replace every bolt every time we pull the fixture up. No, I did have, who was that, it might have been ADB stop out here just a few weeks ago and wanted to demonstrate. I can see that being handy. Well I'm sorry, we don't have that.

INTERVIEWER:
Do you use anything like handheld iPads or phones, whether you log in your work and help you use GPS to find fixtures and equipment?

Interviewee #14:
No we have not, but they're working on a program and have been promising that for quite some time. That I can see being even more useful. As far as for operations, writing up a work order and, you know, dropping a pin right there for us to go to it. Because you know how that is Sometimes descriptions aren't the best way to find a light out there.

INTERVIEWER:
Can you talk a little bit about your responsibilities as a shop leader versus other electricians? I assume since you have an airfield lighting maintenance shop, you are air side and maybe there's another shop for landside? Is that right?

Interviewee #14:
Yes. So that's how we are in *Airport #8* we have two separate electric shops, two separate supervisors, two separate crews. We call them airfield shop and buildings, the building electric shop, as it implies, they take care of the terminal, everything over there. Airfield shop takes care of the airfield, among other things, everything outside most all exterior lighting, pole lighting, sign lighting, inbound outbound at the terminal. We also take care of all handheld radios. We also locate anything that is ours, we locate underground utilities as far as ours before any digging, and other duties as assigned. We run the sound system outside if there's a news conference or something like that. And, of course the airfield, trying to keep it up. That's about it.

INTERVIEWER:
I'm going to move on to the first topic of maintenance strategy and maintenance strategy includes approaches like reactive maintenance, proactive maintenance, predictive maintenance. I don't know if you're familiar with those terms. I'm curious if you are if you describe what strategies do you use it your airport? Do you use any of those or some version of it.

Interviewee #14:
We try to be more proactive than reactive. Of course, you know, if a sign goes down or a light goes out, that's going to be reactive on our part, but we try to be proactive to the point that we every which is today is the day every Thursday, we meg every circuit on the airfield. Therefore we can chart a decline. We can try to try to get ahead of the curve on that. We have four vaults. All of our vaults have generator backup. We'll crank them every Thursday. Just look it over and then quarterly, we'll load test each of those

generators. Quarterly we will test our SMGCS system on the three runways that have it just to make sure we're still looking good there. Especially right before the season, before it gets winter time.

INTERVIEWER:
Do you change your frequency or the maintenance on this SMGCS during winter? Or do you have to do most of it before winter?

Interviewee #14:
We get a little more before winter, you know, but at least quarterly, we'll go through it. And we don't mind. You know, late summer, early fall, something like that when the weather's pretty good being able to … in case we have to work on it, you know, then it's not so, it's not getting out there and when it's so bad, and that's about when we're going to need it anyway. But it's not exactly, we'll do a minimum of quarterly. If we have time. We hadn't done it a little bit, you know, we'll just turn it on and play with it when we have a runway closure.

INTERVIEWER:
Okay, do you have regular runway closures for maintenance? Or do you just do it when it's available?

Interviewee #14:
Usually when it's available, or as needed, we have one runway, actually two runways, that Monday is really the only practical time to close. Unless it's just a true emergency. CARGO AIRLINE #1 prefers these two, one of them, they cross a lot, the only East West runway. The other runway, that one thing they prefer to use, and Monday is their slowest day. So we, we try to about every Monday, one of those are going to be closed, but the others really as needed.

INTERVIEWER:
Now, some of the maintenance you use to describe before you do regularly would be something I would call may be calendar-based maintenance or something that nobody has to tell you to do it you just know, based on your records to do it. But I assume also, somebody does inspections, regular inspections, and generates requirements, how does that work?

Interviewee #14:
Yes sir. The operations department has somebody on every shift at least once, on every shifts, I mean, three times a day just looks over the airfield. And they're mostly the ones Well, they're the only ones that will write something up like that, generate work orders. We, one of our one of our guys comes in at 5am every day, between five and seven, just rides the airfield and looks it over, repairs what he can. If it's just, you know, a lamp or whatever, like that, then if its more than they can deal with ... because that's a slow time five to seven … and if it's a little bit more than what they can deal with, you know, we'll make a note and then we'll get with operations department about maybe having a closure on a taxiway or something like that during the next day or two.

INTERVIEWER:
Are you able to keep up with the inspections or do you usually have things that go on for a few days? And then sit on a backlog?

Interviewee #14:
You know, usually not. Not too much. But yes, you know, there's always going to be something that's just not priority. At that point, we'll get there when we can. But for the most part, they within four or five days, never says anything longer than that.

INTERVIEWER:
Okay. You mentioned priority and that's something I want to ask you about. Do you have a formal process or maybe an informal process for prioritizing your work orders? Like say, in the morning, you find out you got a couple items that came up on inspections, but you got a few items that are come up when on your calendar maintenance. Do you have a system that helps you prioritize that or do your guys just kind of know what's priority? How's that done?

Interviewee #14:
As it arises and we'll make that decision. Operations when they write up a work order and our work order system, it's got a priority on there and they might put priority one or priority two but it will try to address the priority one quicker. But a lot of things that come up just you know as we can you know electricians out there on the early morning, as we call it, it's not really an inspection but a look to repair. You know he'll see something, it might not be priority one, but he's already there. He's got he's got the tools, he's got the materials he's needing, to change a lamp or whatever, he'll just get it then, sometimes even before it even gets written up.

INTERVIEWER:
What kind of things would you consider priority one?

Interviewee #14:
Mandatory signs. Guard lights, wig wags. Stop bars especially. That would be that would be a priority one. An unusual amount of say, center lines on the runway or TDZs, if we had a lightning storm or if for some reason the Tower turns them on high all at once. that'll pop a lot of lamps. That what I'd say is priority one. That may be different than what operations has.

INTERVIEWER:
Do you have written maintenance procedures? How do you train people on the them? Is it more OJT?

Interviewee #14:
Yeah, mostly. Of course. We have maintenance manuals on regulators and all of our equipment. We try to maintain somewhat of a library. Those are some, you know, when

we get a new guy, we'll show him where this is and that is, when they get time to, you know, kind of go over the this. But a lot of it is just hands on.

INTERVIEWER:
What about record keeping? Do you keep any records of measurements or other or inspections that you use and refer to later?

Interviewee #14:
Yeah, like the meg reading I was mentioning. We keep a log book in every vault so we can view that. Every week when they go in to record this week's data, they'll kind of look back and see what this regulator or this circuits been doing for the last few months. And that's really, really about it. We have a program of changing out our regulators. So we keep up with, you know, when installed, the age of it, and maybe we sort of might be thinking about replacing this one or that one.

INTERVIEWER:
That makes me think of another program. Are you familiar with asset management programs?

Interviewee #14:
No, I'm not.

INTERVIEWER:
Okay, because that's a popular maintenance management program that a lot of airports are doing. And it requires things like developing an inventory of every asset that you have on an airport. So, making a list. And then in a computer system, a big database and then recording things like when it was installed and what is expected life is and so that way, you know, you get automatically generated report some things about things that are going to be coming up on their expected life. And but it also would require you to provide a lot of updated information. Like when you do maintenance, that database has to be updated. And it will include things like the last time this thing was worked on or how frequently it was worked on. Do you have any programs like that there at *Airport #8*?

Interviewee #14:
No we don't. That does sound interesting there.

INTERVIEWER:
Yeah, generally, you can apply it to a whole airport. There are places that have started to implement it. It does require a lot of work to get started. And, but then it also requires some extra work to maintain because you can imagine, well, that's why some of those things like the handheld devices for tracking work orders, makes things easier to keep everything up to date on the computer rather than having to do it manually

Interviewee #14:
Yeah I can see that. Instead of having to come back in from the field.

INTERVIEWER:
Often when they do it, it's the whole airport. So it's a big computer system, training. So it's fairly big deal when they do it, I think I think like ADB offers a program that will do it just for lighting, but I don't know how popular it is. Nobody has mentioned having that one.

Interviewee #14:
Like I said, an ADB rep came by here a few weeks going and mentioned that. Yeah, well, I don't know how that would work with us to be honest.

INTERVIEWER:
I'm gonna move on to the next topic, which is about measuring maintenance performance. And we kind of talked about a little bit, but do you have any quantitative measures that you regularly keep track of and report to higher management that summarize the performance of the lighting system? Or the maintenance organization?

Interviewee #14:
Not really, we do like a yearly evaluation of each employee. That would be the only thing I can think of. Not really.

INTERVIEWER:
I talked to one airport that said they were thinking about doing an availability calculation for the lights, you know, how much time they're actually operating. But they said with the LED lights, they are pretty much 100% all the time. So it was kind of pointless. But okay, yeah, I was just wondering if you had any, any kind of metrics type things. How about any informally how do you know that the lighting is working well? How do you get feedback on that? Or, if it's starting to degrade, how would you know?

Interviewee #14:
Once a shift they'll do a field inspection, and then five times a week, we also do it, but any other anybody else has a closure for taxiway or a runway for, you know, dirt work, the painters may have it closed, we'll light it up and just go out there and just look it over. And we find a lot of things like, you know, just try to stay on top of it that way.

INTERVIEWER:
I'm going to move on to the next topic, this is deciding on the maintenance approach.

Interviewee #14:
Let me back up just a second on that one, it just hit me. Some of our lights are monitored with our control system. So we can see, you know, that they're out all of our guard lights,

a lot of the lead on lead off because of the SMGCS system, and stop bars, we can, we can look on the computer here at the shop with the main computer and just, you know, get a list of what needs to be done. You know, for instance, like guard lights, if somebody's got a runway closed today, we'll go out and look, we can look before we ever leave the shop, and see how many guard lights are out and have that many on the truck when we go.

INTERVIEWER:
Okay, so do you look at that on a regular basis? Or, do you just do it as needed? Or how does that work?

Interviewee #14:
Yeah, we'll probably need it but generally somebody is looking at the whole airfield on guard lights, somebody is going to do it every day, just out of habit. And it doesn't take that long. And then one of them would come to me and say, Hey, you know, 9-27 You know, we're getting quite a few out maybe we need to get out there. And I'll coordinate a closure and/or a work plan with operations to get them get them out there and change them out.

INTERVIEWER:
Do you use anything like the lamps out function for any of the other regular circuits like edge lighting circuits and such.

Interviewee #14:
Some of the runway, it'll just tell you know, like, they won't tell us which lamps or which lights are out but it'll tell us on this edge light circuit, this runway edge light circuit we have like four lights out or something like that. The guard lines and some of the lead-ons that are SMGCS-controlled stop bars We can see exactly which one it is.

INTERVIEWER:
I've heard some say that the lamps out doesn't work very well, but does it work okay for you?

Interviewee #14:
It works okay, It's not it's not 100%. Like the edge lights. If it's an inset on our runway, its going to have two lamps. If its elevated its going to have one lamp. Well, this thing is just looking for, I know that 100% X amount of Y. And so if its 100 watts less or something is gonna say one light. What I'm getting at is, the long way is, is that an inset might show up as two lights are out, and it'd be one inset. But you know, it's not 100% accurate. Its just another tool that we can use. It's just something that lets us know, if nobody has been out to look at that last little bit, you know, they like to go ahead and look at this and double check.

INTERVIEWER:
It seems like it might be kind of hard to find a light that's out that way, if all you know …

Interviewee #14:
It is, you know, if I happen to know that, one is out, or see that, if we've got a closure, or somebody's got to closure we will light it up, say hey, let's make sure we look for runway edge lights, the computer is showing we got two out.

INTERVIEWER:
I'd like to move on to deciding on the maintenance approach. This gets into how the program is organized and who makes the big decisions. Who are who are the key decision makers in your maintenance management program? Who would normally decide that you maybe should adopt a new procedure? or change the schedule? And do you team with other departments like engineering for any of these decisions?

Interviewee #14:
Probably more operations than engineering. And they might come up with an idea or started a discussion from either direction, or it might be somebody on my staff that would say, Hey, you know, it might be a good idea if we do this, we will we'll discuss pros and cons, then, pretty much probably left up to me, if we're going to do it or not. Sometimes we might have to discuss with operations to make sure that we're capable or that we can do it that way. That's pretty much everything has been set before my time, and this is pretty well worked out. Okay.

INTERVIEWER:
Let's say you needed a capital improvement project, like all the all the cabling on taxiway system needed to be replaced, how would that get identified and done?

Interviewee #14:
That's when I would talk to my boss about we need to put this in the budget, and work on this, and it would just kind of go up the ladder from that. But then I'd have to give a justification for it, you know, from how long is gonna last. How's it going to impede air traffic and that kind of thing. And then the decision would be made well above me about that.

INTERVIEWER:
Okay, have you had any, what I describe as downward directed programs, like something that management told you to change that maybe seemed like a good idea wasn't necessarily generated by you guys like some, sometimes, like LEDs. Some of those get projects get started because of an energy assessment for the airport. But I think most maintenance guys, not all, but most like the LEDs. But do you have any programs like that, that get sent to your guys to work on?

Interviewee #14:
No, not really. We've incorporated a few like LEDs. You're asking if someone wanted to implement a program that we didn't particularly like? Is that what you're asking?

INTERVIEWER:
Not so much that, as who puts their hands into the management of the program? How hands on are those guys? Or is it mostly, do you pretty much decide how the maintenance program is going to be done because I find at some airports, mostly small airports, you'll get facility managers and even airport directors that'll come out and say they want this done. And then other airports will have engineers involved. That say hey, this is a program that we want to implement, or are you a little bit more independent?

Interviewee #14:
They will … usually on a larger project that's something that honestly I don't know where it came from. But I'll be asked my opinion of it or some input on how to implement it. But, you know, most things that are just totally left up me are the day-to-day management. Like we were, we were budgeted in and replacing sign panels before … my predecessor started it because even before him, they kicked that can down the road so long now all of all of those panels are being in pretty bad shape. So we were doing like $70,000 a year, panel replacement, well, that wouldn't wasn't even touching it. And somebody from one of my vice presidents sees this and says, well, why don't we just look into replacing all signs. There's how that one got kicked off. So we're, we're still in the planning stages of replacing every sign on the airfield, with new LED signs. I mean, I can ask for something or say, you know, what is the chances of this, and engineering thing get involved. For the most part its engineering.

INTERVIEWER:
As far as the sign panels go, do you think that like the airlines were complaining about the panel's or was that just something else?

Interviewee #14:
The FAA was. It was on our Part 139 inspection. They brought it to our attention. Some were faded and all, but after that, another electrician and myself, before I got this position, a few years ago, we catalogued every sign out there, and took pictures and graded on the support. We realized what kind of position we were in. And it started kicking around, let's just replace signs with newer LED signs and so forth. That's been about a two year planning project.

INTERVIEWER:
So you're still working on that.

Interviewee #14:
Yes, it sort of got kicked off to the side a little bit, when somebody else came up with a couple other very large projects and development was just swamped with that. They got some help, an engineering firm. I don't know why, but they're still looking into it. They didn't realize it wasn't as simple as pulling an old sign up and popping a new one down. We've got things like distances off taxiways and runways. When those signs were put in, there were different requirements like having to feed it to the leg instead of an exposed

cord. So we got to adjust for that. You know how that it, sometimes there’s just more to it than what you think.

INTERVIEWER:
So is this identifying work that you guys would do in house? Or would you contract that out?

Interviewee #14:
Oh, no, we’d have to contract that work out. We've got 467 illuminated signs, and I've got five electricians. It’s all we can do to maintain. There's no way we can do a project of that size.

INTERVIEWER:
Actually, that reminds me of something I didn't ask earlier. Do you have portions of your maintenance that you normally subcontract? Do you have a regular contract that does some portion of it?

Interviewee #14:
No sir. If a project like that sign project comes up, or something like that, yes. But not as far as regularly having anybody out here to help us.

INTERVIEWER:
I've heard of like some airports will have a contract with their manufacturer to maintain the ALCMS like on an annual basis. And then some, some airports have photometric testing contracts. I'm just wondering if you if you have anything regular like that, but it sounds like no?

Interviewee #14:
No sir, no we don't.

INTERVIEWER:
Next, I want to move on to the factors that affect your approach to maintenance and we kind of touched on it already a little bit but what are the factors that influenced your decisions about how the maintenance program is run? And I have divided them into two types internal and external. So let me just go over the internal first. Like, there might be things internal to your organization such as staff qualifications, staff size, your budget, or the management. Do any of those things affect your maintenance decisions? And I bring it up as, do you wish you had better qualified people? And if you did, you would do this? Or change how you did things? Or if you had a better budget? would you change things? If you had more people? would you change things? Do any of those type of things affect how you do your maintenance?

Interviewee #14:
Oh, absolutely. The size of my staff, with five people you really got to prioritize and try to plan ahead quite a bit. It would make our life easier if we had a bigger staff. As far as everything else. No. Some larger projects have been talked about, more or less discussed

that with development. We try to put that in a time frame of when we can do it, or if it's even needed, or if I can think I can justify it. The size of the crew is my biggest concern.

INTERVIEWER:
What might you do different if you had a larger crew?

Interviewee #14:
I think I can get to more things that aren't priority one quicker, non-airfield-related. We're responsible for things other than just on the airfield, we'd be more able to keep up with it a lot better.

INTERVIEWER:
There was one airport that said they actually have to have two separate teams, operating independently in order to keep up with the important maintenance within the timeframe that they're allowed to work. You have any problems like that?

Interviewee #14:
I'm not sure I'm understanding what you're what you're asking. But, you know, we had, we do have two electric shops.

INTERVIEWER:
Well, they're saying they've got basically, I think, an hour and a half, two hours in the morning, where they can get most of their maintenance done. And they just can't do it with one team, they have to divide and conquer. So that means they're pretty much independent, they can't share a truck or share equipment.

Interviewee #14:
That's the way we are, you know, with the two different shops, and each, each electrician that works with me, has their own vehicle. And when we have a closure, or we just get out there and work with operations, do repairs, they're all independent. Very seldom do we work in pairs or anything, we'll all be out there about the same time. Of course there are things that it just takes two or three people. And we'll have to plan for when we can do that.

INTERVIEWER:
Now, talking about things that are external to the organization that might affect your approach to maintenance. And examples might be things like weather, does the seasons affect it, or maybe your geography, maybe in a water table, or maybe you're all on rock everywhere, or maybe the FAA or the airlines. These are just all things that are kind of outside your control ,outside your organization. Do any of those affect your maintenance approach?

Interviewee #14:
Oh, yeah. Weather predominantly. We plan things every day on the weather. Then we also have to think about the busy times we just we try to work around the busiest times for air traffic. And that gets harder and harder every day.

INTERVIEWER:
Are you talking about on a daily basis, or seasonal?

Interviewee #14:
A daily basis, just weather and air traffic.

INTERVIEWER:
What are your big weather concerns? What type of weather really impacts you?

Interviewee #14:
Well, but mostly like today, you know, thunderstorms, there's lightning, tornadoes likely and then the winter time just you know of course it is. It's coming down sleet or snow and we're not maintaining anyway because we're all on the phone the snow removal. Yeah just the inclement weather it is dangerous for those guys to get out there.

INTERVIEWER:
They have the electricians operating the snow equipment?

Interviewee #14:
Oh yes sir, everybody, everybody does, painters, electricians, I lead one of the snow teams it's all hands on for that. Of course, we're in *Airport #8*. We're not exactly known for our snowfall. Most winters we might do just one or two. But, this year, we did the longest one I've ever did. We just did six days of continuous snow operations.

INTERVIEWER:
Do you have heaters on your lights?

Interviewee #14:
No, sir. We had a few in one contract and that got put in, but and that's just very few maybe 30 or something. But no, we do not have heaters.

INTERVIEWER:
Are you happy about that? Or have no opinion? Do you think it'd be better, or what?

Interviewee #14:
You know, here again, in *Airport #8*, it is really not a factor for us. I can see where about in Chicago it would be handy. Honestly, for me, it would be just one more component that I have to keep up.

INTERVIEWER:
How about the FAA? I know they do their part 139s. But do they influence your maintenance in any way?

Interviewee #14:
Oh, yeah. And it's usually on the 139. They'll come up and say hey, have you noticed this? They'll alert us of a change or something.

INTERVIEWER:
How detailed do they get in there 139 inspections?

Interviewee #14:
You know, I don't want to shoot myself in the foot. But here again, it depends on the inspector. They get pretty in depth with us. They'll stay here for … matter of fact, we're scheduled next month for ours and they'll be here four days, they will look over all the records and everything and then they want to see that SMGCS work. So one night, they'll want to be run around and see all the lights at night and the reflectivity of the paint. They want to see the SMGCS route, they'll want to see it work. They get pretty in depth.

INTERVIEWER:
How about any of the airlines? Do they ever contact you and ask for things or contact your management staff?

Interviewee #14:
They never contact me? I think that building group deals more with the airlines.

INTERVIEWER:
How about the design of your airport. It may be hard, if that's the only airport you've worked on, to compare it to others. But do you think there's any features in the design of your airport that make it easier or more difficult to maintain?

Interviewee #14:
Yeah, no, as you said, this is the only airport that I've ever worked at. So it's hard to compare. And honestly, I can't think of anything that would help us, or hurts us, as far as the design of it.

INTERVIEWER:
Just generally, aside from anything I brought up, do you think there's any other things that influence your decision making about maintenance.

Interviewee #14:
No, just prioritizing or, you know, trying to get ahead of the curve as best we can. Including keeping spare parts that we don't normally use. Sometimes that gets to be a problem with our warehouse staff. This just a pet peeve. But if I haven't requested one in a year, they'll just do away with it. And not even ask me. You know, there's just some things that you need, but I don't need it on a regular basis. Trying to keep trying to keep enough spare parts that I don't have to wait on something is a concern. Mainly because it's hit me a couple of times in the last several months. But that's really about it. Things have worked out so far for us.

INTERVIEWER:
Are your fixtures and signs and other regulators … are they all fairly up to date, are they older equipment, or a mix?

Interviewee #14:
It's a mix. That's one reason I mentioned about we're replacing regulators at about two to a year, which is not enough in my opinion. We've got several regulators that came up that are no longer supported for parts. And so we started replacing a few of those and just keeping the ones that we're taken out of commission for the scavenged parts. We got kind of a mix on that, and the lights too. For the most part, they're fairly new. Since I've been here, they replaced … or there's been addition to it … and they would go with this brand. You know, which we've tried to get down to it getting some fairly compatible, at least a couple of different, so you don't have to keep so many parts. So far, most everything is still supported with spare parts, so I consider it new enough.

INTERVIEWER:
And do you pretty much have LEDs everywhere. Or, do you still have a lot of incandescent?

Interviewee #14:
We're predominantly incandescent, we've got a few LED taxiway edges. And one area, we might have 30 centerline, taxiway centerlines.

INTERVIEWER:
Do you prefer the incandescent?

Interviewee #14:
I would prefer LED, but we keep incandescent because of CARGO AIRLINE #1. CARGO AIRLINE #1 has got a forward looking thermal imaging system of some sort that they've gotten most of their planes so they need a heat signature. And of course the LED is not working out for them. So they balked on that. And that's reason why we're keeping mostly incandescent.

INTERVIEWER:
How about other technology upgrades like your ALCMS, is that fairly modern?

Interviewee #14:
It gets updated. Its 20 plus years old. But it gets constantly updated.

INTERVIEWER:
How does airfield traffic have affect your ability to access the runway for maintenance? Are you pretty much able to get to the maintenance on the runway anytime? Or just certain times of the day? Or certain times of the week?

Interviewee #14:
Oh no. We have to pre plan that for a closure to do anything. We have a meeting weekly, every Wednesday, with all the stakeholders, FAA, CARGO AIRLINE #1, airlines, contractors that are doing projects and so forth. And we schedule out, we need to get it here, to do this. And when's the best time that we can do it? What's the best day? So it's all scheduled. Of course if we see something on the taxiway, change one or two lights maybe, we get with operations duty manager who's got the field that day. And you know, he can make a decision as to whether you know it with the FAA But okay, you need 30 minutes. You know, how about somewhere between 10 and 12? We can work something out like that.

INTERVIEWER:
Okay, well that that hits My standard questions. I'm kind of down to the catch all any other important information about airfield lighting maintenance management. One of the things that interests me about *Airport #8* is the is the heavy cargo operations. And I, and I noticed one of the impacts of that is your need to stick with incandescent lights for CARGO AIRLINE #1. Do you think there's other aspects of cargo operations that make *Airport #8* a little more unique?

Interviewee #14:
From what I gather a lot of other airports do a lot of their just regular maintenance and stuff at night. And we do ours in the day. Because CARGO AIRLINE #1 are busier at night. We do schedule, that's a main factor of us scheduling any kind of closure, or work, because the amount of traffic they have. They have just over 450 flights a day. So that's a heavy influence on us.

INTERVIEWER:
So how many hours a day do you typically have access to do maintenance?

Interviewee #14:
Here again, some days we might not even get out there, we've got other things to do. And then they might be for three or four days in a row. We're out there all day. You know, once again, it's just whatever we can schedule.

INTERVIEWER:
Are there certain times of the year or maybe the month that are especially busy? Like I would imagine around Christmas time CARGO AIRLINE #1 gets extra busy? Does that? Anything like that affect you?

Interviewee #14:
Yes, the Christmas rush. You hit is on the head right there. Thanksgiving, just after the first year, it's very, very difficult for us to get out there. They'll step their operations up and even subcontract out a lot of flights.

INTERVIEWER:
Have you made any recent changes to your staff or your equipment or your training that affects lighting maintenance? Any, anything has happened in the past year or two that have affected things?

Interviewee #14:
Well, the COVID is about it. That really affected us. Nothing I planned on anyway,

INTERVIEWER:
how did COVID affect your maintenance program?

Interviewee #14:
The biggest thing was, we had to split the shop, I had to, I've got to two people at a satellite shop. And then the other three are with me, just so if somebody was to get sick, we wouldn't wipe out the electric shop. That's been a logistic nightmare trying to keep those other two guys in a place that you know … We're set up for one shop and I'm trying to get tools, parts, you know, equipment stuff, you know, over there thinking it's just going to be a few weeks or a few months at the most. It's been over, it's been a year this month that we've been apart like this. That's the most right there … and getting parts. Everybody's saying you know what, due to the COVID, and I understand that it is affecting, but it is really affected us just getting parts here. It's not just my shop, but the paint shop, the mechanics, you know, everybody. So, we're really having to look ahead try and try to keep things on hand, hoping nothing goes down that I have to get parts in soon.

INTERVIEWER:
If you were to change your program, maybe your maintenance strategy or maybe equipment to help you do airfield lighting maintenance in general even better, what would you want to change?

Interviewee #14:
I can't really think of anything other than just having a bigger staff that I can't think of anything we would change.

INTERVIEWER:
Is there anything that you want to ask me?

Appendix F

Category Development Maps

Figure F1

Map of Focused Codes Used to Develop the Access Category

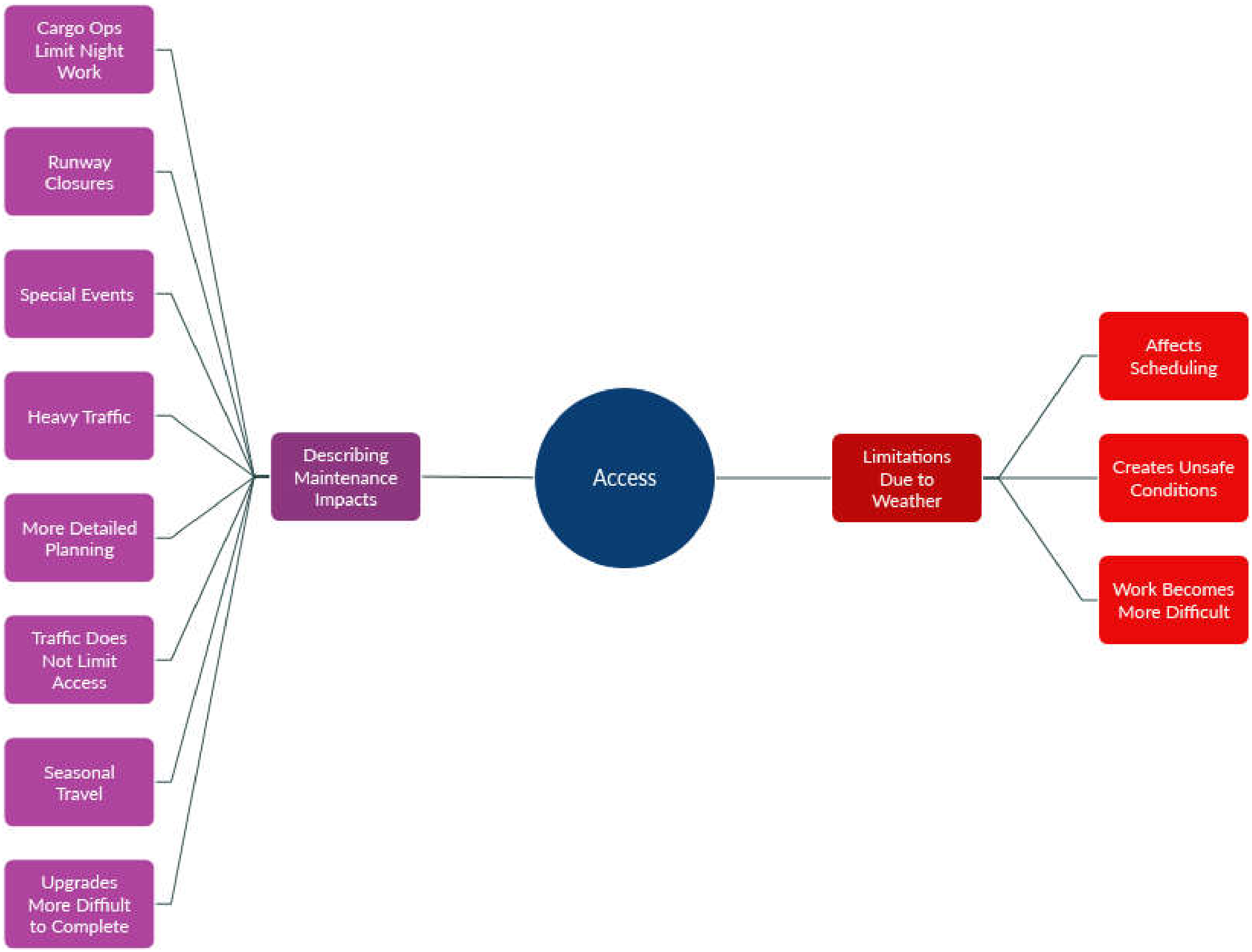

Figure F2

Map of Focused Codes Used to Develop the Budget Category

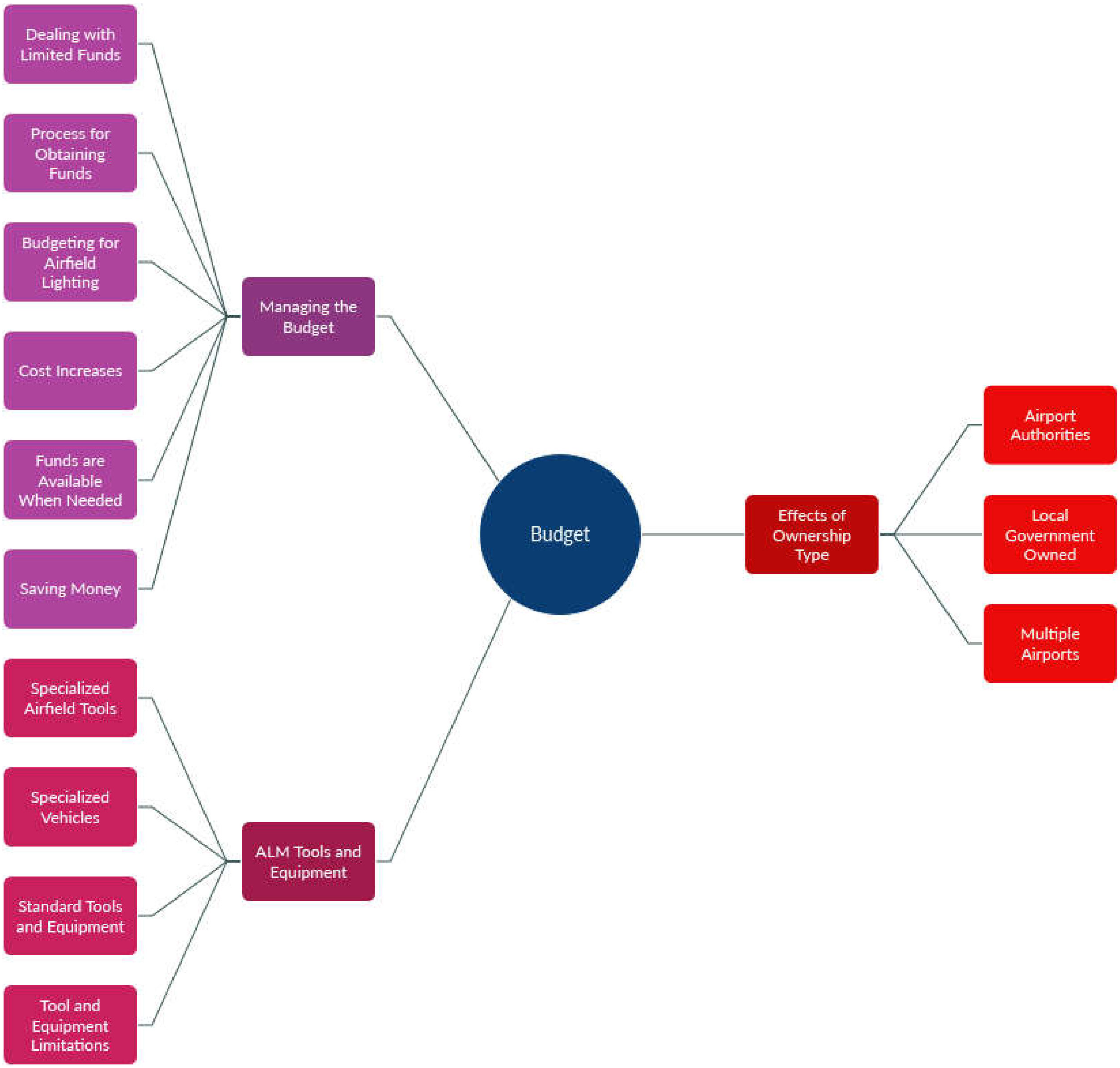

Figure F3

Map of Focused Codes Used to Develop the Condition Category

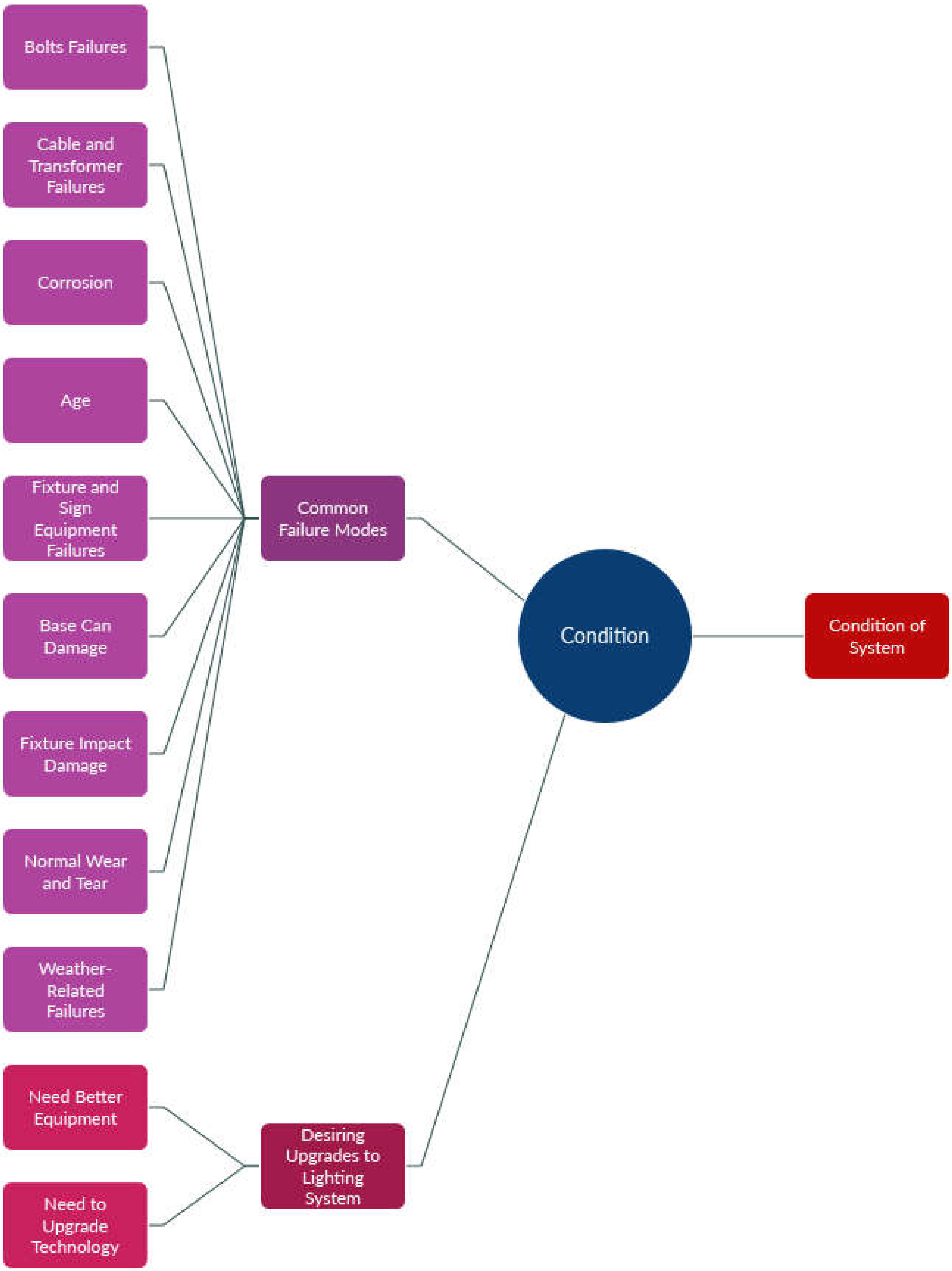

Figure F4

Map of Focused Codes Used to Develop the Design Category

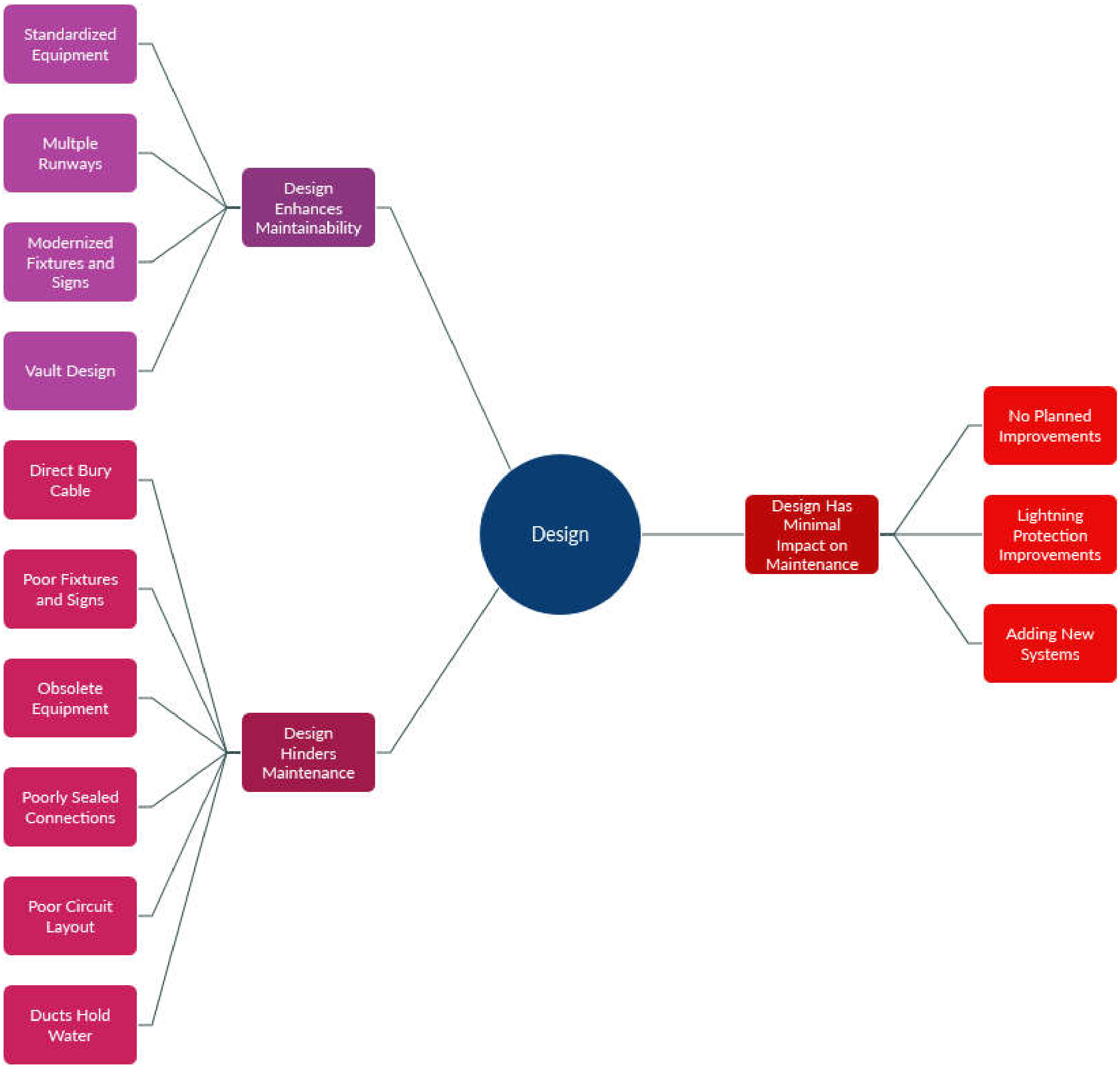

Figure F5

Map of Focused Codes Used to Develop the Environment Category

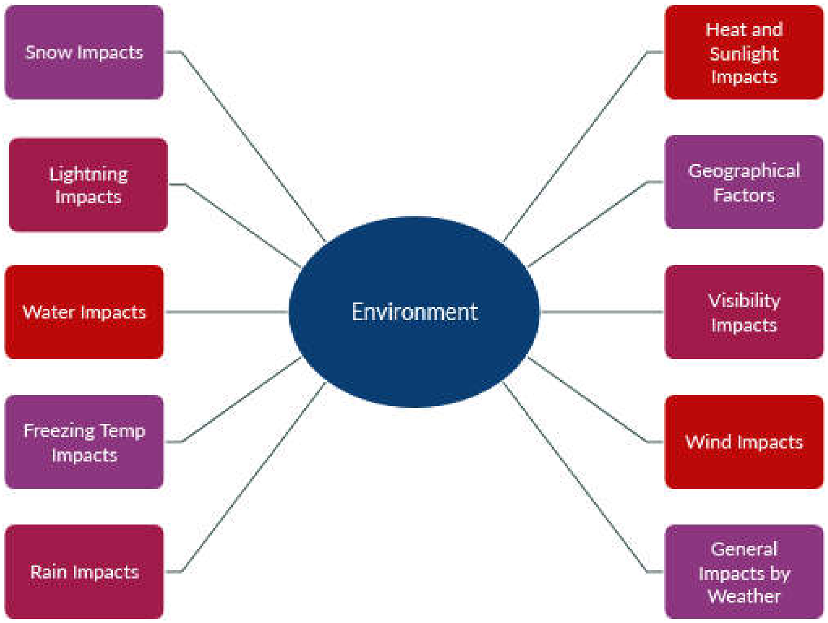

Figure F6

Map of Focused Codes Used to Develop the Impetus Category

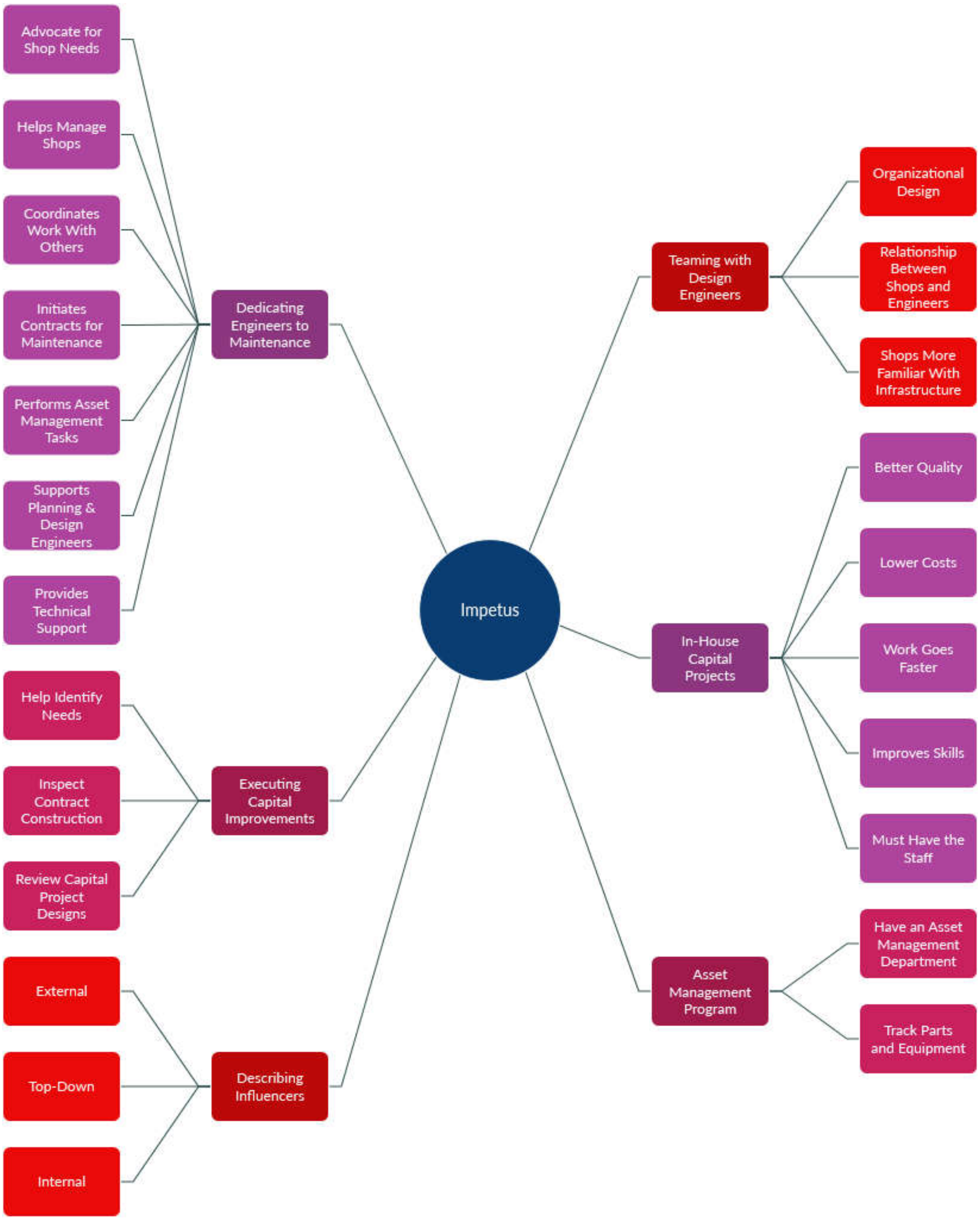

Figure F7

Map of Focused Codes Used to Develop the Regulations Category

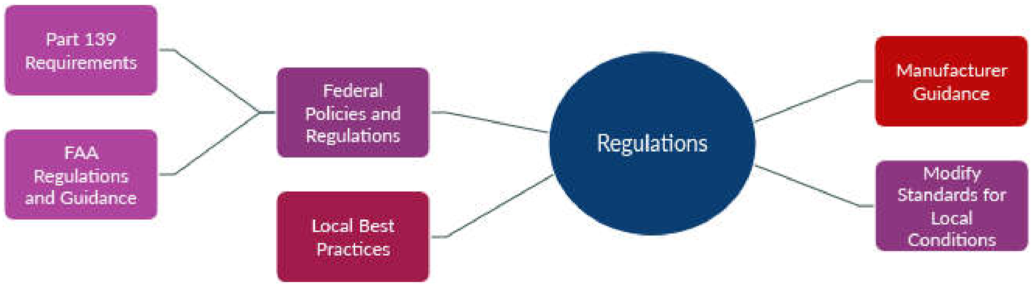

Figure F8

Map of Focused Codes Used to Develop the Staff Category